

**Department of Chemical Engineering**

**Investigation of Compressible Fluid Behaviour in a Vent Pipe during  
Blowdown**

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**This thesis is presented for the Degree of  
Master of Philosophy (Chemical Engineering)  
of  
Curtin University**

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**Declaration**

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: .....

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# Dedications

To Mum and Dad

*“Never regard study as a duty, but as the enviable opportunity to learn to know the liberating influence of beauty in the realm of the spirit for your personal joy and to the profit of the community to which your later work belongs”*

Albert Einstein

## **Abstract**

In the process industry, upset conditions can result in the release of fluids to the atmosphere. Such a release process is known as 'Blowdown'. Accurate modeling and prediction of the blowdown process is important in determining the consequences of venting operations and the design conditions required for vent and flare systems. The predicted information such as the rate at which the fluids are released, the total quantity of fluids released and the physical state of the fluid is valuable and helps in evaluating the new process designs, process improvements and improves the safety of the existing processes.

Blowdown events, amongst other transient processes, are the subject of particular interest to the chemical, oil/gas, and power industries. In the process plants, particularly in the hydrocarbon industry, there are many large vessels and pipelines operating under pressure and containing hydrocarbon mixture. Depressurization of such equipment's is frequently necessary during maintenance, and in an emergency it may have to be rapid. Hazards arise because of the very low temperatures generated within the fluid during the process and also from the large total efflux and high efflux rates that arise from the large inventory of the long pipelines and high pressure vessels. This inevitably leads to a reduction in the temperature of the vessel / pipeline and associated vent system, possibly to a temperature below the ductile-brittle transition temperature of the material from which the vessel, pipeline or piping is fabricated. To date, a number of blowdown models and simulation codes related to pressure vessels and pipelines have been developed to estimate the blowdown conditions in pressure vessels and pipelines. There is no general model developed specifically for analyzing the conditions developed in a vent pipe.

The scope of this work encompasses investigating the behavior of compressible gas in a vent pipe, during venting, by developing a vent pipe model. A fluid dynamic and thermodynamic approach is used in developing the model. The investigation is focused on the pressure, temperature and flow rates of flowing gas and pipe wall temperatures. The model is validated with experimental data generated by performing steady-state venting runs using compressed air. The model is also validated by comparing the simulations performed in Aspen Hysys for single component gases such as air, carbon dioxide, methane and multicomponent gases which are in very close agreement.



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## **Brief Biography of Author**

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He has written the following paper in the support of this thesis:

- “Investigations into Compressible Gas Behavior in a Vent Pipe during Blowdown”, a paper to be submitted for PSE-2012 conference, Singapore.

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## Nomenclature

$A$	Area	(m <sup>2</sup> )
$C_p$	Specific heat at constant pressure	(kJ/kg)
$C_v$	Specific heat at constant volume	(kJ/kg)
$D$	Diameter	(m)
$D_H$	Hydraulic diameter or pipe diameter	(m)
$f$	Friction factor	(-)
$G$	Mass flux	(kg/m <sup>2</sup> -s)
$g$	Gravitational constant	(m/s <sup>2</sup> )
$h$	Enthalpy	(kJ/kg)
$h_o$	Stagnation enthalpy	(kJ/kg)
$L$	Length	(m)
$L^*$	Critical length	(m)
$M$	Mach number	(-)
$M_w$	Molar mass	(kg/kmole)
$\dot{m}$	Mass flow rate	(kg/s)
$P$	Pressure	(kPa)
$P_o$	Stagnation pressure	(kPa)
$P^*$	Critical pressure	(kPa)
$Pr$	Prandtl number	(-)
$R$	Universal gas constant	(kJ/kmol.K)
$Re$	Reynolds number	(-)

$r$	Recovery factor	(-)
$s$	Entropy	(kJ/kg-K)
$T$	Temperature	(°C)
$T_o$	Stagnation temperature	(°C)
$T^*$	Critical temperature	(°C)
$T_{aw}$	Adiabatic wall temperature	(°C)
$V$	Velocity	(m/s)
$V^*$	Critical velocity	(m/sec)
$Z$	Compressibility factor	(-)
$\rho$	Density	(kg/m <sup>3</sup> )
$\rho_o$	Stagnation density	(kg/m <sup>3</sup> )
$\rho^*$	Critical density	(kg/m <sup>3</sup> )
$\varepsilon$	Roughness	(m)
$\gamma$	Specific heat ratio	(-)
$\mu$	Viscosity	(Pa.s)

# **Chapter 1**

## **Introduction and Objectives**

Designing sustainable processes is one of the key challenges of the chemical industry. This is by no means a trivial task as it requires translating the theoretical principles of chemical engineering into design practice. Process design is central to chemical engineering and can be considered to be the summit of chemical engineering, bringing together all of the components of that field. Properly designed, constructed, operated and maintained equipment will not fail provided that its design conditions are not exceeded. Risk reduction is another challenging task. Safety in process plants starts at the design stage and is followed by series of steps in order to reduce the risk completely.

In process plants, particularly in hydrocarbon industry, there are a large number of vessels and process piping which contain / carry large amounts of flammable inventories of hydrocarbons. Thus, the likelihood of an occurrence of an incident or risk associated in such industry is high. Such incidents can be significantly reduced by performing safety assessments and appropriate safety precautions. Despite many safety precautions within the hydrocarbon industry, equipment failures or operator errors may cause upset in process conditions beyond safe levels. If these conditions rise too high, they may exceed the maximum strength of process vessels and process piping systems. This can result in the rupturing of process vessels or piping, causing major releases of toxic or flammable hydrocarbons. Such a sudden release process is called 'Blowdown'. Blowdown events, amongst other transient processes, are the subject of particular interest to the chemical, oil/gas, and power industries. Blowdown can be an unexpected process as seen on ruptured pipelines/process vessels or can be planned during maintenance of the process equipment's. Accurate modeling and prediction of the blowdown process is important in determining the consequences of venting operations and the design conditions required for vent and flare systems. The primary purpose for blowdown is to reduce pressure and remove inventory in the least amount of time possible. Hazards mainly arise due to the changes in equipment process conditions taking place during the blowdown process especially high efflux rates. This inevitably leads to a reduction in the temperature of the vessel / pipeline and associated vent piping system, possibly to a temperature below the ductile-brittle transition temperature of the material from which the vessel, pipeline or piping system is fabricated. At a temperature below the ductile-brittle transition temperature, the equipment material has a much greater tendency to shatter on impact instead bending or deforming. It is under these



circumstances that the lowest wall temperatures will often be observed. In such cases, prior estimations of the resulting temperature drop in the fluids and the equipment involved are of primary importance. Such estimations can be predicted by developing models for performing simulations of blowdown operations.

Today, safety is equal in importance to production and has developed into a scientific discipline which includes many highly technical and complex theories and practices. More complex processes require more complex safety technology. Examples of the technology of safety include hydrodynamic modeling of flow through relief systems, developing mathematical techniques to determine various ways that processes can fail and the probability of its failure etc. Many blowdown models related to pressure vessels and pipelines have been developed till date but each one has their own pros and cons. There is no general model developed specifically for analyzing the fluid conditions developed in a vent pipe. A simple model for analyzing a gas blowdown in vent pipe is required. The main objective of this work is to investigate the effects of changes in gas flow conditions at different pressures and develop a simple steady-state vent pipe model and validate the developed model by performing simulations in Aspen Hysys.Plant and experimental analysis.

## **1.1 Objectives**

As mentioned above, accurate prediction of blowdown conditions is of primary importance. A number of blowdown models have been developed but no specific model is available for predicting the blowdown conditions in a vent pipe. A thorough investigation of gas behavior in a vent pipe during blowdown is required. Therefore, this study aims at developing a simple model for a vent pipe by performing steady-state calculations in MS Excel simultaneously utilizing Visual Basic code. Thermophysical properties for the gases are extracted from the REFPROP software by writing a Visual Basic code. The REFPROP software calculated the thermophysical properties using the GERG 2004 equation of state. This equation of state has been proved to be better than AGA8-DC92, Peng-Robinson and other cubic equation of state. Pressure and temperature variations of gas, temperature distribution on the vent pipe wall and the mass flow through the vent pipe are the key parameters which are to be predicted by modeling. These parameters govern the entire steady-state venting process. Hence, to investigate this venting process of the gas in a vent pipe and to validate the model, a 24m long test rig is designed and constructed. Experiments related to compressible gases such as air are conducted. The literature available on venting through vent pipes is very scarce. Modeling of vent pipes associated with pressure vessels and long pipelines is mentioned in literature but these models are based on

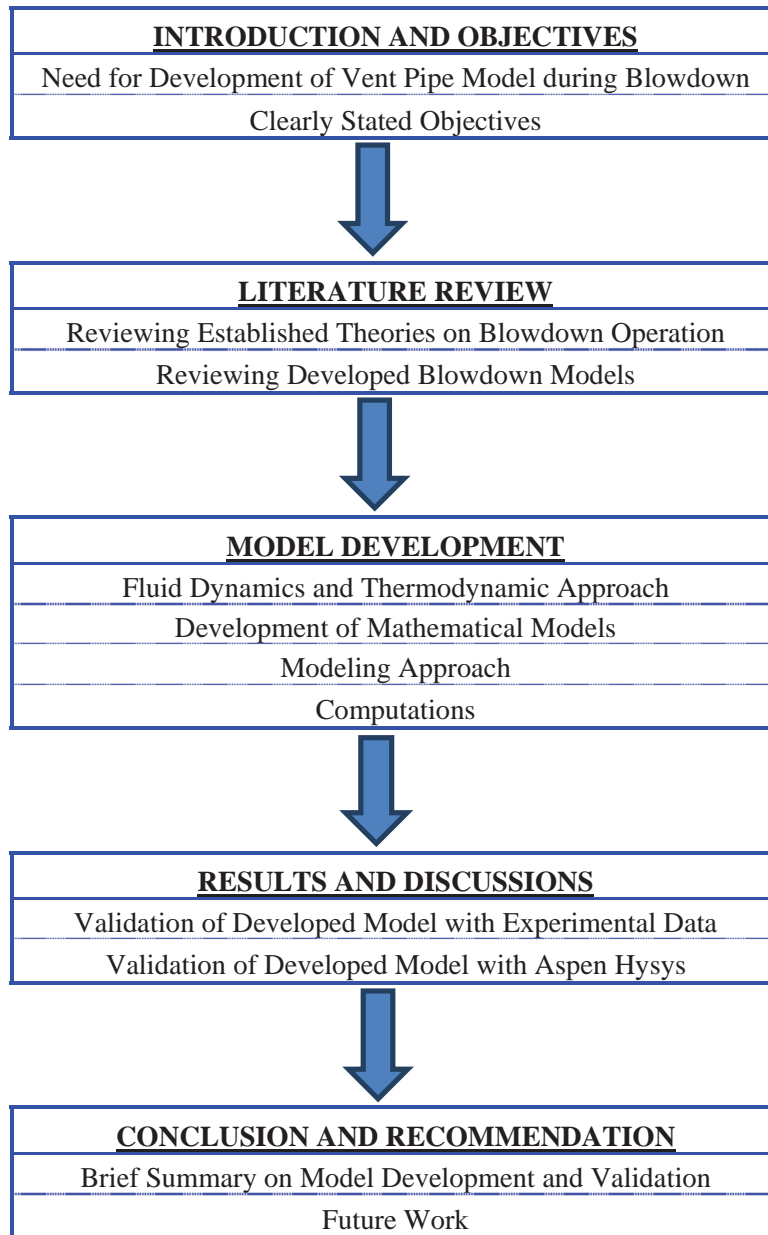
hypothetical assumptions (no validation). Few validated models do exist but are not available on commercial scale. This investigation will be a significant contribution to the field of blowdown operations.

The main aim of this research is to achieve the following objectives:

1. Design and construction of a test rig. A combination of knowledge of related processes and application of chemical and mechanical engineering 'first principles' will be used to satisfactorily design and fabricate the test rig.
2. Investigation of the behavior of fluids during blowdown using fluid dynamics and thermodynamic approach.
3. Development of a vent pipe model into Microsoft Excel Visual Basic in order to predict the pressures and temperatures of the inventory (gas) and the vent pipe wall temperatures experienced during venting.
4. Analyzing the results obtained from blowing down the test rig with air gas and providing a brief discussion with respect to thermodynamic theories.
5. Validating the developed model with the results obtained from the test rig blowdown and Aspen Hysys.Plant.

## 1.2 Thesis Outline

This thesis comprises of the following in detail as shown below in the form of a flowchart:



## **Chapter 2**

### **Literature Review**

A brief literature review related to the blowdown of pressure vessels / pipelines', accentuating the development of a simple steady-state gas flow model in a vent pipe, provides research progress to date. An extensive literature on blowdown modeling and experimentation related to pressure vessels and pipelines exists and is discussed in this section of the thesis.

The first section of the literature review explains comprehensively the purpose of blowing down a pressure vessel / pipeline followed by a brief description of blowdown process in pressure vessels and pipelines. Different release cases are tabulated and the need to design Emergency Depressurization System is highlighted in this section. The second section emphasizes on the current industrial practices in designing Emergency Design Systems (EDS) and operation of a typical pressure relief valve. The third section involves reviewing of thermodynamic Joule-Thomson phenomenon taking place during the blowdown. This part will also provide insights into the responsible parameters for causing changes in process conditions during blowdown. The fourth section provides details of hazards related to depressurizing a pressure vessel / pipeline. This part also provides an insight of the brittlement theory related to metals. The next section is introduced here, which gives an extensive review on blowdown process modeling from safety perspective and provides detailed investigations performed by various researchers on blowdown modeling. A quick summarization of the available literature review is provided towards the end of this chapter with an objective to focus on a simple gas flow vent model.

### **2.1 Blowdown**

In the last few decades, oil & gas industries have shown excellent developing trends with respect to production and technology. National Petroleum Council (NPC) of United States evaluated the future demand and supply in oil and gas. This showed a growth by 50-60% in the demand for energy by 2030 (Holditch and Chianelli 2008). Growing demand for energy produced from natural resources such as oil and gas, coal, nuclear energy etc. calls for a strengthening in exploration and development. However, it is evident from the fact that growing demand for energy will pose a greater risk for the hazards that may arise in process industries. Processes involved in the production of oil and gas facilities are always associated with risks and should be recognized for probable hazards. One such process operation is the risk associated with

‘Blowdown’. According to API (American Petroleum Institute 2007), the depressurization of a plant or part of a plant, or equipment is known as ‘Blowdown’

During emergency situations in gas processing plants or on oil or gas platforms, the pressure of the vessels / pipelines containing inventory must be reduced to avoid possible accidents. This is mostly done by discharging the inventory to a flare or vent system (Evanger et al. 1995) and it is called ‘depressurization’. The purpose of blowing down or depressurising a pressure vessel or a pipeline filled with inventory is to prevent the vessel or the pipeline from rupturing against ‘overpressure’ caused mainly due to process upsets or during a major fire exposure so that the resulting impacts to the vessel or pipeline are minimal. Sometimes, leaks due to abrupt rupture of process vessels or pipelines can result in emergency depressurization of the system. There are different instances during which blowdown of pressure vessels or pipelines section becomes necessary. These may be for a planned maintenance schedule especially during the shut-down or to protect the process equipment (vessel/pipeline) from over pressurization or in emergency situations which arises in the vicinity of fire. Thus, the entire blowdown process can be characterized to be a rapid release process. (Nolan 1996) has categorized such releases as described in table 2-1.

Table 2-1: Various release categories (Nolan 1996)

Catastrophic Failure	A vessel or pipeline opens completely immediately releasing its contents.
Long Rupture	A section of pipeline is removed being vented to atmosphere whose CS areas are equal to the CS area of the pipe.
Open Pipe	The end of a pipe is fully opened exposing the CS area of the pipe.
Vents, PRV	Smaller diameter piping or valves may be opened or fail which release vapours or liquids to the environment unexpectedly.
Normal Operation Releases	Process storage or sewer vents, relief valve outlets, tank seals, which are considered normal and acceptable practices that release to the atmosphere.

## 2.2 Blowdown Process

The physical phenomenon that occurs during depressurization or blowdown begins with an inventory filled vessel / pipeline reaching a trip pressure and the vessel / pipeline being isolated (Marian, Vuthaluru, and Ghantala). Such an arrangement is shown in figure 2-1 and figure 2-2 where an air receiver with automatic isolation and blowdown valve is installed and a gas pipeline with a sectionalizing valve in centre, a typical shop fabricated blowdown riser and

valve on the left, and a typical field fabricated riser on the right (Gradle 1984). As cited in the literature (Richardson and Saville 1991; Haque, Richardson, and Saville 1992; Norris III, Exxon Production Research Co, and R.C. Puls 1993; Fairuzov 1998), there exists a significant difference in the blowdown process occurring inside a vessel and long pipeline. Spatial uniformity of pressure distinguishes a vessel from a pipeline (Haque, Richardson, and Saville 1992).

### 2.2.1 Blowdown of Pressure Vessel

Skouloudis and Haque et al. have well explained the detailed phenomenon of the blowdown process from pressure vessels during top venting transients (Skouloudis 1992; Haque et al. 1989) and is addressed here. The initial process is actuated by opening of pressure relief valve (PRV) in both cases. The pressure vessel filled with inventory comprises of gas zone at the top, liquid zone at the bottom and sometimes a third zone for free water formed from condensation below the liquid zone. As soon as the relief valve opens, vapour contained in the freeboard volume of the pressure vessel will be released and the pressure falls rapidly inside the vessel. The liquid phase cannot follow this rapid change of pressure with a prompt change in

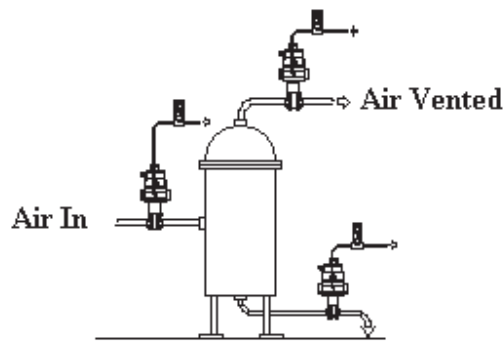


Figure 2-1: An air receiver with automatic isolation and blowdown valve installation (Spirax Sarco Limited 2011)

temperature and the liquid becomes superheated. This leads to thermodynamic disequilibrium between the phases which are re-established after a short time by vigorous re-evaporation of the liquid. During this period the high depressurization rate is reduced followed by a marked pressure recovery which might occur when the vapour volume produced by evaporation exceeds the volume of the mixture which flows out of the vessel. Vapour still discharges through the vent line together with some droplets

entrained from the interface separating the predominantly liquid and the predominantly vapour regions of the vessel. As soon as this level reaches the vent line a distinct two phase mixture is discharged with large liquid content. Nevertheless, the evaporation processes continue and the thermodynamic disequilibrium is reduced. The interface level gradually collapses so that the vent line is no longer blocked. Then a predominantly vapour mixture again leaves the vessel

with several liquid droplets entrained. During this process the pressure in the vessel falls continuously until a new state of equilibrium has been established with the surroundings.

### 2.2.2 Blowdown of Pipeline

Richardson et al. and Fairuzov have well explained the detailed phenomenon of the blowdown process from pipeline (Richardson and Saville 1991; Fairuzov 1998) as is addressed here. The process of pipeline depressurization can be divided into three stages: depressurization wave

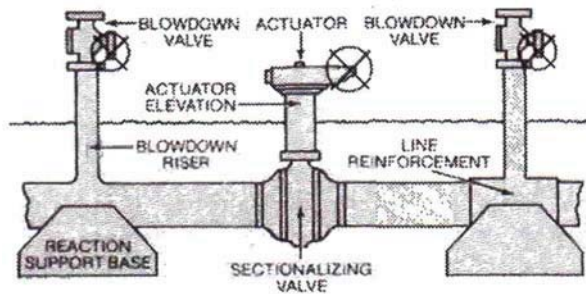


Figure 2-2: Gas pipeline with a sectionalizing valve in centre, a typical shop fabricated blowdown riser and valve on the left, and a typical field fabricated riser on the right (Gradle 1984)

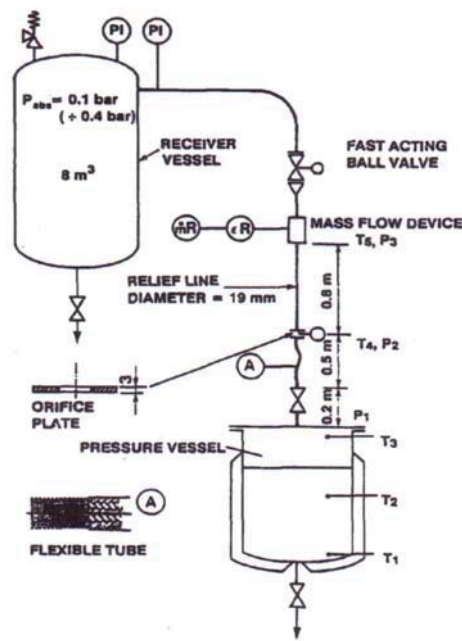
propagation, choked critical flow from the line and unchoked critical flow from the line. Upon opening the blowdown valve, an expansion wave travels from the ruptured or open end of the line to the intact end of the line. The pressure at the intact end is unchanged from the initial pressure. The flow is choked at the ruptured or open end. After the expansion wave has reached the intact end of the pipeline, the fluid pressure inside the pipeline is very close to the saturation pressure corresponding to the fluid temperature. The pressure at the intact end starts to fall. However, this does not affect the flow condition at the open end of the pipeline and is still choked. The main contribution to the pressure drop in the line arises because of the friction at the wall. When the pressure in the line starts decreasing sufficiently, the flow from the ruptured end ceases to be choked. The main contribution to the pressure drop in the pipeline is again caused due to friction at the pipe wall. In case of flashing liquids, flashing occurs within the whole pipeline. The flashing process causes constant changes in the flow pattern. The fluid temperature decreases due to the drop in the fluid pressure. The pipe wall is cooled by the fluid flowing through the pipeline.

In both cases as the inventory passes through the choke Joule-Thomson expansion takes place. Rapid cooling takes place due to isenthalpic expansion of the high pressure gas through the throttling process. Due to Joule-Thomson expansion, the contained inventory cools and draws heat from the vessel / pipeline walls, thus producing an auto-refrigeration effect or cooling the vessel / pipeline walls. In case of gaseous phase expansion will take place. If liquid inventory is present, flashing takes place soon after its pressure reaches the saturation pressure corresponding

to the fluid temperature (Fairuzov 1998) and the composition of the inventory changes with decrease in pressure (Nageshwar 2003). Under this instance the mass flow rate of inventory depends on the supply pressure and will decrease as the supply pressure decreases (Hong et al. 2004). Such a rapid release process accentuates the designing of emergency depressurizing system and is discussed in the next section.

### 2.3 Blowdown or Emergency Depressurizing Systems

In process industry, especially in hydrocarbon processing facilities, severe risks with respect to fire, explosions and vessel ruptures are always associated. Designing safe technology has always been a challenge for chemical engineers. Among the prime methods to prevent and limit the loss



potential from such incidents are the provisions of hydrocarbon inventory isolation and removal system (Nolan 1996). These systems are referred to as Emergency Depressurizing Systems (Nolan 1996). For the emergency system relief in a chemical plant several types of venting device are installed such as nozzles, long pipes with or without bends, orifice plates or other safety relief valves. A typical layout of vent testing facility is shown in figure 2-3. Currently, industry tends to use American petroleum Institute's Recommended Practices 520 (American Petroleum Institute 2008) and American petroleum Institute's Recommended Practices 521 (American Petroleum Institute 2007)

for specification and designing of emergency depressurization systems (Roberts et al. 2004). API RP 521 defines a vapour depressurizing system as a protective arrangement of valves and piping intended to provide for rapid reduction of pressure in equipment by releasing vapours. API RP 521 defines a pressure-relieving system as an arrangement of a pressure-relieving device, piping and a means of disposal intended for the safe relief, conveyance and the disposal of the fluids in a vapour, liquid or gaseous state. Such a relieving system may consists of only one pressure relief valve or rupture disc, either with or without discharge pipe, on a single vessel or line. The function of blowdown facilities is to provide a means of venting the high pressure gas to the atmosphere in a relatively short period of time (Gradle 1984). To relieve the overpressure build-



up in the vessel or pipeline, the pressure vessels / pipelines are installed with blowdown valves or pressure relief valve (PRV) or pressure safety valve (PSV). These valves sense the overpressure and are actuated automatically or manually to relieve the overpressure by reducing the inventory and pressure within the isolated process vessel or pipeline section. The relieved inventory is routed to a safe location e.g. to a blowdown or knockout drum and then to a flare or a vent system to safely remove the vapours from the area and dispose without impact to the environment.

### 2.3.1 Pressure Safety Valve

Typically, hydrocarbon pressure vessels are provided with a pressure safety valve (PSV), to

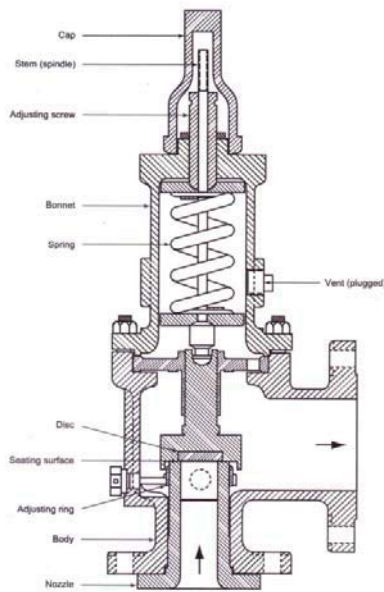


Figure 2-4: Spring loaded PRV (American Petroleum Institute 2008)

relieve internal pressure that develops above its designed working pressure. The purpose of the PSV is to protect the vessel from rupturing due to overpressure generated from process condition or exposure to fire heat loads that generate additional vaporization pressure inside the vessel. A blowdown valve is a pressure relief valve which is designed to open at a predetermined pressure in order to protect a vessel or system from excess pressure by removing or relieving fluid from that vessel or system. A typical arrangement of a spring loaded PRV is shown in figure 2-4. Although, different types of PRV's are available all differ from each other with respect to their operating function. As described in (American Petroleum Institute 2008), a spring loaded PRV consists of an inlet nozzle which is connected to the vessel or the system to be protected against overpressure, a movable disc which rests on the nozzle head under normal operating conditions and a spring which controls the position of the disc. The movable disc controls the flow through the nozzle. The spring loaded PRV works on the principle of force balance which acts on the movable disc on the nozzle. The spring load is preset to equal a force exerted on the movable disc (closed position) to equal the force exerted on the closed disc by the inlet fluid through the nozzle. Under normal operating conditions, the disc is seated on the nozzle head until the pressure exceeds the set pressure. Once the inlet pressure exceeds the set pressure, the pressure force overcomes the spring force and the valve opens. When the inlet pressure is reduced to the closing pressure, the valve re-closes. The

of the disc. The spring loaded PRV works on the principle of force balance which acts on the movable disc on the nozzle. The spring load is preset to equal a force exerted on the movable disc (closed position) to equal the force exerted on the closed disc by the inlet fluid through the nozzle. Under normal operating conditions, the disc is seated on the nozzle head until the pressure exceeds the set pressure. Once the inlet pressure exceeds the set pressure, the pressure force overcomes the spring force and the valve opens. When the inlet pressure is reduced to the closing pressure, the valve re-closes. The

valve reseats when the inlet pressure or vessel pressure has dropped sufficiently below the set pressure and this pressure at which the valve reseats is called the closing pressure. The gas then passes through a vent system to the flare or vent header. A number of thermodynamic changes take place in the gas properties while releasing the gas through the vent pipe into the atmosphere. These changes in gas properties can have an impact on the vent pipe, thus, affecting the material of construction of the metal wall, especially when low temperatures are experienced in the process. To understand this phenomenon, the thermodynamic physical properties should be well understood.

## **2.4 Thermophysical Property**

When a gas expands through a restriction from a high pressure to low pressure changes in temperature takes place. This process occurs under conditions of constant enthalpy and is known as Joule-Thomson expansion (Shoemaker, Garland, and Nibler 1996). Joule-Thomson expansion is a thermodynamic physical property which is experienced during blowdown. The temperature change is related to pressure change and is characterized by the Joule-Thomson coefficient. The temperature drop increases with increase of pressure drop and is proportional to the Joule-Thomson coefficient (Maric 2005). Joule-Thomson expansion takes place under adiabatic conditions such as well insulated vessel or pipeline. In case of an uninsulated vessel or pipeline the pressure change is rapid or the velocity of flow is high such that no heat transfer takes place. The Joule-Thomson expansion phenomenon can be well understood by passing a gas through a restriction while the fluid is allowed to expand adiabatically. During this process, no work is done and the changes in potential and kinetic energy are negligible. It has been proved that the gas flow through the restriction results in an isenthalpic (constant enthalpy) process (Jones and Hawkins 1986). Thus, the gas escaping through the choke from vessel or pipeline into the vent system will follow an isenthalpic path. At the same time, the gas flow pattern is affected because of the entrance valve port area and frictional resistance in the vent pipe (Gradle 1984). According to (Gradle 1984), an increase in the valve port area will increase the mass flow rate through the vent system resulting in choked flow condition. At the same time an increase in pressure drop results by an equivalent amount to valve port area opening. The pipe frictional effects will equally contribute to the pressure drop and will tend to increase the flow path resistance, thus, reducing the flow rate through the valve. Nonetheless, due to Joule-Thomson expansion the bold inventory contained in the vessel or pipeline cools and draws heat from the vessel / pipeline walls thus producing an auto-refrigeration effect. Generally, when Joule-Thomson expansion takes place, one of the two effects may take place- Joule-Thomson Cooling

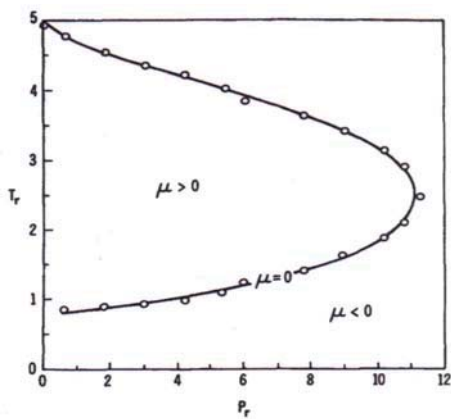


Figure 2-5: Typical inversion curve - Data for nitrogen gas (Wisniak and Avraham 1996)

effect and Joule-Thomson Inversion (heating) effect (Wisniak and Avraham 1996). Various authors (Wisniak and Avraham 1996; Maric 2005) have investigated and modelled the Joule-Thomson coefficients and inversion curves. An inversion line is a curve formed by passing through maximum temperature points for a given constant enthalpy line. As shown in the figure 2-5 the inversion curve divides the pressure-temperature plane for nitrogen gas into two zones. In the zone inside the inversion curve the adiabatic Joule-Thomson effect is positive, so that decreasing the pressure leads to a decrease in

temperature whereas outside the inversion curve the adiabatic Joule-Thomson effect is negative and a decrease in pressure leads to an increase in temperature. It is understood that an expansion that begins from the inversion pressure leads to the highest cooling effect (Wisniak and Avraham 1996).

## 2.5 Blowdown Effects

The problem related to the blowdown of pressure vessels / pipelines containing mixtures of hydrocarbons are well known amongst industries involved in plant designing and hydrocarbon extraction (Speranza and Terenzi 2005). As discussed earlier, during blowdown / depressurisation of a pressure vessel or pipeline the most common effect encountered is the Joule-Thomson Cooling effect. The primary hazard associated during this process is the occurrence of brittle fracture in the vessel / piping material due to sudden decrease in temperature.

Generally, steel type such as carbon steel and other ferritic steels which form the material of construction for most pressure vessels / pipelines become susceptible to brittle fracture with decrease in temperature (Khazrai, Haghghi, and Kordabadi 2001). The susceptibility of steel such as carbon steel to brittle fracture is related to temperature. As the temperature decreases, the susceptibility to brittle fracture increases (King 2006). If the temperature reaches close to or below the ductile-brittle transition temperature of the vessel / pipeline material of construction, the equipment will be prone to failure (Mahgerefteh and Wong 1999). The Joule-Thomson cooling effect provides the mechanism for low temperature exposure.

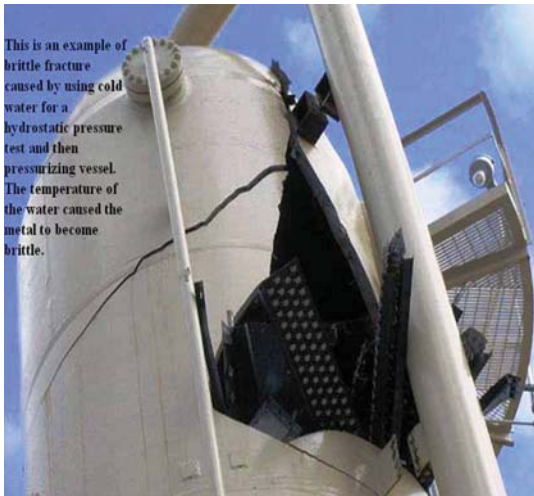


Figure 2-6: Brittle fracture developed in a pressure vessel (Keenan 2009)

Another key factor which increases the probability of metal brittle fracture is the minimum level of applied stress to propagate a brittle fracture. When the temperature of a body is raised, or lowered, the material expands or contracts. If this expansion or contraction is wholly or partially resisted, stresses are set up in the body (Case, Chilver, and Ross 1999). For the crack to propagate through the material of construction, it must have sufficient energy

which is available in the form of ‘overpressure’. At lower temperatures the yield strength is greater and the fracture is more brittle in nature.

The reason for this could be atomic vibrations (Shackelford 2005). As the temperature of material decreases, atomic vibrations decrease and the atoms do not slip to new locations in the material. As the stress increases, the atoms break their bonds and do not form new ones. This decrease in slippage causes little plastic deformation before fracture. Thus, brittle fracture occurs with rapid crack propagation and results in a catastrophic failure of a material with little or no plastic deformation (King 2006). Figure 2-6 shows a pressure vessel under brittle fracture caused by cold water for a hydrostatic pressure test and then pressurizing the vessel. The temperature of the water caused the metal to become brittle.

A secondary hazard arises if there is a significant liquid. During complete blowdown of pressure vessel, the gas-liquid interface reaches the top of the vessel choke. This results in a significant liquid carryover with the gas into the vent or flare system. Carryover of a significant quantity of liquid can present considerable operational difficulties to a flare or vent system designed to handle gas alone (Haque, Richardson, and Saville 1992).

## 2.6 Investigations into Developed Simulation Codes and Models

The depressurization process is not amenable to simple analysis due to its highly transient unsteady-state nature. There are several parameters that characterize the venting processes and are classified according to their significance as geometrical, operational and physicochemical during depressurization. The influence of these parameters during depressurization is well studied (Skouloudis 1992). Nonetheless, the resulting effects from blowing down a pressure

vessel / pipeline can pose a significant safety hazard (Cumber 2001). Therefore, a fundamental study of the blowdown process is crucial in the assessment of safety practices and procedures to prevent or minimise the consequences of controlled or uncontrolled releases (Chen, Richardson, and Saville 1995a). Predicting the conditions occurring during blowdown has always been a challenge to chemical engineers (Mahgerefteh and Wong 1999). Consequently, in recent years there have been a number of theoretical and experimental studies relating to blowdown simulation with varying degree of sophistication (Mahgerefteh, Saha, and Economou 1999) and several empirical correlations have been proposed (Weiss, Botros, and Jungowski 1988). These models / coded programs developed are distinct from each other (very limited) in the range of applicability.

Several numerical codes are available for monitoring some or all of the parameters which are directly related to the depressurization of vessels or pipelines. These codes have been developed for different types of application and although in principle solve similar sets of conservation equations for the mass, momentum and energy. Despite based on the same principles, these codes / programs differ significantly from each other in context to describing the phenomenology of the transient, the method of solving the pertinent equations, homogeneity / non-homogeneity and thermodynamic equilibrium / disequilibrium assumptions for multiple phases. A number of benchmark exercises were conducted (Skouloudis 1992) which concentrated on the hydrodynamic aspects of venting of vessels containing fluids (water / refrigerant R114) under high pressure, identification of parameters characterizing the emergency relief as well as the problems associated with the theoretical modeling of such processes with four American codes namely RELAP, SAFIRE, RELIEF and DEERS

RELAP and its derivatives codes RELAP4/MOD6, RELAP5-EUR/MF (Worth, Staedtke, and Franchello 1993) were developed to describe the transient single and two phase flows in complex networks on the basis of a one dimensional approach. Correlations for single phase natural and forced convection, sub-cooled and saturated nucleate boiling, critical heat flux, transition boiling, minimum heat flux, annular and dispersed film boiling and calculations for friction factors are included in the code. RELIEF (Nijsing and Brinkhof 1996) and DEERS (Skouloudis 1992) codes also use a one dimensional mass, momentum, and energy conservation equations. RELIEF code discretizes the vessel into several control volumes but a single control volume for a vent line. DEERS code can be used in the venting of a large variety of systems. However, the use of a single two phase model throughout the whole transient restricts the accuracy of its predictions. CHARME-01 (Stoop, Bogaard, and Koning 1986), a thermo-

hydraulic computer program developed in the late 1970's provided more accurate computational results in comparison with other numerical solution techniques in the calculation of transient thermo-hydraulic phenomenon. CHARME-01 code based on the Method of Characteristics (MOC) and includes proper treatment of the shock wave phenomenon. A comparison of CHARME-01 and RELAP4/RELAP5 was demonstrated by (Stoop, Bogaard, and Koning 1985) while describing the thermo-hydraulic loading condition of the reactor pressure vessel vent line in the event of hydrogen being released from the reactor vessel into the vent line. All these codes consisted of specific models for predicting the different conditions taking place during blowdown / depressurization of reactor vessels.

The DIERS computer program SAFIRE (System Analysis for Integrated Relief Evaluation) was developed primarily for vent-sizing calculations and for the interpreting the results of the large-scale chemical reacting fluids. SAFIRE code is written in ANSI Standard FORTRAN-77 comprising of 9000 lines of FORTRAN with 66 subroutines (Tilley and Shaw 1990). The main feature of the SAFIRE is its ability to handle up to 10 simultaneous chemical reactions with 10 components. The program solves one dimensional mass, momentum, and energy conservation equations in the vent line and can also solve these pertinent equations for vessels; however, it assumes a single control volume for describing the vessel. The code can model many different aspects of emergency relief situations such as (Tilley and Shaw 1990)

- Complex runaway reactions with or without gas generation
- External heat loads (eg. Fire)
- Venting of gases or mixtures of liquids and gas
- Vapor-liquid disengagement in the vessel being vented
- Non-idealities in vapor-liquid equilibria and in gas compressibility
- Various vessels and vent line geometric combinations

SAFIRE has a wide range of vent flow calculation routines implemented as subroutines. Example: Compressible gas flow through a nozzle is handled by subroutine GASN using conventional gas dynamic relationships. Similar subroutine GASLT can also be used to solve the compressible flow through a nozzle. While there are many vent flow models available in SAFIRE, not all can be used in all situations. The choice of the most appropriate model for a particular scenario requires the user to have a detailed knowledge of the range of application of each model (Cumber 2001). The friction factor for vent line required for calculating the frictional pressure drop has to be user defined. The two phase friction factor is calculated based



on the single phase relationship which is based on the liquid phase viscosity (only). The physical properties for the components must be provided by the user in the input data in terms of the coefficients to the correlations included in SAFIRE. The use of several input options in characterizing the venting process makes the code user-dependent. An improper specification of a flow model may lead to gross under-sizing of vent system with catastrophic consequences, thus making the code very versatile. SAFIRE is not an appropriate tool for the inexperienced user (Tilley and Shaw 1990). The model assumes a Homogenous Equilibrium Model (HEM) and thermodynamic equilibrium for two phase system (Skouloudis 1992). A further difficulty with the application of SAFIRE is that model robustness has been found to be a problem (Cumber 2001).

For long gas pipelines in hydrocarbon service, the most impressive study was found by Botros et al. (Botros, Jungowski, and Weiss 1989). In this study, a very mechanistic analysis that included pipeline friction drop was supported by a full scale gas pipeline blowdown. Two physical models were described one which takes into account the main pipeline as the volume model (without frictional losses) with stagnation conditions inside the main pipe and the other as the pipe model (with frictional losses) with velocity increasing towards the exit. Solutions for the relevant model equations were obtained analytically and real gas properties for the gas (natural gas) were obtained numerically. Blowdown time was calculated and the results were compared with those obtained using the graphs (Gradle 1984) and own field measurements of a straight pipe section and a compressor station yard piping. Effects of stack entrance and friction losses and discharge coefficient were also evaluated. The study relates only to the main pipeline section and effects of stack entrance and friction losses upstream of the blowdown valve (throat area) are evaluated at which point sonic flow discharge results. Depending on the pressure in the main pipeline, a subsonic or supersonic flow will result downstream of the blowdown valve. The piping downstream of the blowdown valve or throat is neglected to provide simplicity in modeling approach.

We agree to the fact that the physical processes taking place during blowdown are a complicated mixture of several phenomena typically comprising of fluid mechanics, heat transfer, and phase equilibrium. To investigate into these phenomenon, a programme of experimental work was carried out (Haque et al. 1989). The experimental work was focused on depressurization related to pressure vessels which varied from 5 to 110 cm in diameter, with a length to diameter ratio of 10 to 3 respectively. Depressurization experiments were conducted with nitrogen, 70-30% mixture of nitrogen and natural gas/propane mixtures. Measurements were taken which included

the pressure, temperatures at a large number of positions both within the fluid phases and on the wall of the vessel, and composition, all as a function of time which helped in the understanding of the blowdown process. Based on the investigations performed and experimental data available a mathematical model called 'BLOWDOWN' program was developed. The objective of this model is to be able to simulate all physically significant effects. Initial development (Haque et al. 1989) of 'BLOWDOWN' incorporated the presence of only two zones: the top zone contains only vapor together with any suspended liquid-phase droplets; and the bottom zone containing all liquid phase. The developed model provided a good understanding of the physical processes occurring during the blowdown, even for multi-component multiphase systems. However, it should be noted that there might be a possibility of free water formation settled below zone2. With this in mind, Haque et al. extended the above work and incorporated zone3 for free water (including dissolved hydrocarbons) in the 'BLOWDOWN' program (Haque, Richardson, and Saville 1992). This program was validated again (Haque et al. 1992) with a number of experiments performed on pressure vessels and case studies. The measurement results and predictions were found to be in good agreement.

The distinction between the blowdown of vessel and blowdown of a pipeline is that there is a significant pressure difference within the latter but not within the former. This significant pressure difference is mainly due to frictional effects encountered at the wall of the pipeline. Also, in case of blowdown of pipelines it becomes necessary in predicting high efflux rates that arise when the very large inventories are involved. With this in mind, an extension of the 'BLOWDOWN' program which can simulate the depressurization of a pipeline was undertaken (Richardson and Saville 1991). Richardson and Saville divided the pipeline into a number of elements and performed mass, momentum and energy balances for each element with variability in elemental size to satisfy a number of requirements (Richardson and Saville 1991). Pertinent equations involved in blowdown of gas line and condensate is well described and the developed model is validated with two case studies – one for the blowdown of the gas line between Piper and MCP-01 and the other is for the full-bore blowdown of a typical condensate line. A comparison of BLOWDOWN predictions with the measurements made during eight of the tests using LPG carried out by Shell and BP on the Isle of Grain in 1985 (Richardson and Saville 1996). Four of the tests were for full-bore depressurizations and four for depressurizations with orifices at the open ends of the lines. In all cases mentioned above, the BLOWDOWN predictions were found to be in good agreement.



Although mentioned the use of 'BLOWDOWN' program in simulating vessel / pipeline and associated vent / piping system (Haque, Richardson, and Saville 1992; Richardson and Saville 1991, 1996), no thorough calculation procedures or computer algorithms have been described. Also, the thermodynamic, phase and transport properties for BLOWDOWN are calculated using PREPROP, which is a computer package developed to calculate thermo-physical properties of multi-component mixtures by an extended principle of corresponding states which as well as introducing uncertainties associated with its accuracy (Jones and Hawkins 1986), makes the simulation computationally demanding (Mahgerefteh and Wong 1999).

A simple mechanistic model FRICRUP coded in FORTRAN program for predicting the blowdown process of vessels and pipelines for both single phase and multiphase flow was developed (Norris III, Exxon Production Research Co, and R.C. Puls 1993). A homogenous equilibrium model and thermodynamic equilibrium model assumption, along with no relative velocities between vapor and a liquid phase is assumed. The fact of steady-state hydrodynamic conditions prevails in the vented pipe after the vessel is presented. Experiments are conducted incorporating gases such as air, carbon dioxide and carbonated water for the validation of FRICRUP code. The results of experiment and predictions by model are in good agreement. The importance of pipe friction during the blowdown process is well highlighted. This factor confirmed that the modeling of pipelines as vessels can be easily seriously inadequate. Despite of its sophistication, the model does not agree very well for multiphase flow as can be seen from experiments performed with carbon-dioxide which could be because of the assumption of thermal equilibrium. Further experiments were carried out using several hydrocarbon gases including both methane and heavier mixtures (Norris III and Exxon Production Research Co 1994). The pronounced difference in the blowdown behavior between pipelines and vessels noted in the non-hydrocarbon experiments was confirmed for the hydrocarbon gases tested. The basic assumptions for the model remained the same and similar results were obtained as obtained when dealing with non-hydrocarbon gases.

Investigations into the blowdown of carbon dioxide from initially supercritical conditions have been performed (Gebben and Eggers 1995). The supercritical condition selected for the blowdown process was such that on pressure release flashing occurs after saturation condition has reached. Experiments were accomplished for initial conditions that varied in temperature, pressure, and minimum diameter of the venting line. Results showed that by enlarging the cross sectional area of the venting line the outgoing mass flow rate from the vessel is increased.

Thermo-hydraulic phenomenon were discussed, particularly the pressure transients, the axial temperature profile, and the axial void fraction profiles.

In order to evaluate the temperature effects of depressurization on the outside surface of the steel wall, a full scale depressurization tests on parts of the topside piping on a riser platform in operation was conducted (Evanger et al. 1995). The experimental results generated were compared to the simulation CFD (Computational Fluid Dynamics) code PIA, developed at NTH/SINTEF division. A one-dimensional and two dimensional analysis is performed by the code PIA and incorporates a finite difference technique for numerical calculation of general heat and mass transfer both in fluid and solid material. A brief description on the experimental set-up is given and the calculations performed for the outer steel pipe wall temperatures are in good agreement with the measurements. However, it seems to be that PIA gives satisfactory results for gas systems with not too much liquid present in the inventory.

Guerst's variational principle for bubbly flow was extended to generalized multi-component two phase dispersions, and formulated a two fluid model for single and multi-component vapor-liquid mixtures (Chen, Richardson, and Saville 1995a). In particular focus was on the development of the energy conservation equation and equations of motion for compressible single or multi-component vapor-liquid mixtures using a thermodynamic equilibrium assumption. As described (Chen, Richardson, and Saville 1995a), the Guerst's variational principle allows both phases to be compressible in deriving the momentum equations which contradicts the definition of compressible flow. In the second part of the article, a simplified numerical method for solving two phase, multi-component flow equations was proposed and a detailed study of the blowdown from pipelines containing one and two component flashing mixtures was presented (Chen, Richardson, and Saville 1995b).

A mathematical model for simulating the blowdown of a pipeline conveying flashing multicomponent mixtures was developed (Fairuzov 1998). The major features of the model comprise of hydrodynamic model, break-flow model and heat transfer model are well explained. Fairuzov suggested that a large amount of heat is transferred from the pipe wall into the fluid during the blowdown process and hence the adiabatic assumption for simulating the blowdown process is not valid. Based on this assumption, the effect of thermal capacitance was incorporated into the model by employing a new approach in the formulation of energy conservation equation for the fluid flow in the pipeline. The study revealed that the thermal capacitance of the pipe wall has a significant influence on the two-phase flow behavior and

should not be neglected in the analysis of blowdown of long pipelines containing flashing liquids. The model was compared to experimental data of and the model predictions hold in good agreement to the experimental data. The effects of friction on the blowdown time were assessed.

Further development of BLOWDOWN model, based on cubic equation of state, for blowdown of vessels containing high pressure hydrocarbons was carried out (Mahgerefteh and Wong 1999). The model, termed as BLOWSIM incorporates the Soave Redlich Kwong EOS, Peng Robinson EOS and the newly developed TCC cubic EOS for simulating vapour space blowdown of vessels containing multicomponent hydrocarbon mixtures. BLOWSIM model takes into account the non-equilibrium effects between phases, heat transfer between each fluid phase and their corresponding sections of vessel wall, interphase fluxes due to evaporation and condensation, and the effects of sonic flow at the orifice. BLOWSIM predicts the discharge rates, pressure as well as the fluid and wall temperatures with time. The fluid phase material balances depending on the zones formed inside the vessel, thermodynamic trajectories for fluid phases, heat transfer between vessel wall-fluid phases, discharge calculations and calculation of thermophysical properties are well explained. The performance of BLOWSIM is evaluated by comparing the predictions generated to the predictions generated from BLOWDOWN as well as to the published field data for high pressure blowdown of a full size vessel containing a condensable hydrocarbon mixture. The model accurately predicts the vessel pressures as a function of time and is in close agreement with BLOWDOWN. The minimum average bulk gas temperature is predicted to within 2 K, the unwetted wall temperature is overestimated by ~4 K and the wetted wall temperature is underestimated by ~5 K when compared to measured data. The authors have provided reasoning for this over-estimation and under-estimation. The instantaneous formation of liquid phase at the start of depressurization is predicted much earlier by the BLOWSIM model than when compared to BLOWDOWN program.

An efficient numerical simulation (CNGS-MOC), based on the method of characteristics for simulating full bore rupture of long pipelines containing two phase hydrocarbon is developed (Mahgerefteh, Saha, and Economou 1999). The long CPU time has been largely addressed, and this has been synonymous so far with such types of simulations by using curved characteristics in conjunction with Compound Nested Grid System (CNGS). Curved characteristics are used as they can afford the use of much larger discretization grids; while at the same time improve the global accuracy. The method of characteristics is adopted to simulate the full bore rupture or blowdown of long pipelines containing condensable or two phase hydrocarbon mixtures. This

technique is employed as opposed to Finite Difference method and Finite Element Method as both have difficulty in handling the choking condition at the ruptured end. The MOC handles choked flow intrinsically via the Mach line characteristics and is more accurate than the FDM and FEM. The field data were from pipeline depressurization tests carried out in the Isle of Grain (Richardson and Saville 1996) as well as those recorded during the night of Piper Alpha tragedy. The performance of MOC in simulating Full bore rupture throughout the discharge process is compared to other solution techniques including META-HEM (Chen, Richardson, and Saville 1995a, 1995b), MSM-CS (Chen, Richardson, and Saville 1995a, 1995b), BLOWDOWN (Haque, Richardson, and Saville 1992; Haque et al. 1992) and PLAC (Hall, Butcher, and The 1993). The simulations were performed on the basis of a homogeneous equilibrium model (HEM) in which all phases are assumed to be at thermal and phase equilibrium. Due to the absence of any theoretical and experimentally justified data for unsteady friction factor in rough pipes, this parameter was ignored in the model and steady-state friction factor estimated using the Moody approximation to Colebrook's equation. It is the most accurate expression available. Two phase mixtures are simply handled by replacing single phase properties by two-phase mixture properties. The simulations performed consider only rupture in straight, horizontal well anchored pipelines in which the fluid compressibility is by far smaller than pipe wall elasticity. Fluid structure interaction can effectively be ignored. Comparison showed that CNGS-MOC, META-HEM and BLOWDOWN gave very similar predictions with MSM doing less well and PLAC performing very poorly.

A model for predicting of outflow from high pressure vessels and associated vent pipe during accidental failure was developed (Cumber 2001). The model was developed with a view of incorporating its use in the safety assessments of industrial plant used to process or store flammable material which in turn will provide source conditions for the mathematical models of gas dispersion or accumulation and fires. For predicting the outflow, Cumber has sub divided the model into 3 sub models – a sub model for the vessel, a sub model for the vent conditions and a library of physical property data such that thermodynamic and phase information properties can be calculated as required. Model for a transient blowdown is described. The model is based on homogeneity of two phase flow and thermodynamic equilibrium assumption for both vessels and vent pipes. The system of ordinary differential equations is solved using the fourth order Runge Kutta method. The developed model was compared for validation purposes with the experimental data (Hervieu 1991), (Gebbeken and Eggers 1995) and (Haque et al. 1992) and the following was concluded. The vessel pressure and mass flowrate prediction is

well predicted. The vessel temperature is under-predicted, although this does not have a significant effect on the predicted mass flowrate. To ensure the robustness of the model, non-linear system solvers Powell's hybrid method and the Simplex method of unconstrained optimization is incorporated into the model. However, the outflow model can fail when the phase of the vessel contents changes. This is because the non-linear systems of equations describing mass and energy conservation is degenerate at the critical point. The mass flow rate for the gas phase release through a hole is calculated by a variant of the isentropic nozzle flow equations. The gas phase density is evaluated using the cubic EOS rather than the ideal equation of state significantly improves the accuracy of the vent model. Liquid phase release is modeled by the application of Bernoulli's equation, including a liquid head contribution where appropriate. To calculate the mass flow rate for two phase flow through an orifice, the homogenous equilibrium model has been implemented. The two phase mixture is treated as a single phase fluid, and the two phases are taken to be in equilibrium with equal velocities and temperatures. Gas outflow from a vent pipe is calculated by taking the flow of gas from the vessel to the pipe entrance to be isentropic, and the flow of gas along the vent pipe to be isenthalpic with friction effects included. The model of liquid flow through a pipe is a direct extension of Bernoulli's equation with friction and entrance losses included. Two phase flow through a vent pipe is calculated by solving an equation for the conservation of momentum under the homogenous equilibrium assumption for two phase flow.

A model for the simulation of blowdown of pressure vessels containing two-phase (gas-liquid) hydrocarbon fluids was proposed (Speranza and Terenzi 2005). Their model is based on a global mass and energy balance between the phases, gas and occasionally liquid, present in the vessel, at a very stage of blowdown. The model takes into account the heat transfer taking place with the external environment, the presence of many components in the vessel and the possibility of situations in which the phase equilibrium is not appropriate. The model takes into account the strong cooling effect taking place between the wall of the vessel and the liquid in contact with it which helps in avoiding cracks in the vessel wall. The model takes into account the compositional approach, allowing for the presence of many different hydrocarbons within the vessel, as well as non-equilibrium conditions between the phases. The model was validated by performing 2 experiments 100% Nitrogen (I1) and a mixture of hydrocarbons (S9). The predicted conditions during blowdown by the model are in close agreement with the experimental results. It was suggested that before gas escapes through the choke a rapid motion is induced by the acceleration of the gas far upstream, and we can imagine it to get mixed and

homogenized at all the time, especially in the early stages of the blowdown, while pressure is dropping steeply. However, the model does not provide any facts related to modeling of gas in the vent pipe after the choke is mentioned. The model focuses on the average quantities rather than local variations for homogeneity of fluid, pressure drop and temperature.

Several other authors have analyzed the behavior of blowdown of vessel / pipelines and associated vent piping system. Analysis and experiment data on the discharge from carbon-dioxide filled vessels is published in literature (Eggers and Green 1990). Goh has described simplified pipeline method employing quasi-ideal gas thermodynamics and has shown limited experimental validation (Goh 1989). Here experiments were performed with air from which the flow rate for natural gas was estimated. Integrated safety relief valve inlet piping design for compressible gas flow from an overpressurised pressure vessel was performed (Westman 1997). The design was based on ideal gas adiabatic flow principles which involved simultaneous solution of parametric equations derived from these principles. Effects of SRV inlet line pressure loss and the use of pipe bends is highlighted. Mass flow rates calculations for the inlet line and nozzle based on isentropic flow are performed and illustrated; however, its use is restricted only to ideal gas assumption. A simple and practical method for sizing pipelines incorporating the theories of adiabatic and isothermal frictional flow was investigated (Cochran 1996). However, no validations were provided. Based on the concept of critical length, calculations relating to compressible fluid flow incorporating non-linear equations were analyzed (Farina 1997).

## **2.7 Summary of Literature Review**

An extensive literature review related to blowdown of high pressure vessels and pipelines has been carried out. In the last few decades, a number of theoretical and experimental studies relating to blowdown simulations with varying degree of sophistication were conducted based on which different blowdown models were developed. Most of these developed models were in good agreement with the experimental analyses and hence were validated whereas few models did not provide any validations. Moreover, a number of validated models were not well documented properly and are not commercially available. The use of such models is beyond the reach of scientific community. Although detailed investigations were conducted on the fluid behavior inside the pressure vessel and pipelines, very few investigations related to fluid behavior within the associated vent piping system were conducted. As addressed in literature review, very few models provided an insight into the vent pipe modeling. It should be noted that the impact of piping systems on process plant economics is so great that the initial investment in piping systems for new installations has been estimated to range from 18 to 61% of the equipment costs and from 7 to 15% of the total cost of the installed plant (Cochran 1996). Currently, industry tends to use API Recommended Practices 520 and 521 for specification of pressure relieving systems. However, these practices are more relevant to the case of fire scenarios. A thorough investigation of compressible fluids in a vent pipe is therefore required.

The vital and foremost step to tackle this issue is to have more detailed knowledge of events occurring prior to fluid entering the vent pipe through the relief valve. As cited in literature (Norris III, Exxon Production Research Co, and R.C. Puls 1993; Norris III and Exxon Production Research Co 1994), the vent pipe associated with pressure vessels and pipelines for venting purposes contains no mass or momentum storage. As a result a steady-state hydrodynamics can be adopted in vent pipe analysis. Second step will be identification of parameters which bring about changes in the fluid flow conditions along the vent pipe. To date, a number of blowdown models and simulation codes related to pressure vessels and pipelines have been developed based on the same pertinent equations (continuity equation, energy equation and momentum equation) and differ from each other in methods of solving these pertinent equations. There is no general model developed specifically for analyzing the conditions developed in a vent pipe.

Due to unavailability of analysis and data applicable to the simulation of a vent pipe, a combined analytical and experimental program was initiated. The goal was to develop a steady-state adiabatic vent pipe model for a single phase (gas only) compressible gases. The model was

programmed into Visual basic in conjunction with MS Excel spreadsheet because of its simplicity and easy to use user interface. Investigation to be performed will involve determining the thermodynamic fluid properties, pressure drop, temperature drop and mass flow along the vent pipe. The vent pipe model will incorporate the newly developed GERG 2004 equation of state which has proved to be more suitable than other cubic equation of state developed. This will help the model in predicting more accurately the thermophysical properties during the venting process. The developed model will be validated with experimental data obtained for air gas from the test rig designed and constructed in Curtin University's facility. The developed model will be compared to Aspen Hysys.Plant version 7.1, Process Engineering software for single phase single component gases such as air, carbon-dioxide, methane and single phase multicomponent gas mixtures, thus providing additional validation.



## **Chapter 3**

### **Model Development**

Pressure vessels and pipelines, with many more utilization in process industry, nuclear industry, marine and space industry, operating under extreme of high and low temperatures and high pressures, are becoming highly sophisticated (Mackerle 1999). Their operations are often subjected to interference from accidents, corrosion, and human error, etc. A potential of risk is always associated with such equipments and safe operations is an important issue for operators worldwide. A safety assessment must be performed on these equipments and a quantitative risk assessment of their operation should be conducted.

The problems related to blowdown of pressure vessels / pipelines containing compressible gases are well known among process industries. Process modeling and computer simulation have proved to be an extremely successful engineering tool for design and optimization of such processes (Ramirez 1998). The use of simulation has expanded rapidly during the past few decades because of the availability of high speed computers and computer workstations. A number of factors which influence the blowdown of pressure vessels / pipelines were discussed in the literature review. These factors have led to the modeling of blowdown of pressure vessel / pipeline and associated vent piping system. Development of such models has progressed in the last few decades which use the same pertinent equations and differ from each other in the method of solution approach. Despite availability of blowdown models, very few models are available for determining the compressible fluid flow conditions, specifically, in vent piping associated with pressure vessels and pipelines. Robustness and efficiency of these available vent models have been proved to be a problem. Keeping this in mind, we develop a vent pipe model for predicting the pressure and temperature of flowing compressible fluid (gas), surface temperature of the vent pipe wall, and the mass flow rate which can be passed through the vent pipe during blowdown.

Since a simple model for predicting the compressible fluid conditions in a vent pipe is desired, every approach has been made to characterize the model as mechanistic as possible. The user must understand that the developed model will provide a very close estimate of the compressible fluid flow properties which bring about the changes in the vent pipe flow conditions. Assumptions are clearly stated when developing the pertinent equations in order to ensure a better understanding prevails. A well-defined strategy was adopted in developing our vent pipe

model consisting of a series of logical steps. These steps involved problem definition, development of mathematical models for the process, method of solution, computation and interpretation of the results. Problem definition was very precisely stated in chapter 1. The need for a vent pipe model for predicting the compressible fluid flow conditions in vent pipe associated with pressure vessels / pipelines was highlighted.

### **3.1 Development of Mathematical Models**

Compressible flows are limited to low viscosity fluids such as single phase gases and multiphase fluids containing mostly gases. In current work, our investigations are related to single phase gases only. The model will not encounter any phase change. Compressible fluid flow is a complex process, the interpretation of which can be analyzed by a combination of several other physical factors. These factors which impact the compressible fluid behavior will be examined in order to provide a better insight into compressible flow and are discussed in the concept of compressible fluid behavior. Before proceeding with the modeling theory for the vent pipe model, basic concept of fluid dynamics involved with the compressible fluid flow is described. This will help us in better understanding of our vent pipe model theory.

#### **3.1.1 Basic Conservation Equations**

All analyses concerning the motion of compressible fluids must necessarily begin, either directly or indirectly, with the statements of the four basic physical laws governing such motions. These physical laws are independent of the nature of the particular fluid and are as follows:

- Law of Conservation of Mass – The Continuity Principle
- Momentum Principle
- The First Law of Thermodynamics
- The Second Law of Thermodynamics

##### **3.1.1.1 Law of Conservation of Mass – The Continuity Equation**

The Principle of Conservation of Mass, when referred to a system of fixed identity, simply states that the mass of the system under consideration is constant. This statement is a concise summary of experimental observation, relativity and nuclear effects being absent (Shapiro 1954). Under unsteady state conditions, both density and velocity are functions of space and time. Thus, applying the continuity equation for a fixed identity occupying the control volume is

$$\frac{\partial}{\partial t}(m_{c.v}) = \int dw_{in} - \int dw_{out} \quad 3-1$$

Where  $m_{c.v}$  - Instantaneous mass within the control volume;  $dw$  - Mass rate of flow entering and leaving the control volume

Thus, it can be stated that the rate of accumulation of mass within the control volume is equal to the excess of the incoming rate of flow over the outgoing rate of flow. Under steady state conditions, the total mass remains constant, thus, there will be no mass accumulation. For a control volume at any instant, the mass rate of flow is a function of element of control volume and the local mass density. Thus for a steady state, the continuity equation can be expressed as

$$\int \rho_{in} V_{in} dA_{in} = \int \rho_{out} V_{out} dA_{out} \quad 3-2$$

In general form,

$$\dot{m} = \rho V_n A \quad 3-3$$

Where  $\dot{m}$  – Mass flow rate of the compressible fluid;  $\rho$  – Instantaneous mass density of the fluid corresponding to the inlet and outlet area;  $V_n$  - Instantaneous velocity of the fluid corresponding to the inlet and outlet area

### 3.1.1.2 Momentum Principle

When the net external force acting on a system is zero, the linear momentum of the system in the direction of the force is conserved in both magnitude and direction. This is the principle of conservation of linear momentum. When there is a net external force, however, the linear momentum is no longer conserved. The resultant behavior is described by Newton's second law of motion, which is more general than the momentum principle.

According to Newton's second law of motion, the resultant of forces applied to a particle, which may be at rest or in motion, is equal to the rate of change of momentum of the particle in the direction of the resultant force. Newton's second law of motion yields:

$$\sum F = \frac{d}{dt}(mV) \quad 3-4$$

Where  $\sum F$  – Sum of the forces acting on the particle in any one direction;  $(mV)$  – Kinetic momentum in the same direction

The rate of change of momentum of a fixed-mass system can be related to the rate of change of momentum of a control volume in accordance to the following equation

$$\Sigma F = \frac{\partial}{\partial t} \int_{cv} V\rho dV - \int_{cs} V(\rho V \cdot dA) \quad 3-5$$

Under steady state conditions, the rate of change of momentum within the control surface is zero, thus the above momentum equation reduces to

$$\Sigma F = - \int_{cs} V(\rho V \cdot dA) \quad 3-6$$

It should be noted that even if frictional forces or non-equilibrium regions exists within the control volume, the momentum equation is still valid. This allows the momentum principle to be used in evaluating the forces generated by the flow of fluid.

### 3.1.1.3 The First Law of Thermodynamics

The First Law of Thermodynamics or Law of Conservation of Energy states that energy can neither be created nor destroyed but can be converted from one form to another. The total energy is always conserved. From the first law of thermodynamics or law of conservation of energy we can conclude that for any system, open or closed, there is an “energy balance” as

$$\left[ \begin{array}{c} \text{Net amount of energy} \\ \text{added or transferred to the system} \end{array} \right] = \left[ \begin{array}{c} \text{Net increase in stored} \\ \text{energy of system} \end{array} \right]$$

Mathematically the first law can be represented as

$$Q_{sys} = U_{sys} + W_{sys} \quad 3-7$$

Where  $Q_{sys}$  – Net amount of heat associated with the system;  $W_{sys}$  – Net amount of work associated with the system;  $U_{sys}$  – Net amount of energy stored inside the system

Thus for a steady-state steady flow system we have,

$$\delta Q + \delta W + \int_{cs} \left( \left( h + \frac{v^2}{2} + gz \right) \cdot (\rho V \cdot dA) \right) = 0 \quad 3-8$$

Where  $\delta Q$  – Net amount of heat associated with the system or control volume;  $\delta W$  – Net amount of work associated with the control volume and is different from system work; The integral term represents the shaft or expansion work, or flow work;  $h$  – Enthalpy of the system

### 3.1.1.4 The Second Law of Thermodynamics:

The Second Law of Thermodynamics is far-reaching principle of nature that has been stated in many forms. One of the following two forms mentioned in (Jones and Hawkins 1986; Nageshwar 2003) are usually the most valuable:

The Clausius Statement: *“It is impossible for any device to operate in such a manner that it produces no effect other than the transfer of heat from one body to another body at a higher temperature”*

The Kelvin-Planck Statement: *“It is impossible for any device to operate in a cycle and produce work while exchanging heat only with the bodies at a single fixed temperature”*

These two statements of the second law and many other statements are entirely equivalent in their consequences. The first law of thermodynamics introduces the internal energy property and the second law of thermodynamics introduces the entropy property. The property entropy often provides a means of determining if a process is reversible, irreversible, or even possible. This application of entropy is based on the principle of the increase of entropy, which states that the entropy of an isolated system always increases or, in the limiting case of a reversible process, remains constant with respect to time.

Thus in mathematical form we have,

$$\left(\frac{dS}{dt}\right)_{isolated\ system} \geq 0 \quad 3-9$$

With the understanding that time is the independent variable, this statement is usually written

$$\Delta S_{isolated\ system} \geq 0 \quad 3-10$$

Thus, based upon the above basic physical laws, the following conditions should exist under steady state conditions

- The mass flow rate is constant. This means that the mass flow rate at the entrance is the same as at the exit and that the mass contained within the volume neither increases nor diminishes at any time.
- The rate of change of momentum within the control volume is zero.
- No change in properties or in energy level of fluid occurs at the entrance, at the exit, or at any point within a control volume
- The rate at which energy, in the form of heat or work, crosses the boundaries of the control volume is constant.
- The entropy of an adiabatic closed system always increases

### **3.1.2 Theoretical Aspects Related to Compressible Fluid Flow Behavior**

The flow of compressible fluids during blowdown from large pressure vessels or pipelines into vent systems is influenced by a number of factors (Skouloudis 1992). These factors could be classified according to their significance as geometrical, operational and thermophysical parameters. The geometrical parameters which influence the venting process rely to a certain extent on the size, type of material of construction and orientation of the vent piping associated with the pressure vessels / pipelines. The operational factors which influence the flow of fluid into the vent pipe system are the vessel / pipeline conditions present prior to blowdown and the changes taking place in the gas behavior (heat transfer) inside the pressure vessel or pipeline during blowdown. The thermophysical factors include the physical and transport properties of the fluids contained in the vessels / pipeline. These thermophysical factors affect the flow regimes of compressible fluid in vent systems, thus determination of these properties along the vent pipe is central to this investigation.

The changes taking place in the properties of the compressible fluid enforces the thermodynamic behavior of the fluids to be taken into account. These changes taking place during expansion or compression in the vent pipe are brought about by two processes: isothermal process and adiabatic process (Bansal 2005). When compression or expansion of gas takes place under constant temperature conditions, the resulting process is an isothermal process. In such a process, heat transfer takes between the system carrying the compressible gas and the surrounding. On the other hand, in an adiabatic process expansion or compression takes place with no heat transfer between the system and the surrounding. Such a process occurs if the system is well insulated. The use of these two models depends on the situation encountered. It has been cited in literature (Cochran 1996; Shapiro 1954; Saad 1993; Yuhu et al. 2002) that isothermal models best describe the flow of compressible gases taking place through long uninsulated pipelines while the adiabatic model is more appropriate for shorter and insulated piping's such as the vent systems. The solution obtained by incorporating the isothermal model yields higher pressure drop at the same mass flow rate and provides a more conservative estimate for the pipe diameter sizing. On the other hand, an adiabatic model at constant pressure drop predicts higher efflux rates and so is frequently the choice for conservative design of emergency depressurization system. Moreover, the velocity of flowing gas in a short pipe is fast enough so that no time is provided for heat transfer to take place and hence the flow can be modeled as adiabatic.

Frictional effects, heat transfer effects and changes in cross sectional area contribute to the changes of compressible fluid behavior taking place in the vent pipe. As we adopt an adiabatic approach to develop our model, the heat transfer effects can be neglected. The vent pipe is a constant cross-sectional area pipe; hence area changes are not relevant to our model. Thus we consider pipe wall friction to be the chief factor bringing about the changes in compressible fluid properties. In vent pipe subjected to compressible flow, the losses encountered due to friction are of two types: skin friction and form friction. The skin frictional losses are encountered due to internal surface roughness of the pipe present between the flowing fluid and the pipe material. Form frictional losses are due to obstructions present in the piping system such as bend pipe fittings, control valve or anything that changes the course of motion of the flowing fluid. Thus, change in properties of fluid taking place inside the vent pipe is due to frictional effects generated at the wall surface. This is because the behavior of flowing fluid depends strongly on whether the fluid is under the influence of solid boundaries. The effect of solid boundary on the flow is confined to a layer of the fluid immediately adjacent to the solid wall where shear stress is confined (McCabe, Smith, and Harriott 2001). The effects of friction on compressible fluid flow parameters are explained in detail using the Fanno curves in the later part of this chapter.

Based on the above theoretical aspects related to compressible fluid flow behavior, we understand that the behavior of compressible fluid in the vent pipe associated with emergency blowdown facilities should follow an adiabatic path in which the changes in fluid flow properties are brought about due to frictional effects. Thus, we progress with the development of a vent pipe model based on adiabatic and frictional approach.

### **3.1.3 Model Assumptions**

#### **3.1.3.1 Steady State Analysis**

The geometry visualized in the development of model comprises of a source and vent pipe arrangement. The source can be visualized to be a pressure vessel / pipeline which has all the mass storage of the system at isobaric and isothermal conditions throughout its volume. The source delivers the supply of compressible gas to the vent pipe arrangement through a nozzle at subsonic conditions. Norris et al. have developed their pipeline model based on this approach and have provided validated results (Norris III, Exxon Production Research Co, and R.C. Puls 1993; Norris III and Exxon Production Research Co 1994). The vent pipe arrangement contains no mass or momentum storage. As a result, steady-state hydrodynamics are used in the vent pipe

analysis. These steady-state hydrodynamics do, however, contain all frictional pressures drops in the system. The pressure, temperature, and fluid properties are considered continuous across both the source-vent pipe boundaries.

### **3.1.3.2 One Dimensional Approach**

As discussed earlier a number of factors influence the behavior of compressible fluid in a vent pipe which results in complexity of the process. Because of the complicated nature of the problem, it will be assumed that the flow is one-dimensional, i.e. that all properties are uniform over each cross section or a flow in which the rate of change of fluid properties normal to the streamline direction is negligibly small compared with the rate of change along the streamline. The assumption of one dimensional flow is justified largely by the great simplifications it makes possible (Shapiro and Hawthorne 1947). According to (Shapiro and Hawthorne 1947; Shapiro 1954; Parker 1989) one-dimensional treatment introduces no significant errors especially when changes in stream properties in the direction of flow are much larger than in the direction normal to flow and when changes in properties in the direction normal to flow are the same in all planes, *that is*, the velocity, temperature, and density profiles are unchanged. An additional assumption is inherent in the one-dimensional analysis, namely, that the effect of turbulence on the computation of the mean properties is small.

### **3.1.3.3 Clearly Stated Assumptions**

- The flow is considered to be steady and one dimensional for single-phase gas through a constant cross sectional area vent pipe
- No mechanical work done or heat exchange on or by the fluid during the flow
- Differences in elevation produce negligible changes compared with the frictional effects and hence neglected
- Specific heats are constant across a particular cross sectional area for a given segment or vent pipe length
- Friction is restricted to wall shear
- Velocity gradients within a cross section are neglected



### 3.1.4 Development of Adiabatic Frictional Model

The flowing compressible fluid at a short distance above the vent pipe wall possesses some momentum, whereas the fluid immediately adjacent to the pipe wall, where the fluid velocity is zero, has no momentum. The flowing compressible fluid must therefore acquire momentum from faster flowing layer above it, which in turn receives momentum from the next layer up and so on (McCabe, Smith, and Harriott 2001). Each layer is dragged along by the layer above it except the wall where all the momentum is delivered as shear force. Momentum is thus transferred from a region of high fluid velocity to low fluid velocity. The rate of momentum transfer is governed by velocity gradient which acts as the driving force. Our purpose is to find in analytical form the variations in all stream properties along the vent pipe profile of constant area. As discussed earlier, the change of fluid properties is brought about by frictional force and will depend upon the amount of frictional force. In order to evaluate this frictional force generated by the flow of compressible fluid, we apply the momentum principle and obtain a differential form of relation between the fluid properties and friction (Saad 1993; Shapiro 1954).

$$dp + \frac{4f}{D_H} \frac{\rho V^2}{2} dx + \frac{\rho V^2}{2} \frac{dV^2}{V^2} = 0 \quad 3-11$$

Where  $f$  - Fanning friction factor;  $D_H$  - Hydraulic diameter or the diameter of the vent pipe;  $\rho$  - Density of the compressible fluid;  $V$ -Velocity of the flowing stream

#### 3.1.4.1 Static Property Relations

The physical phenomenon that causes changes in fluid is viscous friction and is measured by the term  $4f/D_H$  in equation 3-11. Relevant equations discussed earlier necessary to the solution of the problems pertaining to frictional flow in constant area vent pipe are the continuity equation, energy equation and the increase in entropy principle by second law of thermodynamics. Additional equations include the real gas equation and the equation for Mach number. All equations are summarized in the table 3-1 below:

Table 3-1: Pertinent equations related to frictional flow in constant area vent pipe

Real Gas Law	$P = \rho ZRT$ (a)
Continuity Equation	$\dot{m} = \rho AV$ (b)
Energy Equation	$h_o = h + V^2/2$ (c)
Definition of Mach number	$M^2 = V^2/Z\gamma RT$ (d)
Increase in Entropy principle by Second Law of Thermodynamics	$ds \geq 0$ (e)

Equation 3-11 and above five equations incorporate seven different fluid parameters which can be or are inter-related to each other. These property equations can be related to each other by defining a single independent variable, the value of which can be changed following which the other dependent variables can be calculated. By defining a single parameter we easily determine the corresponding values of these compressible fluid properties. Since the effect of friction on the changes encountered in compressible fluid parameters is desired we define the independent variable as  $4f/D_H$ . The entire derivation for relating the compressible fluid parameters to the independent variable is given in (Saad 1993; Shapiro 1954). It should be noted that the derivation given in (Saad 1993; Shapiro 1954) incorporates the perfect or ideal gas law. We incorporate a compressibility factor, Z, to deviate the behavior to real gas. However, when deriving the real gas relation, the compressibility factor cancels off and results in same equations as of for ideal gas behavior (refer Appendix E for derivation). The table 3-2 below summarizes the various static property relations for the compressible fluid.

Table 3-2: Static property relations for adiabatic flow in constant area vent pipe

Friction and Mach number relation	$\frac{4f}{D_H} dx = \frac{2(1 - M^2)}{\gamma M^2 \left(1 + \frac{\gamma - 1}{2} M^2\right)} \frac{dM}{M}$	(a)
Frictional effects on velocity	$\frac{dV}{V} = \frac{\gamma M^2}{2(1 - M^2)} \frac{4f}{D_H} dx$	(b)
Frictional effects on density	$\frac{d\rho}{\rho} = -\frac{\gamma M^2}{2(1 - M^2)} \frac{4f}{D_H} dx$	(c)
Frictional effects on pressure	$\frac{dP}{P} = -\frac{\gamma M^2 [1 + (\gamma - 1)M^2]}{2(1 - M^2)} \frac{4f}{D_H} dx$	(d)
Frictional effects on temperature	$\frac{dT}{T} = -\frac{\gamma(\gamma - 1)M^4}{2(1 - M^2)} \frac{4f}{D_H} dx$	(e)

Where  $f$  - Fanning friction factor; M - Mach number;  $\rho$  - Density of compressible fluid; P - Static pressure of flowing fluid; T - Static temperature of flowing fluid;  $D_H$  - Hydraulic diameter of vent pipe; dx - Differential vent pipe length

### 3.1.4.1.1 Static Property Deviations with Friction

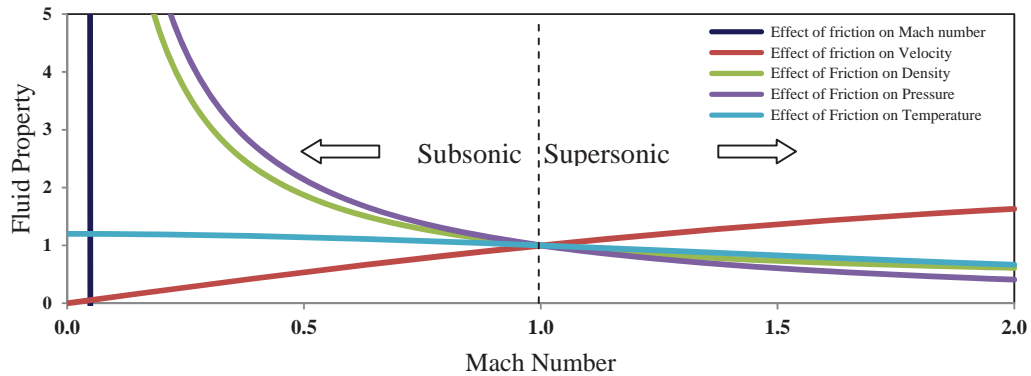


Figure 3-1: Variation of fluid properties with friction

Figure 3-1 gives a better understanding of the variation of compressible fluid properties due to friction. Equations involved in plotting the property relations are tabulated in table 3-2. It is seen that frictional flow in a vent pipe causing changes in compressible fluid properties is always decreasing in a subsonic or supersonic flow and becomes negligible at Mach unity. Figure 3-1 can be well explained by taking into consideration the inlet flow conditions in the vent pipe. One should understand that continuous transitions from subsonic to supersonic flow or from supersonic to subsonic flow, are impossible (McCabe, Smith, and Harriott 2001) until and unless the flow is mechanically altered. We restrict our vent pipe model to subsonic region. By referring to figure 3-1 we can say that with decreasing frictional effects the velocity of the fluid is increasing along with increasing Mach number. Pressure, temperature and density are found to be of decreasing order in subsonic region. The compressible fluid entering the vent pipe at subsonic condition ( $M < 1$ ) will attain Mach number less than 1 or approach unity at the exit of the vent pipe. At Mach unity, choked flow results at the exit of the vent pipe. Relevant adjustments are made to overcome the choking condition. Overall it can be said that friction has the net effect of accelerating a subsonic stream.

Although not incorporated in our model, we give the reader an idea of what changes are caused due to friction in supersonic flow. The compressible fluid entering the vent pipe at supersonic condition ( $M > 1$ ) will always try to approach Mach unity at the exit of the vent pipe. This is because the frictional effects at the exit of the vent pipe are at minimum. In the supersonic region, velocity is of decreasing order. When Mach of unity is attained for initial supersonic condition, choking takes place which involves the appearance of shock waves. Adjustments are made by increasing the vent pipe length to overcome choking condition. Overall, it can be said

that friction has the net effect of decelerating a supersonic stream. A better understanding of the effects of friction on fluid properties is provided when discussing the Fanno curves in the latter section.

### 3.1.4.2 Stagnation Property Relations

Now that the static properties for flowing compressible fluid are defined we define the stagnation properties for these compressible fluid. In a steady state adiabatic process, when the fluid is decelerated to zero velocity provided that no work interaction occurs the resulting properties of the fluid are called stagnation properties. Stagnation properties are developed by taking into account the process to be adiabatic and frictionless, *that is*, isentropic process. Such a process is encountered in variable cross sectional area where the frictional effects are minimal. Stagnation properties provide a convenient reference state in analyzing the flowing compressible fluid properties, *that is*, static properties. Stagnation properties are more related to the source conditions. Although valid for variable cross sectional area, (Shapiro 1954; Shapiro and Hawthorne 1947) have suggested that these isentropic stagnation properties are valid for adiabatic frictional constant area vent pipe. These properties are defined by (Saad 1993; Shapiro 1954; Bansal 2005) are represented in table 3-3:

Table 3-3: Stagnation property relation

Stagnation and Static Pressure Relation	$\frac{P_o}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/\gamma-1}$ (a)
Stagnation and Static Temperature Relation	$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} M^2$ (b)
Stagnation and Static Density Relation	$\frac{\rho_o}{\rho} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{1/\gamma-1}$ (c)

Where  $P_o$  – Stagnation Pressure;  $T_o$  – Stagnation Temperature; M: Mach number;  $\gamma$  - Specific heat ratio. Stagnation enthalpy and stagnation temperature are considered to be a constant throughout the process whereas stagnation pressure is not. Compressible fluid when brought to rest adiabatically, the static enthalpy of the fluid is equal to the stagnation enthalpy, and the static temperature is equal to the stagnation temperature. However, the pressure is equal to the initial stagnation pressure only if the fluid is brought to rest both adiabatically and reversibly, *that is*, isentropically. Adiabatic frictional process is considered to be an irreversible process. According to (Saad 1993; Shapiro 1954)

$$\frac{ds}{R} = -\frac{dP_o}{P_o}$$

3-12

Where  $s$  - Entropy;  $P_o$  - Stagnation pressure. The above equation provides a better understanding of relationship between entropy and stagnation pressure. For an increase in entropy, there will always be a decrease in the stagnation pressure. The relative change in stagnation pressure therefore provides an indication of degree of irreversibility of the process. Friction present in the vent pipe causes an increase in the entropy and therefore stagnation pressure decreases. The property relations in table 3 have been derived by (Saad 1993; Shapiro 1954; Shapiro and Hawthorne 1947; Bansal 2005).

### 3.1.4.3 Estimation of Mass Flow

The function of blowdown facilities on pressure vessels / pipelines is to provide a means of venting the high pressure inventory to atmosphere in a very short period of time (Gradle 1984). The short blowdown time is always associated with high velocities and high mass flow-rates. Flow of compressible fluid such as natural gas and other gas mixtures is dependent upon Reynolds number, friction factor, pipe roughness, pipe diameter, pipe length, temperature, pressure, pressure drop and gas properties (Ouyang and Aziz 1995). The prediction of mass efflux from pressure vessels / pipelines through vent system is a central step in the design of emergency depressurization system. Accurate predictions are required for optimum design. This is analyzed in our vent pipe model. The relevant equations adopted for analyzing the flow in vent pipes depend on the basic physical law of fluid mechanics, *that is*, the Continuity Equation. For a constant area flow, mass flux is independent of length. The mass velocity can be evaluated at any point inside the entrance of the vent pipe. The process of blowdown of pressure vessels / pipelines is characterized to be an unsteady process where the properties of compressible fluid are functions of space and time causing the flow to change throughout the flow path. However, we discussed earlier, as per the geometry visualized in the model analysis steady state hydrodynamics prevail in vent pipe. Thus, for steady state conditions, the mass rate of flow across two different sections of the vent pipe can be expressed by continuity equation as

$$\dot{m} = \rho AV$$

Where  $\dot{m}$ - Mass flow rate;  $\rho$  - Density,  $A$  - Cross sectional area;  $V$  - Velocity of flowing fluid

The mass flow per unit area or the mass flux,  $G$ , can then be written as

$$G = \frac{\dot{m}}{A} = \rho V \tag{3-13}$$

For vessels or pipelines of commercial interest, the pressure to be released almost always results in sonic velocity at some restriction, and choked flow results (Norris III, Exxon Production Research Co, and R.C. Puls 1993). Choked flow is the condition wherein the mass flow rate becomes independent of the downstream conditions i.e. that point at which further reduction in

downstream pressure does not result in change of the mass flow rate (Haque, Richardson, and Saville 1992). Basically, a limit occurs because acoustic signals can no longer propagate upstream. This limit occurs when the fluid velocity just equals the propagation velocity. Such a condition is seen at Mach unity. Thus it is advisable to relate the gas flow relation in form of dimensionless Mach number. The mass flux in terms of static pressure and static temperature can be expressed as

$$G = PM \sqrt{\frac{\gamma}{ZRT}} \quad 3-14$$

The above equation for mass flux in terms of stagnation properties can be expressed as

$$G = \frac{P_o}{\sqrt{T_o}} \sqrt{\frac{\gamma}{ZR} \frac{M}{\left(1 + \frac{\gamma-1}{2} M^2\right)^{(\gamma+1)/2(\gamma-1)}}} \quad 3-15$$

Where  $P_o$  – Stagnation Pressure;  $T_o$  – Stagnation Temperature;  $M$ : Mach number;  $\gamma$  - Specific heat ratio;  $Z$  – Compressibility factor.

According to equation 3-15, for a given Mach number, the flow is proportional to the stagnation pressure and inversely proportional to the square root of stagnation temperature. For a given

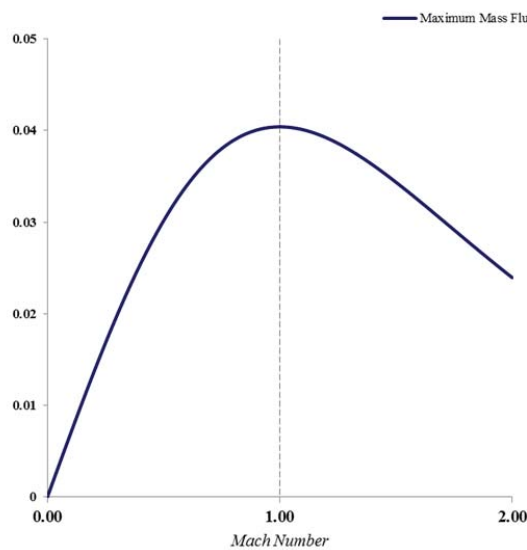


Figure 3-2: Condition for maximum mass flux variable (Shapiro 1954). The condition at which maximum flow can be achieved occurs at Mach unity. This condition is plotted in figure 3-2.

#### 3.1.4.4 Estimation of Adiabatic Wall Temperature

During blowdown of pressure vessels / pipelines, the time required to reduce the overpressure build-up and inventory is influenced by high efflux rates. This inevitably leads to a reduction in

geometry, stagnation and downstream pressures, and assumed friction factor, these equations 3-14 & 3-15 define the flow (Parker 1985). If choking condition is attained at the exit of the vent pipe, the rate of flow through the system increases and the flow is choked by the vent pipe. The mass rate of flow can be increased only by decreasing the stagnation temperature and /or increasing the stagnation pressure. For this reason, flow test data for many applications over wide range of pressure and temperature levels, are plotted with  $G \sqrt{T_o}/P_o$  as the flow

the temperature of the vessel / pipeline and associated vent pipe system, possibly to a temperature below the ductile-brittle transition temperature of the material from which the vessel / pipeline and associated vent piping is fabricated (Haque, Richardson, and Saville 1992; Haque et al. 1989; Marian, Vuthaluru, and Ghantala). At this temperature, the probability of failure of equipment material is high. The temperature of flowing gas in the vent pipe along with high speed velocities will influence the temperature of the vent pipe wall. Due to high velocities encountered viscous stresses set-up which do shearing work on the fluid particles which results in an increase in internal energy as well as the temperature of fluid very close to the wall (Saad 1993). This work is dissipated in form of viscous heating. At high velocities, dissipation is largest close to the wall. The flow is not locally adiabatic and a difference will exist between the wall temperature and the stagnation gas temperature (Prandtl 2004). Also, the adiabatic wall temperature will be realistically higher than the flowing gas temperature.

The adiabatic wall temperature has been well studied in the boundary layer flow on a flat plate and is usually correlated with the recovery factor (Shi et al. 2001). It has become common knowledge that for laminar flow recovery factor,  $r$ , is  $P_r^{1/2}$  while for turbulent flow recovery factor is  $P_r^{1/3}$ . These equations neglect the fact that the recovery factors are also influenced by Mach number (Kaye 1953) given by the expression:

$$\ln r = \left[ \frac{N+1+0.528M_1^2}{3N+1+M_1^2} \right] \ln P_r \quad 3-16$$

Where  $r$  - Recovery factor;  $P_r$  - Prandtl number;  $N$  - Reciprocal of the exponent of the turbulent boundary-layer velocity profile approximated by power law. This relation holds for Prandtl numbers greater than 0.65 and less than 0.75. Equation 3-16 is not validated.

The investigations related to adiabatic wall temperature are very few (Shi et al. 2001). Although many of these approximations are valid for flat plates, these can be applied to circular pipes. (McAdams, Nicolai, and Keenan 1946) have performed investigation related to adiabatic wall temperature for the subsonic turbulent flow in a pipe and have defined the recovery factor as:

$$r = \frac{T_{aw}-T}{T_o-T} \quad 3-17$$

Where  $T$  : Bulk mean gas temperature;  $T_o$  : Stagnation gas temperature;  $T_{aw}$  : Adiabatic wall temperature;  $r$ : Recovery factor. A number of approximation and typical ranges for recovery factor are provided with no proper validations (Kaye 1953). (Shi et al. 2001) Shi et al. have defined the recovery factor as a function of Prandtl number and Knudsen number. The recovery factor for continuous flow is always equal to Prandtl number and will increase above Prandtl

number as Knudsen number increases (Shi et al. 2001). Validations are been provided by Shi et al. for the proposed method of determining the recovery factor. Hence, we equate the recovery factor to Prandtl number and calculate the adiabatic wall temperature using the relation by McAdams et al. into our model. The use of recovery factor relation for predicting the outlet pipe wall temperature will be confirmed with validation of the model.

### 3.1.4.5 Effects of Friction - Fanno Process

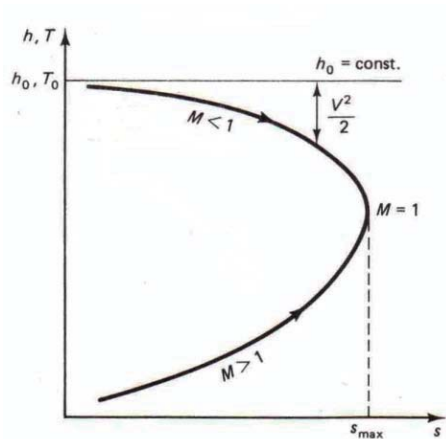


Figure 3-3: Fanno curve (Enthalpy - Entropy diagram) Adapted from (Saad 1993)

The effects of friction on the flow parameters in a vent pipe during blowdown can be well explained by means of Enthalpy-Entropy diagram. The curve formed on such a plane is defined by Continuity Equation and Energy Equation is known as the Fanno curve. The Fanno process is one steady, adiabatic flow with friction in a duct in which the cross sectional area does not change along its length (Chan and Woods 1992). The friction leads to a force on the fluid in the

opposite direction to the flow. In Fanno flow, the stagnation enthalpy and mass flux are constant in all sections of the vent pipe. The continuity equation and energy equation, describes the Fanno process in the plane of thermodynamic properties, enthalpy and density as (nomenclature remains the same as defined earlier)

$$h_o = h + \frac{V^2}{2} = h + \frac{G^2}{2\rho^2} \quad 3-18$$

The above equation indicates that when the flow of gas is accelerating in velocity, the enthalpy is decreasing by a corresponding amount, and when the gas is decelerating the enthalpy increases. As enthalpy is a function of temperature, it is valid that similar results will be seen in the temperature profiles.

The gradient of the Fanno curve is given by (Chan and Woods 1992) expressed as

$$\left(\frac{\partial h}{\partial \rho}\right)_{FANNO} = \frac{V^2}{\rho} = \frac{M^2}{\rho} \left(\frac{\partial P}{\partial \rho}\right)_S \quad 3-19$$

Where the subscript FANNO indicates that the differentiation is taken while keeping stagnation enthalpy and mass flux unchanged. The slope of the Fanno curve in the enthalpy-entropy plane is given by (Saad 1993; Shapiro 1954; Chan and Woods 1992)



$$\frac{dh}{ds} = \frac{\gamma T M^2}{M^2 - 1}$$

3-20

Equation 3-20 expresses enthalpy as a function of temperature, Mach number and entropy and implies that the effect of friction in a Fanno flow is to drive the flow towards Mach unity, with enthalpy and pressure decreasing in the subsonic branch and increasing in the supersonic branch. This is represented in figure 3-3. The upper part of the curve represents the subsonic condition whereas the lower portion represents the supersonic condition. Since the flow is adiabatic with friction, the second law of thermodynamic tells us that entropy may increase but may not decrease. Thus the path of states along any one of the Fanno curves must be towards the right. Thus a subsonic flow may therefore never become supersonic and a supersonic flow may never become subsonic, unless a discontinuity is present. Frictional effects present in the vent pipe alone cannot change subsonic flow into supersonic flow or vice versa because part of such processes will involve decrease in entropy, thus, violating the increasing entropy principle by Second Law of Thermodynamics. Emphasis is on frictional effects taking place in the subsonic region. In subsonic flow, frictional effects increase the internal energy with a corresponding reduction in the density of the fluid. The mass flow rate per unit area or mass flux must remain constant in the vent pipe during subsonic flow condition. In order to achieve this, constant mass flow rate condition, there must be an increase in velocity leading to expansion of compressible fluid. Friction has no effects on stagnation temperature or on stagnation enthalpy; however, friction reduces stagnation pressure in both subsonic and supersonic flow.

#### **3.1.4.6 Estimation of Friction factor**

Friction is the chief factor bringing about changes in fluid properties. The drag of a fluid at the contact between the fluid and the pipe is caused by friction factor (Ellenberger 2010). As cited in (Bansal 2005; Ellenberger 2010; Ouyang and Aziz 1995), there are two major friction factors available in fluid mechanics which are used to determine the pressure loss due to friction in pipes: the Fanning friction factor and Darcy-Weisbach or Moody friction factor. The Darcy friction factor is four times larger than the Fanning friction factor. The variation of the friction factor with Reynolds number and pipe roughness for circular pipes can be divided into different regimes (Govier and Aziz 1972): laminar flow, smooth wall turbulent flow, partially rough wall turbulent flow and fully rough wall turbulent flow. Partially rough wall turbulent flow and fully rough wall turbulent flow are also named as partially developed turbulent flow and fully developed turbulent flow (Ouyang and Aziz 1995). For Laminar flow, the friction factor can be shown to be a simple function of Reynolds number (Bansal 2005):

$$f = \frac{16}{Re}$$

3-21

Where  $f$  - Fanning friction factor and  $Re$  - Reynolds number. The friction factor is only a function of Reynolds number for smooth wall turbulent flow, and a function of relative pipe roughness for fully rough wall turbulent flow, whereas it depends upon both the Reynolds number and relative pipe roughness in partially rough wall turbulent flow.

Table 3-4: Explicit approximation for Colebrook-White friction factor equation

(Moody 1947)	$f = 0.001375 \left[ 1 + (2 \times 10^4 (\epsilon/D) + (10^6/Re))^{1/3} \right]$	(a)
(Wood 1966)	$f = 0.026(\epsilon/D)^{0.225} + 0.133(\epsilon/D) + 22(\epsilon/D)^{0.44} Re^{1.62(\epsilon/D)^{0.134}}$	(b)
(Jain 1976)	$f^{-0.5} = 2.28 - 4 \log[(\epsilon/D) + (21.25/Re^{0.9})]$	(c)
(Churchill 1977)	$f = 2[(8/Re)^{12} + 1/(A+B)^{1.5}]^{1/12}$ $A = \{2.457 \ln[(\epsilon/D)^{0.9} + 0.27(\epsilon/D)]\}^{16}$ $B = (37530/Re)^{16}$	(d)
(Chen 1979)	$f^{-0.5} = -4 \log\{0.2698(\epsilon/D) - (5.0452/Re) \times \log[0.3539(\epsilon/D)^{1.1098} + (5.8506/Re^{0.8981})]\}$	(e)
(Zigrang and Sylvester 1982)	$f^{-0.5} = -4 \log\{(\epsilon/3.7D) - (5.02/Re) \times \log[(\epsilon/3.7D) + (13/Re)]\}$	(f)
(Serghides 1984)	$f = 0.25\{A - [(B-A)^2/(C-2B+A)]\}^{-2}$ ; $A = -2 \log[(\epsilon/3.7D) + (12/Re)]$ ; $B = -2 \log[(\epsilon/3.7D) + (2.51A/Re)]$ ; $C = -2 \log[(\epsilon/3.7D) + (2.51B/Re)]$	(g)
(Swamee and Jain 1976)	$f = 0.25\{\log[(\epsilon/3.7D) + (5.74/Re^{0.9})]\}^{-2}$	(h)
(Romeo, Royo, and Monzon 2002)	$f^{-0.5} = -2 \log\{(\epsilon/3.7D)(5.03/Re) \log[(\epsilon/3.83D) - (4.6/Re) \times \log\{[\epsilon/7.8D]^{0.9924} + [5.33/208.82 + Re]^{0.9345}\}]\}$	(i)
(Sonnad and Goudar 2006)	$f^{-0.5} = 0.8686 \ln\{[0.4587R]/s^{(s^{(s+1)})}\}$ ; $s = 0.1240(\epsilon/D)R + \ln(0.4587R)$	(j)

In practical situations, the flow of compressible fluid (gas) is turbulent. A number of different approximations are been reported to analyze the friction on turbulent flow regime. These methods can be classified as smooth pipe correlations and rough pipe correlations. Our investigations are only related to rough pipes hence we do not consider smooth pipe correlations into our vent pipe model. Difficulty of solving turbulent flow problems in rough pipes lies in the fact that hydraulic friction factor is a complex function of relative surface roughness and Reynolds number (Brkic` 2011). The equation for computing the friction factor in the Darcy-Weisbach pipe friction loss equation, as presented by Colebrook and White (Colebrook 1939), has been preferred because of its presumed superior accuracy and sound theoretical basis (Bernuth 1990).

The Colebrook and White (CW) equation which related to pipe roughness and Reynolds number, is customarily given by (Franzini, Finnemore, and Daugherty 1997)

$$\frac{1}{\sqrt{f}} = -2 \log \left[ \frac{(\epsilon/D)}{3.7} + \frac{2.51}{Re \sqrt{f}} \right] \quad 3-22$$

Where  $f$  - fanning friction factor;  $(\epsilon/D)$  - Relative pipe roughness;  $Re$  - Reynolds number. Colebrook equation is transcendental which means that it cannot be solved by using only

elementary functions and basic arithmetic operation in definitive form (Brkic` 2011). Clearly, the above Colebrook and White equations are implicit in the friction factor estimation, and requires either an iterative numerical scheme or by graphical representation for solution. An alternative solution to iterative methods is the direct use of an explicit equation which is precise enough to calculate the value of friction factor.

Numerous researches (Moody 1947; Wood 1966; Jain 1976; Churchill 1977; Chen 1979; Zigrang and Sylvester 1982; Serghides 1984; Swamee and Jain 1976; Romeo, Royo, and Monzon 2002; Sonnad and Goudar 2006) have been conducted in this area. The most widely used explicit approximations for Colebrook-White equation postulated since the end of 1940s are synthesized in table 3-4. These approximations differ from each other in degree of accuracy. Average percentage errors generated by these approximations when compared to Colebrook-White equation have been indicated in table 3-5. Referring to the accuracy table 3-5, we can say that the deviation of Serghides approximation (Serghides 1984) table 3-4 equation (g) from the Colebrook-White equation for rough pipe results in a very low average error compared to any other approximation listed in table 3-5. Hence we apply Serghides approximation for Colebrook-White equation into our model for determining the friction factor in the transitional and turbulent flow ( $Re > 2100$ ) at any relative roughness ( $\epsilon/D$ ). The Serghides approximation for Colebrook-White equation is derived by applying Steffenson's accelerated convergence technique to an iterative, numerical solution of Colebrook-White equation. The constants A, B and C are approximations of Colebrook-White equation obtained by three iterations of direct substitution method (Serghides 1984).

Table 3-5: Overall average relative errors of fanning friction factor values obtained from different explicit equations compared with those from the CW equation (Ouyang and Aziz 1995; Swamee and Jain 1976; Romeo, Royo, and Monzon 2002; Sonnad and Goudar 2006)

Average	Serghides	Chen	Z-S	Jain	Romeo	Sonnad	Swamee	Churchill	Wood	Moody
Error	0.00037	0.137	0.234	0.929	1.04	1.09	1.34	4.092	5.107	6.276

### 3.1.4.7 Estimation of Thermophysical Properties

The accurate knowledge of thermodynamic properties of gases such as natural gases and other gas mixtures is of indispensable importance for the basic engineering and performance of technical processes (Kunz et al. 2007). These properties can significantly affect the flow regimes occurring during the venting process, thus introducing unexpected variations in the depressurization mechanism (Skouloudis 1992).

The thermodynamic properties of mixtures can be calculated in a very convenient way from the equations of state. The advantage of employing equation of state in determining these properties is because it does not rely on activity coefficient concepts. A number of equations of state are available which serve his purpose. AGA8-DC92 equation of state is currently an internationally accepted standard only for  $P$ - $\rho$ - $T$  relation in homogenous gas region of natural gases. Aside from the restriction to the homogenous gas phase, the AGA8-DC92 equation of state shows significant weaknesses in the description of natural gas properties and covers only a limited temperature, pressure and composition range (Kunz et al. 2007). Cubic equation of states such as Soave-Redlich Kwong (Soave 1972) and Peng Robinson (Peng and Robinson 1976) are widely used in many technical applications due to their simple mathematical structure. Technical applications which demand high accuracy of the calculated mixture properties, the cubic equation of state show major weaknesses with respect to representation of thermal properties in the liquid phase, speed of sound (thus impacting density, velocity profiles) and the description of caloric properties (Soave 1995; Kunz et al. 2007; Won, Smith, and Zeininger 2005). As a result there are inconsistencies in calculations when moving from one region to another. Experimental evidence has also shown that it is most important to model the thermodynamics of depressurization accurately since failure to do so can lead to trajectories through phase (pressure-temperature-composition) space which are grossly in error (Richardson and Saville 1996). For this reason, thermodynamic, phase and transport properties of single phase multi-component fluids involved in the vent pipe model are calculated using a thermophysical computer package called REFPROP (Lemmon, Huber, and McLinden 2009). This program has been developed by National Institute of Standards and Technology (NIST) and provides the thermodynamic and transport properties of industrially important fluids and their mixtures

REFPROP is based on the most accurate pure fluid and mixture models. The program implements three models for the thermodynamic properties of pure fluids: the GERG-2004 equation of state explicit in Helmholtz energy (Kunz et al. 2007). Mixture calculations employ a model that applies mixing rules to the Helmholtz energy of the mixture components; it uses a departure function to account for the departure from ideal mixing (Lemmon, Huber, and McLinden 2009). The GERG-2004 (Kunz et al. 2007) equation of state is a fundamental equation explicit in the Helmholtz free energy as a function of density, temperature, and composition. The GERG-2004 equation of state is developed with a view to overcome the weaknesses and limitations of the previous equations of state. The development and evaluation of GERG-2004 mixture model is based on more than 100,000 experimental data for multiple

thermodynamic properties in different fluid regions (Kunz et al. 2007). The GERG-2004 formulation is able to represent the most accurate experimental binary and multi-component data for gas phase and gas-like supercritical densities, speed of sound, and enthalpy differences mostly to within their low experimental uncertainties. The normal range of validity covers temperatures from 90 K to 450 K and pressure up to 35 MPa for natural gases and other single or gaseous mixture consisting of the 18 components methane, nitrogen, carbon-dioxide, ethane, propane, n-butane, isobutene, n-pentane, iso-pentane, n-hexane, n-heptane, n-octane, hydrogen, oxygen, carbon monoxide, water, helium, and argon (Lemmon, Huber, and McLinden 2009). The uncertainties in gas phase density and speed of sound for a broad variety of natural gases and related mixtures are less than 0.1% over the temperature range 250 K to 450 K at pressures up to 35 MPa (Kunz et al. 2007). Thus, the utilization of REFPROP into the vent pipe model in determining the thermophysical properties will improve the accuracy of predictions of compressible fluid flow properties and make the simulation in the vent pipe model competent.

## **3.2 Modeling Approach**

### **3.2.1 Simulation Object**

As discussed earlier the geometry visualized in model development consists of a source and vent pipe arrangement. The conditions in vent pipe have been proved to be at steady state. In order to perform simulation using vent model, we chose 8 NB schedule 80 stainless steel straight pipe of length 12 m. The roughness of the pipe is assumed to be as 0.00015 m. No fittings are involved hence we neglect the form friction. The vent pipe predictions which we need to calculate are pressure and temperature of the flowing gas, adiabatic wall temperature, Mach number, density, velocity, enthalpy, entropy, friction factor, mass flow, standard volumetric flow, stagnation properties and critical properties. These properties are calculated for each and every segment along the vent profile for specified inlet static pressure and temperature and gas composition. Venting is to atmosphere hence the outlet static pressure is 1 bar atm.

### **3.2.2 Method of Solution**

A number of equations are involved in determining compressible fluid flow properties in a vent pipe during blowdown. One of the methods of applying these is Multi-Step or Segmented Design Method (Ouyang and Aziz 1995). Multi-Step or Segmented Design Method require that calculations be performed over very small segments of the vent pipe and that iterations be employed to obtain the change in pressure, temperature and other thermophysical properties over each segment. The vent pipe length can be equally divided or chosen in such a way that

their sum of the segment lengths is exactly equal to the total vent pipe length. The procedure can be applied from upstream to downstream end of the vent pipe. The method, however, becomes bi-directional for calculating properties at sonic condition.

Table 3-6: Property relations in terms of Mach number

PART A	PART B
$\frac{4fL_{1-2}}{D_H} = \frac{1}{\gamma} \left( \frac{1}{M_1^2} - \frac{1}{M_2^2} \right) + \frac{(\gamma+1)}{2\gamma} \ln \frac{M_1^2}{M_2^2} \left( \frac{1 + \left(\frac{\gamma-1}{2}\right) M_2^2}{1 + \left(\frac{\gamma-1}{2}\right) M_1^2} \right)$ (a)	$\frac{4fL^*}{D_H} = \frac{1-M^2}{\gamma M^2} + \frac{\gamma+1}{2\gamma} \ln \frac{(\gamma+1)M^2}{2\left(1 + \frac{\gamma-1}{2}M^2\right)}$ (f)
$\frac{V_1}{V_2} = \frac{M_1}{M_2} \sqrt{\frac{1 + \left(\frac{\gamma-1}{2}\right) M_2^2}{1 + \left(\frac{\gamma-1}{2}\right) M_1^2}}$ (b)	$\frac{V}{V^*} = M \sqrt{\frac{\gamma+1}{2 + (\gamma-1)M^2}}$ (g)
$\frac{\rho_1}{\rho_2} = \frac{M_2}{M_1} \sqrt{\frac{1 + \left(\frac{\gamma-1}{2}\right) M_1^2}{1 + \left(\frac{\gamma-1}{2}\right) M_2^2}}$ (c)	$\frac{\rho}{\rho^*} = \frac{1}{M} \sqrt{\frac{2 + (\gamma-1)M^2}{\gamma+1}}$ (h)
$\frac{P_1}{P_2} = \frac{M_2}{M_1} \sqrt{\frac{1 + \left(\frac{\gamma-1}{2}\right) M_1^2}{1 + \left(\frac{\gamma-1}{2}\right) M_2^2}}$ (d)	$\frac{P}{P^*} = \frac{1}{M} \sqrt{\frac{\gamma+1}{2 + (\gamma-1)M^2}}$ (i)
$\frac{T_1}{T_2} = \frac{1 + \left(\frac{\gamma-1}{2}\right) M_2^2}{1 + \left(\frac{\gamma-1}{2}\right) M_1^2}$ (e)	$\frac{T}{T^*} = \frac{\gamma+1}{2 + (\gamma-1)M^2}$ (j)

Properties of a fluid determined in table 3-2 at any section of a vent pipe can be related to the properties at any other section of the vent pipe. It is always advisable to relate the property relations in table 3-2 in form of dimensionless Mach number. In order to achieve this, property relations in table 3-2 are integrated between the inlet and exit conditions of the vent pipe. The inlet conditions are represented by subscript 1 and exit conditions by subscript 2. The integrated expressions are tabulated in table 3-6 Part A. A problem develops when the speed of gas is approaching sonic velocity. Obtaining results of table 3-6 Part A will sometimes result in solutions of subsonic to supersonic flow. This will affect the calculation procedures and will result in an error. Hence in order to overcome these situations, we restrict the properties in table 3-6 Part A to approach those characteristic of Mach unity. Properties of a fluid when the gas is flowing at Mach unity are called critical properties and are identified by means of an asterisk (\*). These equations are represented in table 3-6 Part B.

Mass flow rate is a requirement in predicting the properties along the vent pipe segments. Thus, initially we consider the entire length of vent pipe and compute the mass flow rate. In order to calculate the constant mass flow rate, inlet value of Mach number is required. This is achieved

by solving equations (a) & (e) of table 3-6 and equation 23 which relates the inlet and outlet Mach numbers for a segment or for the entire length of the vent pipe.

$$\frac{M_1}{M_2} = \frac{P_1}{P_2} \left( \frac{T_2}{T_1} \right)^{1/2} \quad 3-23$$

This result in two non-linear equations 24 & 25 with three unknown variable: *friction factor, Mach number, and outlet temperature.*

$$\frac{1}{\gamma} \left\{ \frac{1}{M_1^2} \left[ 1 - \left( \frac{P_1}{P_2} \right)^2 \left( \frac{T_2}{T_1} \right) \right] - (1 + a) \ln \left[ \left( \frac{P_1}{P_2} \right)^2 \left( \frac{T_2}{T_1} \right) \frac{1 + aM_1^2}{1 + a \left( \frac{P_2}{P_1} \right)^2 \left( \frac{T_1}{T_2} \right) M_1^2} \right] \right\} - \frac{4fL}{D} = 0 \quad 3-24$$

$$\frac{T_1}{T_2} - \frac{1 + a \left( \frac{P_2}{P_1} \right)^2 \left( \frac{T_1}{T_2} \right) M_1^2}{1 + aM_1^2} = 0 \quad 3-25$$

Where  $a = (\gamma - 1)/2$ ;  $\gamma$ : Specific heat ratio;  $M_1$  – Inlet Mach number for the segment or vent pipe;  $M_2$  – Outlet Mach number for the segment or vent pipe;  $P_1$  – Inlet static pressure for the segment or vent pipe;  $P_2$  – Outlet static pressure for the segment or vent pipe;  $T_1$  – Inlet static temperature for the segment or vent pipe;  $T_2$  – Outlet static temperature for the segment or vent pipe. We have two dependent variables and one independent variable in equations 24 & 25. Since we interested in the effects of friction in the vent pipe, we choose friction factor,  $f$ , as independent variable.

Frictional resistance between the moving gas and pipe wall is quantified using Darcy friction factor,  $f$ . For fully turbulent flow, friction factor is independent of Reynolds number and is determined using the Von Karman equation customarily given by (Cochran 1996):

$$f = -2 \log[(\epsilon/D)/3.7]^{-2} \quad 3-26$$

For flow regimes other than fully turbulent, the friction factor is dependent on Reynolds number. However, the above Von-Karman equation can be conveniently used as an initial estimate of friction factor. On estimating the initial friction factor, the non-linear equation 24 & 25 can be solved by applying Newton's Iteration method for multi-variable non-linear equations. We incorporate the use of Jacobian matrix in calculating our dependent variables. The procedure for Newton's Iteration method can be cited in a (Franz and Melching ND; Bellman 1970; Ortega and Rheinboldt 1970). One of the serious difficulties associated with the use of the Newton's technique is calculation of the Jacobian matrix and its inversion at each step which sometimes results in errors (Bellman 1970). This difficulty is overcome by solving the matrix on excel spreadsheet.

An initial estimate for Mach number is assumed to be 0.01 and for outlet temperature is assumed to be as inlet temperature. In subsonic flow the exit temperature is always decreasing. Hence the inlet temperature will provide a good estimate in calculating the outlet temperature. A minimum of 400 iterations are performed to calculate the final friction factor incorporating a number of nested iterations. After approximating the friction factor value on first iteration, Serghides approximation (Serghides 1984) to the Colebrook-White equation 3-22 is used to estimate the friction factor up to final iteration. Iterations are performed until the friction factor convergence is of the order  $10^{-16}$ . This will improve the accuracy of vent pipe model predictions. The inlet Mach number and outlet static temperature of the flowing gas are calculated from iterations for the final friction factor. The inlet Mach number is used to calculate the steady state mass flow-rate which remains constant for all segments of the vent pipe.

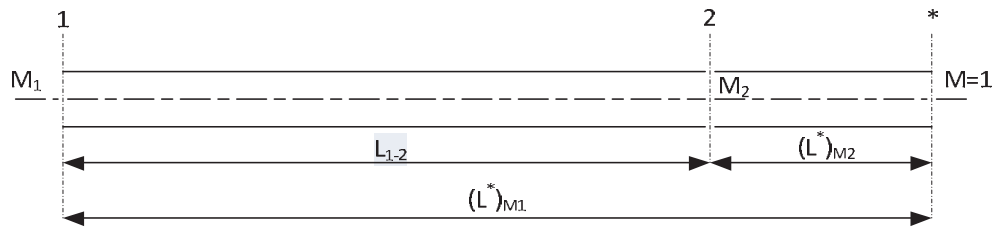


Figure 3-4: Representation of equation 3-27

The predicted compressible fluid properties for each segment of vent pipe depend on the friction term  $4fL/D$ . The accuracy of particular model or method of solution is greatly dependent on the  $4fL/D$  term of the pipe section under blowdown (Botros, Jungowski, and Weiss 1989). For a given segment length,  $L_{1-2}$ , the term  $4fL_{1-2}/D$  is estimated from the following equation 3-27 (Parker 1989; Saad 1993; Shapiro 1954) and is represented in figure 3-4:

$$\frac{4fL_{1-2}}{D} = \left(\frac{4fL^*}{D}\right)_{M_1} - \left(\frac{4fL^*}{D}\right)_{M_2} \quad 3-27$$

Where  $L^*$  - Maximum length of vent pipe which does not cause choking;  $(L^*)_{M_1}$ : Vent pipe length associated with  $M_1$ ;  $(L^*)_{M_2}$ : Vent pipe length associated with  $M_2$ ;  $L_{1-2}$  - Vent pipe length between the section 1 corresponding to Mach  $M_1$ , and section 2 corresponding to Mach  $M_2$

Upon calculating the friction term, the corresponding compressible fluid properties are calculated using the critical property relations in table 3-6 Part B. The resulting venting conditions are then calculated for each segment of the pipe. The exit conditions calculated for a segment becomes the inlet condition for the next segment of the vent pipe. The balances obtained for each segment of the vent pipe are then linked together to satisfy the boundary conditions. The boundary conditions for the vent pipe are specified gas static pressure, gas static



temperature and gas composition at the inlet of the vent pipe and complete pressure drop to atmosphere, *that is*, a pressure of 1 bar atm or choking pressure (at which flow becomes choked) at the exit of the vent pipe.

If choking condition is attained, the user has following 3 options-

- Decreasing the inlet static pressure – At sonic condition by decreasing the inlet static pressure, the mass flow rate will be reduced. Thus, the flow will enter the subsonic region with a shift in Fanno curve
- Increasing the vent pipe length - When a compressible gas flows through a constant area vent pipe, the flow characteristics in the vent pipe are affected by the length of the vent pipe. If the flow entering the vent pipe is at subsonic condition, the gas will accelerate in the vent pipe owing to friction, approaching sonic conditions at the exit. At the same time, the static pressure as well as stagnation pressure decreases in the direction of the flow. Stagnation temperature and stagnation enthalpy will remain constant. If choking condition is attained at the vent pipe exit, the mass flow rate through the vent pipe is at its maximum (refer figure 2) and the flow is choked at the exit. If a further increase in mass flow rate is desired it can be achieved by decreasing the stagnation temperature and or increasing the stagnation pressure at the inlet of the vent pipe (as per equation 15). However, the velocity at the exit of the vent pipe would still be sonic, but the exit pressure would be higher. According to the Fanno process, friction present in adiabatic flow will cause changes in the compressible fluid properties and increases the gas velocity so that the sonic velocity is approached at the pipe exit. Apart from friction factor, the term,  $4fL/D$ , also incorporates the length and diameter of the vent pipe. Precisely, the mass flow rate achieved in the vent pipe depends on friction resistance (Brkic` 2011). Hence, the length of the pipe can directly affect the mass flow through the vent pipe. If the term  $4fL/D$  is as large as the maximum value appropriate for the Mach number at the entrance to the vent pipe, then the gas flow at the pipe exit is at Mach 1 and the length of the pipe is at its maximum. Thus when choking occurs, the Mach number at the inlet of the pipe depends on the length of the pipe and decreases as the length is increased. When the flow is choked, an increase in pipe length produces a reduction in the mass flow, so that the operating point is shifted to a different Fanno line.
- Increasing or decreasing the exit gas static pressure - When a compressible gas flows through a constant area vent pipe, the flow characteristics in the vent pipe are affected by the back pressure at the vent pipe exit. For a constant vent pipe length, an increase or decrease in exit gas pressure will result in a sonic condition depending on the back pressure

applied. In subsonic flow, gas accelerates continuously such that the exit pressure is equal to back pressure. If the back pressure is reduced, the exit pressure of the gas will reduce such that sonic conditions are approached at the exit of the vent pipe. At this point the mass flow will be at its maximum through the vent pipe and the exit Mach number will be at unity. Any further reduction in back pressure will have no effect on the mass flow. In our case venting is straight to atmosphere. On achieving choking pressure, an increase or decrease in exit pressure from back pressure of 1 bar will cause a decrease in mass flow and the Mach number will be less than unity.

This procedure gives the complete state of the line for specified upstream conditions at all points along the vent pipe. Compressible gases used in performing simulations using the vent pipe model were air, methane, carbon dioxide and DBNGP gas mixture. Simulations were performed in the pressure range from 100 KPa gauge up to choking pressure condition. All results are presented in Appendix F.

### **3.3 Computations**

For obtaining solutions to process simulations, several levels of computation are available – ranging from solution by inspection to analytical and high speed computer solution (Ramirez 1998). Because of the complexity and non-linearity of process simulation problems, most solution require high speed computer. All computations related to the vent pipe model were carried out on Core 2 Duo 3.00 GHz computer with 2 GB RAM provided by Curtin University.

The vent pipe model's programming functions were scripted in Visual Basic in conjunction with Microsoft Excel which will act as a user interface for data input, model prediction results, and report generations. The algorithm adopted in computing the predictions of the vent pipe model is presented in figure 3-5. The MS Excel and Visual Basic program functions for the vent pipe model and for obtaining the thermophysical properties are presented in Appendix H.

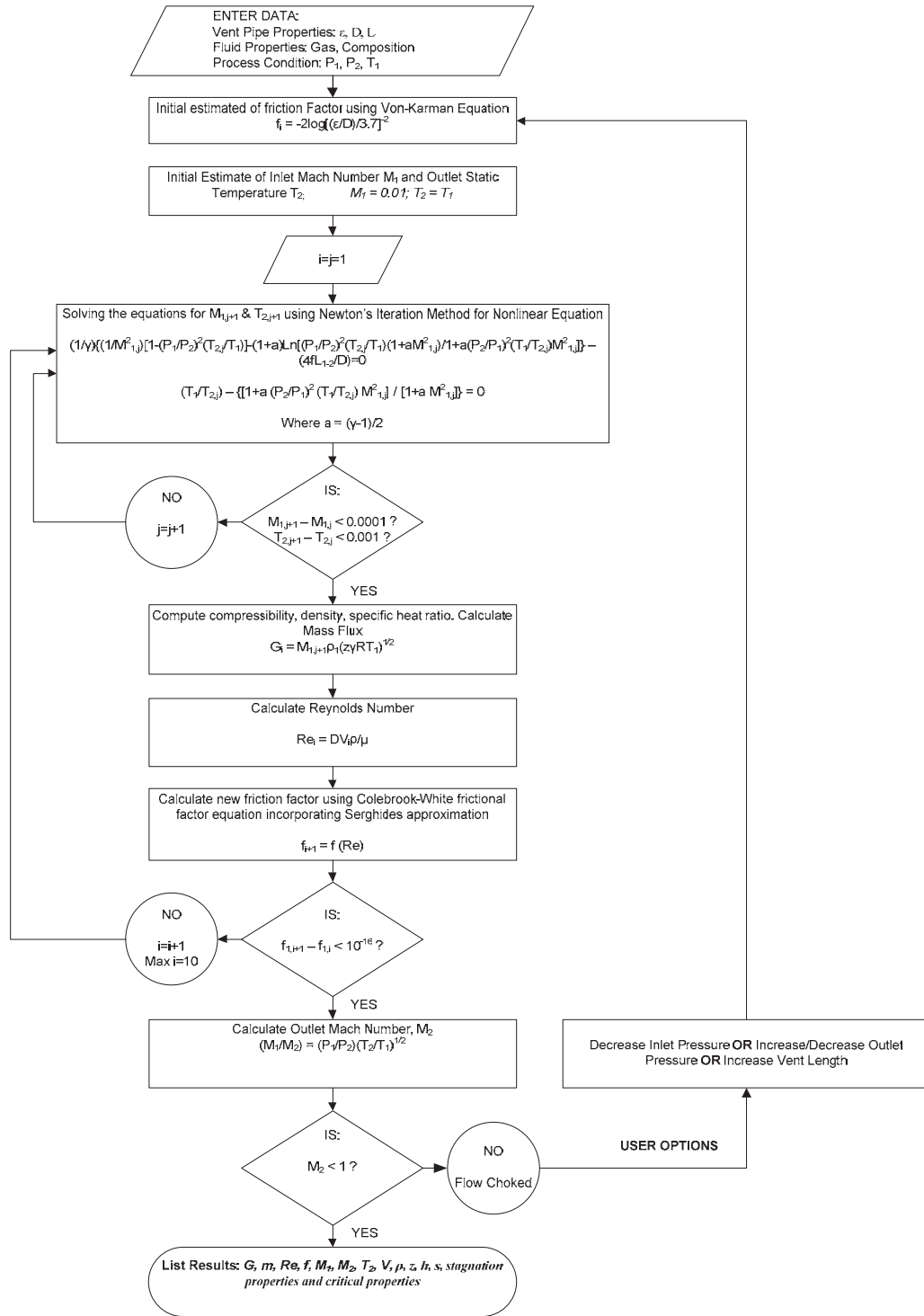


Figure 3-5: Algorithm for vent pipe model

# Chapter 4

## **Results and Discussion**

As discussed in the literature review, the ranges of transient and steady-state vent pipe flow experiments are limited. Venting experiments have been conducted with working fluids such as water and refrigerant R114 with an operating pressure up to 7.2 MPa (Skouloudis 1992). These experiments, which encounter liquid only, are more related to the reactor cooling system for nuclear industry and were conducted for validating models SAFIRE (Tilley and Shaw 1990), RELAP (Worth, Staedtke, and Franchello 1993), RELIEF (Nijsing and Brinkhof 1996) and DEERS (Skouloudis 1992). A wide range of experiments related to blowdown of single phase gas/liquid or multiphase mixtures from pressure vessels and pipelines are been conducted (Evanger et al. 1995; Gebbeken and Eggers 1995; Norris III, Exxon Production Research Co, and R.C. Puls 1993; Haque et al. 1992). A rough idea to model the vent pipe-work associated with vessels and pipelines is mentioned (Haque, Richardson, and Saville 1992). In order to evaluate the performance of the developed vent pipe model and provide experimental data for future development of models, a small facility was constructed to perform venting experiments.

### **4.1 Experimental Design**

The experimental test rig was developed and designed based on first principles of chemical engineering. The test rig was designed for a maximum design pressure of 1500 KPa G. Relevant standard/codes were employed in mechanical designing of the experimental test rig. The design was confirmed and signed for construction by Dr. Hari Vuthaluru, *Associate Prof. Department of Chemical Engineering, Curtin University*, Mr. Clinton Smith, *Principal Process Engineer, Atkins Global* and Dennis Kirk-Burnnand, *Principal Consultant, GHD Pty Ltd*. The construction of the experimental test rig was carried out in Curtin University's Mechanical Workshop by Carl Lewis, *Senior Technician*.

The experimental test rig consists of a vent pipe and an accumulator pipe arrangement. The vent pipe is a 12m long 8NB schedule 80 stainless steel type 316 pipe. The entire test rig arrangement is positioned horizontally on 90° brackets mounted in the wall. In order to achieve a steady-state flow condition, an 11.6 m long 50 NB schedule 40 seamless carbon steel ASTM A106 GR B 3000 pipe was positioned in parallel with the vent pipe. The purpose of the carbon steel pipe was to act as an 'accumulator', a steady supply source of gas through the 12 m vent pipe section in case if the supply from the compressor and gas bottles was observed depleting.

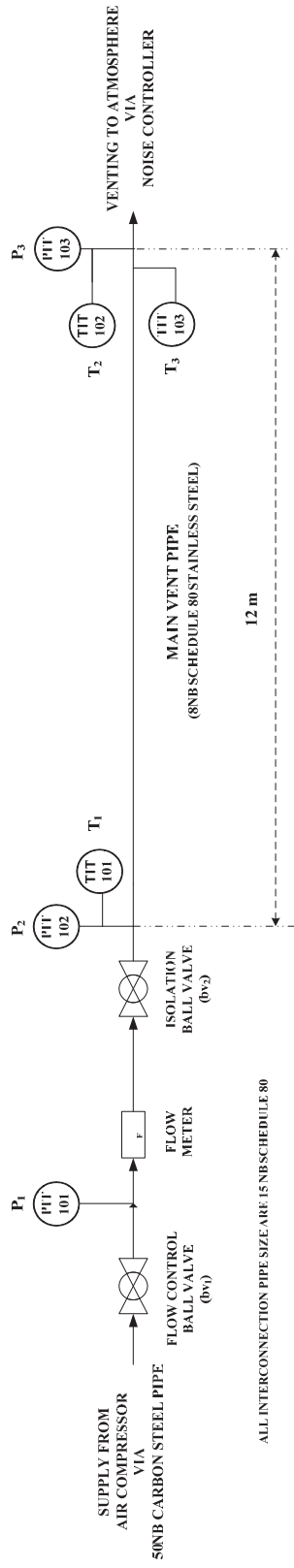


Figure 4-1: Schematic representation of the vent pipe assembly

In order to comply with safety, the vent pipe and accumulator pipe arrangements were hydrostatically tested with water at a pressure of 600 psi for a period of 30 min. No leaks were found and a pressure test certificate (refer Appendix A) was provided. Pressure reliefs were also installed in case of pressure built up in the accumulator. Due to high velocity noise produced at the end of the test section, a noise controller was designed and attached to end flange of the vent pipe. The noise controller is a 150NB SS pipe with 80NB schedule 10s SS pipe inside both welded to a flange. The 80NB pipe has ½ inch perforated holes along its length. The gas exiting at the end of the vent pipe is absorbed by the acoustic foam packed inside the 150NB pipe. The entire arrangement and mechanical drawings can be seen in figure 4-1 and Appendix B. In order to have no heat transfer with the surroundings prevailing adiabatic process assumptions, the entire vent pipe arrangement was insulated with glass wool. Extensive safety and operational controls were instituted to prevent the ingress of unauthorized personnel into the facility during the gas blowdown.

## **4.2 Instrumentation and Data Collection**

The vent pipe tests were performed by measuring the stagnation temperature of the gas at the inlet and exit, temperature of the vent pipe wall at the exit, the temperature of the vent pipe wall at every 1m section of the pipe, pressure and the flow of the gas through the vent pipe. The instruments are selected based on the engineering design parameters which could sustain the maximum design pressure. Pressure transducers were used to measure the pressure of the gas at three different positions: before ball valve (bv<sub>2</sub>), inlet and exit of vent pipe. The 130C Ceramic Pressure Transducer made of Wheatstone bridge circuit transmitting an analog output of 4-20mA was used to sense the pressure. The pressure range of the transducer is 0-20 bar at an accuracy of ±0.1 bar. The pressure transducers were calibrated by the vendor. A digital pressure gauge was also used to give direct measurements. This digital pressure gauge was provided by BOC Gases. RTD's were used to sense the temperature of the gas at the inlet and exit ends. Model RTD-PT100 output was used with initial calibration performed by the vendor. In order to cross check the accuracy, RTD's were immersed in the ice / water bath and corresponding temperatures were recorded. All RTD readings were found to be in close agreement (refer Appendix C for Commissioning and Testing report). The temperatures of the outside of the pipe wall at the vent pipe exit were obtained using Adjustable Ring T-Type thermocouple. These thermocouples make direct contact with the pipe for maximum performance and have grounded junctions. The operating range for these thermocouples is -100°C to 400°C. The temperature sensed by the temperature sensors was confirmed by a Non-Contact Thermometer with Dual

Laser Targeting (temperature gun). The contact thermocouples temperatures were checked for accuracy in the ice / water bath and measurements were found to be in close agreement. The temperature range was  $-50^{\circ}\text{C}$  to  $650^{\circ}\text{C}$  with an accuracy of  $\pm 1\%$ . The outside surface pipe wall temperatures after every 1m section of the vent pipe were obtained using temperature gun. The flowrate of the gas through the vent pipe was monitored and obtained using an IFM Effector 300 Flow Sensor Model SD6000. This flow sensor is been developed especially for compressed air with integrated pipe length. The flow sensor measurement is based on the calorimetric principle transmitting an analogue signal of 4-20mA proportional to the standard volumetric flow. The compressed air meter detects the standard volume flow (to ISO 2533) directly, eliminating the need to correct for temperature and pressure variation. The high measurement dynamics of the system enables reliable detection of minute quantities. The range of the flow meter is 0-75  $\text{Nm}^3/\text{hr}$  at an accuracy of  $\pm 3\%$ . High accuracy and repeatability are ensured by the integration of the measurement sensor's key elements into a defined pipe length.

All data was telemetered to a NI CompactDAQ data acquisition system developed by National Instruments. Model NI cDAQ-9172 is an eight-slot NI CompactDAQ chassis that can hold up to eight I/O modules and is capable of measuring a broad range of analog and digital I/O signals and sensors using a Hi-Speed USB 2.0 interface. The analog signals from the pressure transducer, temperature RTD, temperature thermocouple and flow meter are transmitted to NI input modules NI9203, NI9217 and NI9211 via 2pr screened dekrone cable. The data collection is controlled by the NI LabView Signal Express software *version 3.5* from where trend data is exported to Microsoft Excel for further analysis. The advantage of using LabView Signal Express is that it provides instant interactive measurements that require no programming, thus, making it easier to use. Although the accuracy of the instruments and modules is found to be agreeable there exists a potential for signal noise caused primarily due to power supply fluctuations, signal transmission etc. This difficulty was solved by adopting signal noise reduction technique and is described in next section.

### **4.3 Experimental Data Noise Reduction**

Noise is a high-frequency variation in the process measurement that is not associated with the true process measurement i.e. it is the variation in the sensor reading that does not correspond to changes in the process and can be by background electrical interference, mechanical vibrations and process fluctuations (Riggs and Karim 2006). These signal noises are equivalent to errors which inevitably corrupt the process measurement and render the steady-state performance

during the measurement processing and transmission of signal. Hence it is therefore important to reduce, if not completely eliminate, the effect of noise or errors.

The total error in a measurement, which is the difference between the measured value and the true value of the variable, can be conveniently represented as the sum of the contributions from two types of errors – random errors and gross errors (Narasimhan and Jordache 2000). Random error (Nagy 1992; Narasimhan and Jordache 2000) implies that neither the magnitude nor the sign of the error can be predicted with certainty. In other words, if the measurement is repeated with the same instrument under identical process conditions, a different value may be obtained depending on the outcome of the random error. Gross errors imply that at any given time they have a certain magnitude and sign which may be unknown. Thus, if the measurement is repeated with the same instrument under identical conditions, the contributions of the systematic gross error to the measured value will be the same. Random errors can be caused by a number of different sources such as power supply fluctuations, network transmission and signal conversion noise, analog input filtering, changes in ambient conditions whereas gross errors are caused by nonrandom events such as instrument malfunctioning, miscalibration, wear or corrosion of sensors, and solids deposits. Such gross errors do not apply to our measurement process as no malfunctioning, miscalibration, wear or corrosion exists with our sensing instruments. The instruments purchased from relevant vendors are new which certify calibration performed on them. The temperature instruments have been tested from time to time in ice / water bath to ensure its accuracy. The instruments are well fitted by qualified Mechanical Technicians. The only error relevant in our case is the random errors on measurements as additive contributions.

An abundant literature exists on measurement error and its calculation (Lloyd and Lipow 1962). Characteristics of random error can be described using statistical properties. Hence its mean or expected value is usually the DC voltage we trying to measure, to which noise are added and its variance is the standard deviation of the noise. As recommended by (National Instruments 2006), we assume an identical distribution of each of the samples. Specifically, the means of all the samples are the same, as are the standard deviations. This assumption is convenient because in calculations we can now use the same statistics to describe each of the samples. Characterizing the sample as independent is not a good assumption because the character of noise is often time varying. The standard deviation is a measure of the magnitude of the energy of whatever AC signal is present (just noise, we hope, in case of a DC measurement) and is independent of whatever DC signal is present. Since the true standard deviation is never known,



an estimate of the standard deviation can be obtained by using the following equation recommended (National Instruments 2006)

$$\sigma = \sqrt{E(X_i^2) - \mu^2} \quad 4-1$$

Where  $\sigma$  - standard deviation (just noise in case of DC measurement);  $X_i$  - sample of noise in question;  $E(.)$  - Expectation (average value) of the quantity inside the brackets.

An important requirement for estimating the standard deviation of a measurement error from a sample of measurements is that all the measurements of the variable should be drawn from the same statistical population. We apply this logic to our initial start-up measurements for which the mean or expected value is fixed at 4mA. This makes the task trivial. Now, the standard errors calculated are subtracted from the measured values to obtain a true measured value. It should be noted that the random error generated will not be entirely eliminated (Narasimhan and Jordache 2000). A second type of redundancy, called temporal redundancy exists as we generate more data continually from CompactDAQ to determine a steady-state. Temporal redundancy can be exploited by simple averaging the calculated measurements. This task is accomplished by using a digital filter. Different digital filters such as exponential filter, Moving Average filter, polynomial filters and hybrid filters exists. Each filter type has its own advantages. Moving average  $\widetilde{y}_n(i)$  is a well known low-pass filter defined, for discrete signals, by (Alessio et al. 2002)

$$\widetilde{y}_n(i) = \frac{1}{n} \sum_{k=0}^{n-1} y(i-k) \quad 4-2$$

The moving average is a finite impulse response (FIR) filter which means that the effect of any input lasts only for N steps. The equal weight moving average cancels out periodic noise. The moving average is easy to tune for steady-state or quasi steady-state signals, requiring only the adjustment of the number of input values used to calculate the average. The moving average does not overshoot and reaches correct steady-state after a step change. The moving average is also easy to implement and fast to compute. These calculations are not trivial and are performed in Excel Visual Basic Program. An Excel Visual Basic program is written to accomplish this task of reducing the effects of errors on pressure transducer; temperature sensors and flow meter (refer Appendix D).

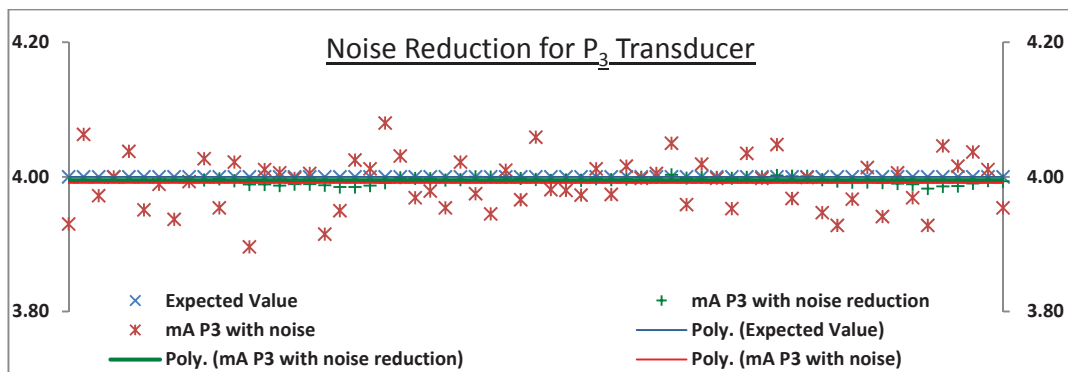
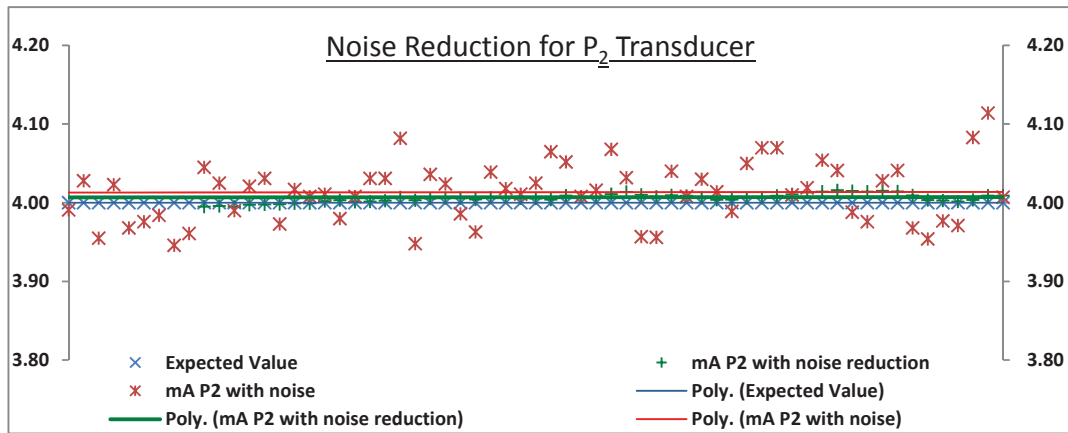
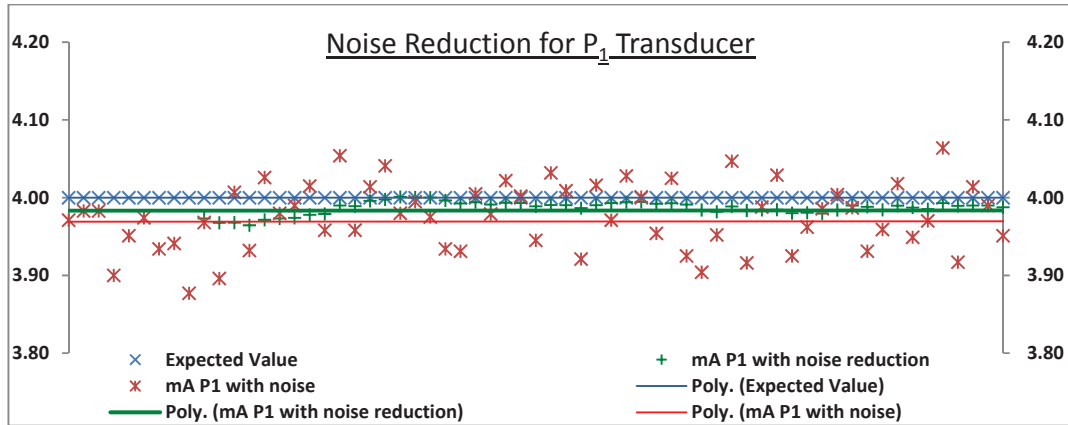


Figure 4-2: Noise reduction for pressure transducers P<sub>1</sub>, P<sub>2</sub>, P<sub>3</sub>

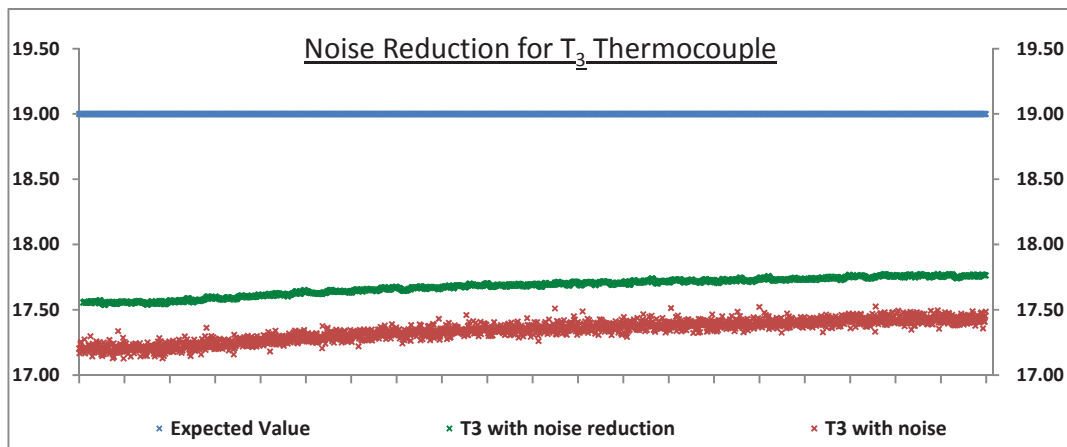
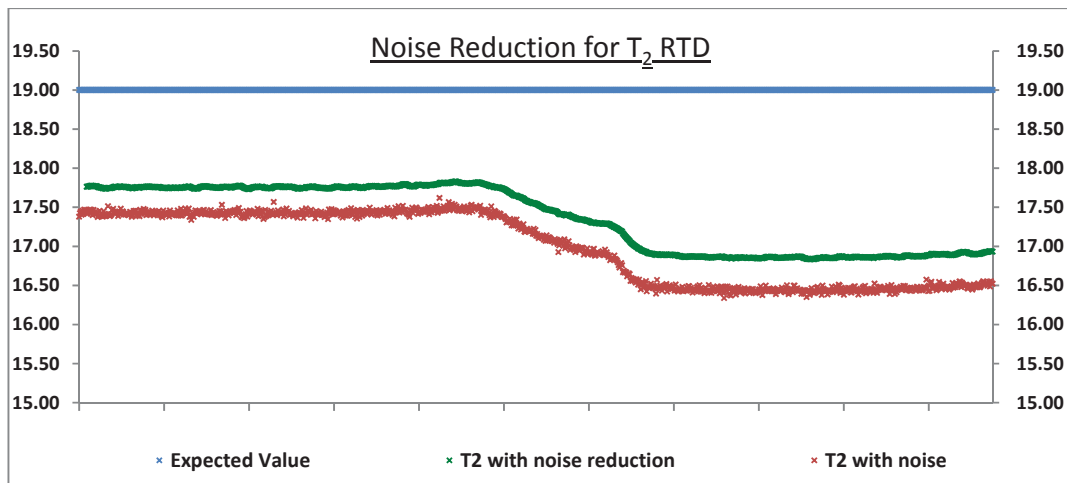
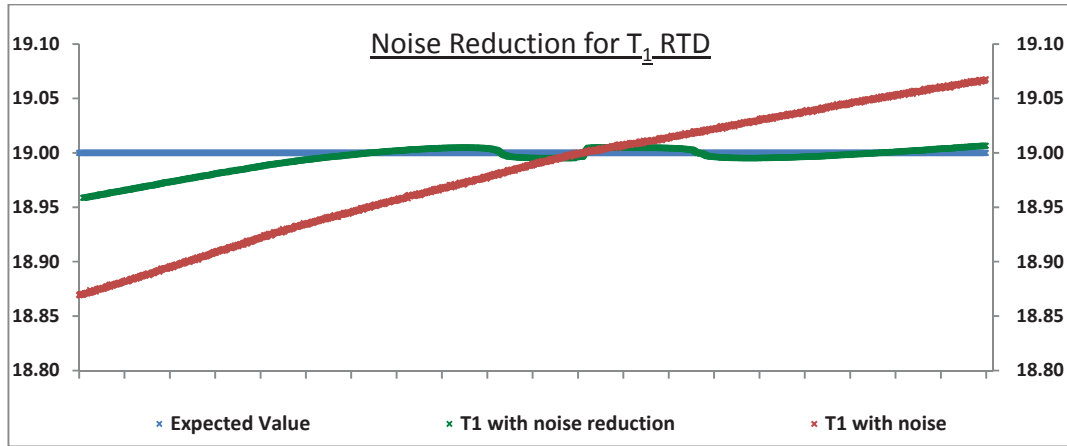


Figure 4-3: Noise reduction for temperature sensors T<sub>1</sub>, T<sub>2</sub>, T<sub>3</sub>

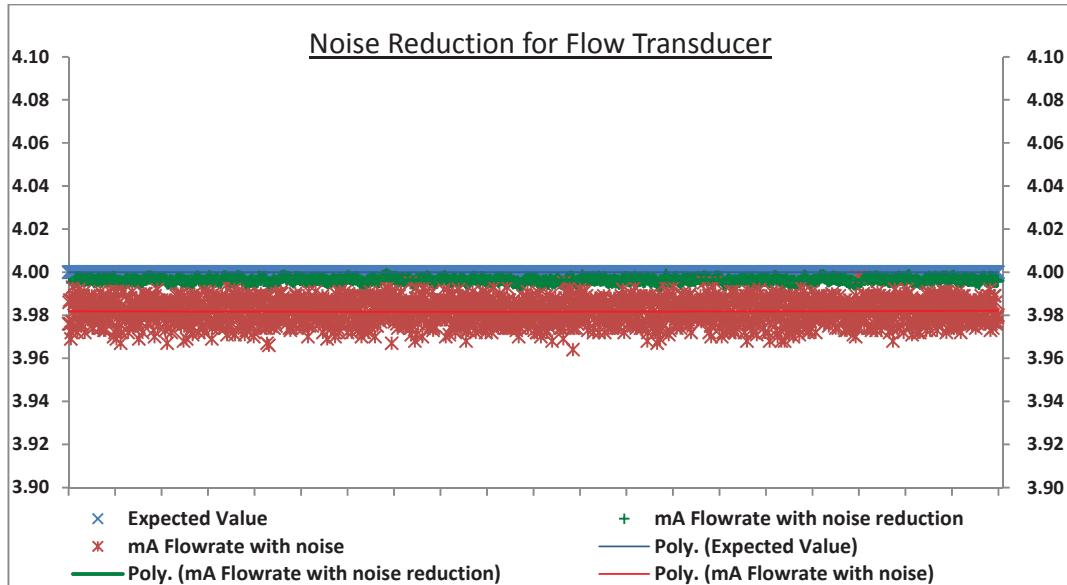


Figure 4-4: Noise reduction for flow-meter

The procedure explained above for noise reduction works well and its implementation can be confirmed by running the program on a set of measurements obtained during 200 KPa gauge test. The graphs are summarized for signals obtained from pressure transducers, flow transducers and temperature sensors. A clear reduction in the effect of random error can be seen in Figure 4-2, figure 4-3, and figure 4-4. Referring to these graphs it can be said that the noise or random error produced during the signal measurement is reduced, thus, attaining the true value of the measurement.

#### 4.4 Experimental Analysis

A total of 9 venting experiments were carried out in the fluid flow laboratory which were designated from VPM-1 to VPM-9 (VPM – Vent Pipe Model). These experiments were divided into three sets each containing 3 experiments. A set differs with respect to the initial pressure. Set-1 experiments were performed at an initial pressure of 200 KPa G, Set-2 at an initial pressure of 300 KPa G and Set-3 at an initial pressure of 400 KPa G. Maintaining a steady-state pressure above 400 KPa G into the vent pipe was not possible due to restricted flow supply from the laboratory air compressor. In all cases, venting was to atmosphere so the back pressure was 0 KPa G. Experiments were repeated in order to ensure reproducibility. Not all experiments were carried out for the same time period. Compressed Air from laboratory air compressor and an instrument graded air in G-size cylinder (single) was used in the experiments. Cylindrical gas bottles were provided by BOC Gases. The air gas composed of 78.12% Nitrogen, 20.96%

Oxygen and 0.92% Argon by mole (BOC Gases 2006). The reason for utilizing air is because of its simplicity and cheapness (Glushkov, Selyanskaya, and Kas'yanov 2003). Air has only a single phase over the pressures and temperatures encountered in our experiment, and departures from ideal gas behavior are small. Also, the restriction of blowing down any supercritical or hydrocarbon gases into the atmosphere on the Curtin University premises favored air only.

A simple procedure was adopted to ensure steady-state conditions are achieved into the vent pipe. A pressure regulator and a bleed valve arrangement was installed initially which did not prove to be effective and was discarded. Two 20 NB full bore ball valves were used in order to achieve steady-state flow conditions. One ball valve ( $bv_1$ ) was placed after the accumulator and other ( $bv_2$ ) before the gas enters the vent pipe. Valve ( $bv_2$ ) was used as the open/close valve whereas the valve ( $bv_1$ ) was used to function as a regulator to achieve the steady-state conditions. Air was supplied by a rubber air hose to the accumulator. Initially, on start-up the valve ( $bv_2$ ) was kept in closed position and valve ( $bv_1$ ) was opened slowly. Pressure gauge installed on the accumulator line was used to observe the pressure required. Once the required air pressure is achieved valve ( $bv_2$ ) was opened slowly and steady-state conditions were achieved with valve ( $bv_1$ ). Pressure, temperature and standard flow readings were recorded as analog values and the entire process was monitored using LabView Signal Express software. Not all experimental readings / logs could be stored as the software was only a demo version provided with Compact DAQ. The results obtained from the experiments are compared with the model predictions and interpreted in the latter section.

## **4.5 Experimental Validation**

Predictions made using the vent pipe model have been conducted with all of the validity experiments VPM-1 to VPM-9. Three selected representative comparisons namely VPM-1, VPM-4 and VPM-7 are given in what follows. In all experiments conducted, air is always in gaseous state. No condensation or formation of two-phase is likely to take place due to low pressures involved. One point that must always be borne in mind while comparing the experimental results and vent pipe model predictions is that the model contains no disposable parameters. Thus there can be no adjustment of parameters in order to ensure good agreement between the experimental measurements and the predictions. The vent pipe model is completely predictive.

The test section is well insulated with glass wool so that the entire arrangement is considered to be an adiabatic process. The RTD's are not fitted exactly in the streamline of the flowing gas.

This is because of area restrictions present with the geometry of RTD tube and the inside diameter of the vent pipe. If RTD's are fitted in such a way that the tip of the RTD is immersed half way into the flowing air stream then this will cause restriction to flow inside the duct. Care is taken to ensure the tip of RTD is not causing any restriction in the flow. Along the duct length the velocity of air is always accelerating towards the exit of the vent pipe. As the air flows inside the duct, RTD senses the temperature of air at the point of contact. At this point, the velocity of air is likely to be decelerated. According to (Saad 1993), when a fluid is decelerated to zero velocity in a steady-flow adiabatic process, the resulting properties of the fluid are called stagnation properties, provided that no work interactions occurs and also gravitational, magnetic, electric and capillary effects are absent. According to this definition, the measured temperature of air will be the stagnation temperature and not static temperature i.e. the temperature measured will not be the actual temperature of the flowing air gas.

#### **4.5.1 Experiment VPM-1**

Stagnation temperature measurements were taken at the entry and exit of the vent pipe. Measuring the stagnation temperature along the entire length of the vent pipe was not possible due to difficulty in getting the instruments fitted along the vent pipe. The system was allowed to attain steady-state condition by controlling the flow. The final steady-state stagnation temperature measurements were recorded. After performing noise reductions on the recorded measurements, these were summarized in figure 4-5. The experimental values were plotted for a steady-state period only. The disturbance occurring prior to achieving steady-state condition was not plotted. The stagnation temperature predictions by the vent model were compared to the experimental values. It was seen that the exit stagnation temperature achieved a steady-state value quicker than the inlet stagnation temperature. The final steady-state value for the inlet stagnation temperature was 19.04°C whereas the exit stagnation temperature value achieved was 18.92°C. The inlet stagnation temperature value obtained from experimental analysis was inputted into the vent model to predict the exit stagnation temperature value. The stagnation temperature values along the vent profile were also predicted and are summarized in figure 4-5. The predicted steady-state exit stagnation temperature was 18.97 °C. This predicted value when compared to the exit experimental value results in a percent difference of 0.26% which equivalent to  $\pm 0.05^{\circ}\text{C}$  and is relatively very small. There is clearly excellent agreement between the predicted stagnation temperature and experimental stagnation temperatures.

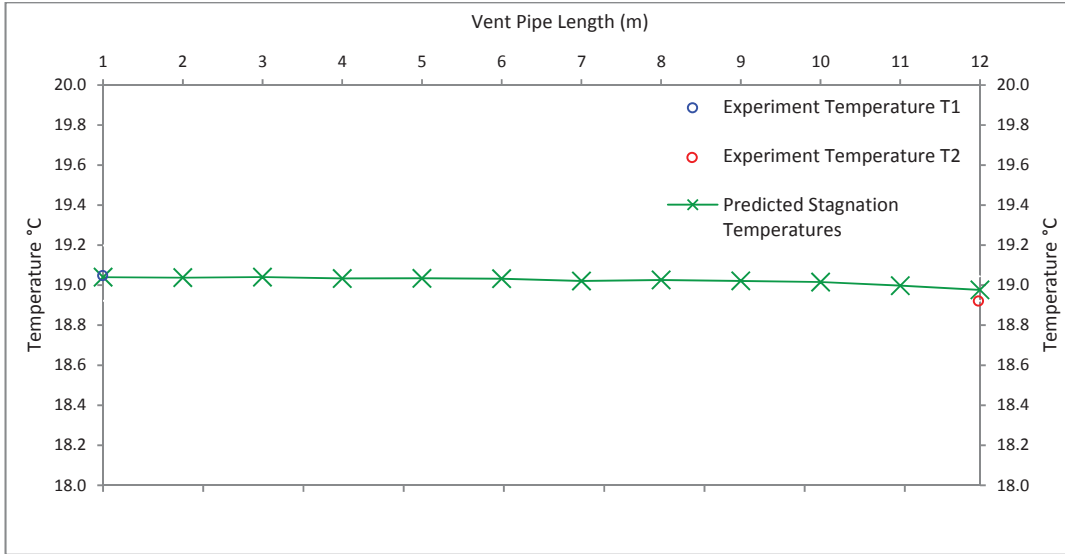


Figure 4-5: Comparison of model predicted stagnation temperatures with experimental stagnation temperatures for VPM-1

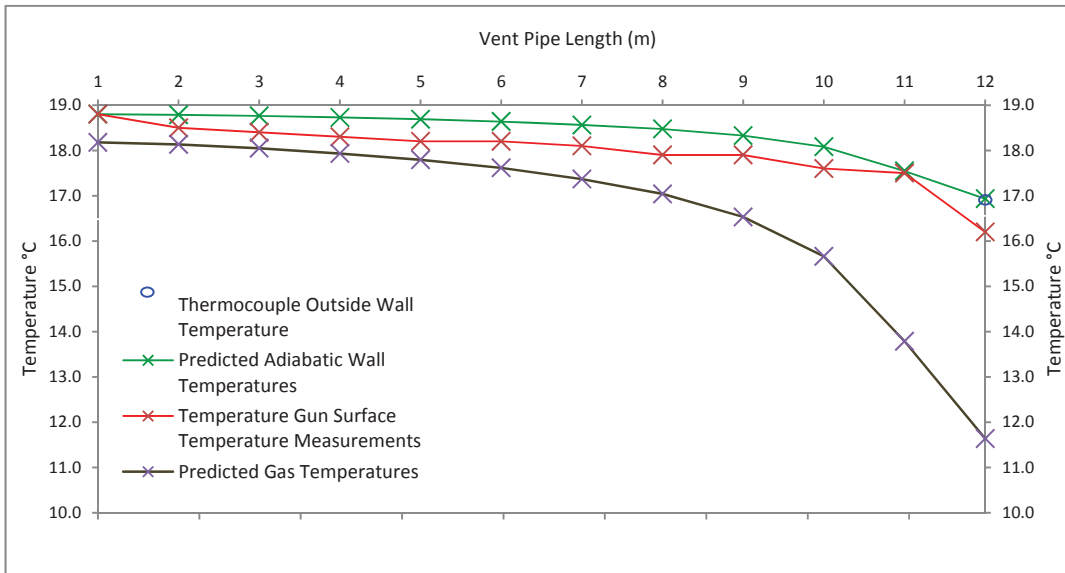


Figure 4-6: Comparison of model predicted wall temperatures with experimental wall temperatures for VPM-1

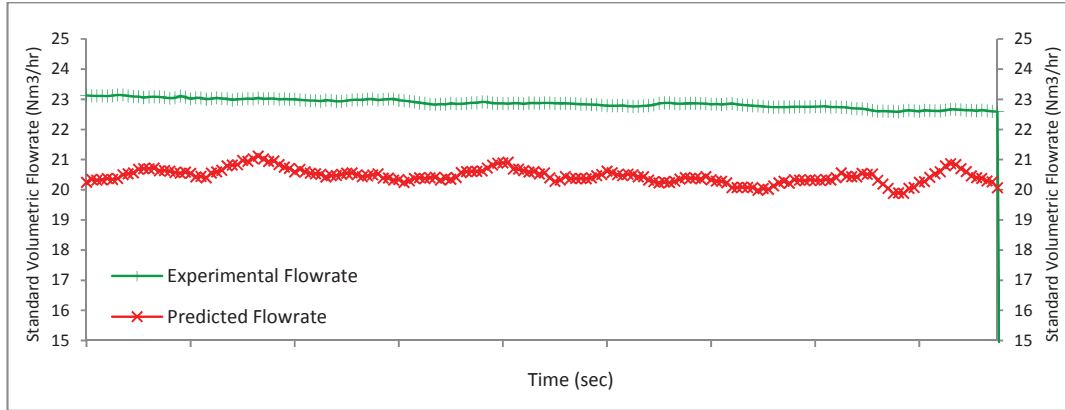


Figure 4-7: Comparison of model predicted standard volumetric flow rate with experimental standard volumetric flow rate for VPM-1

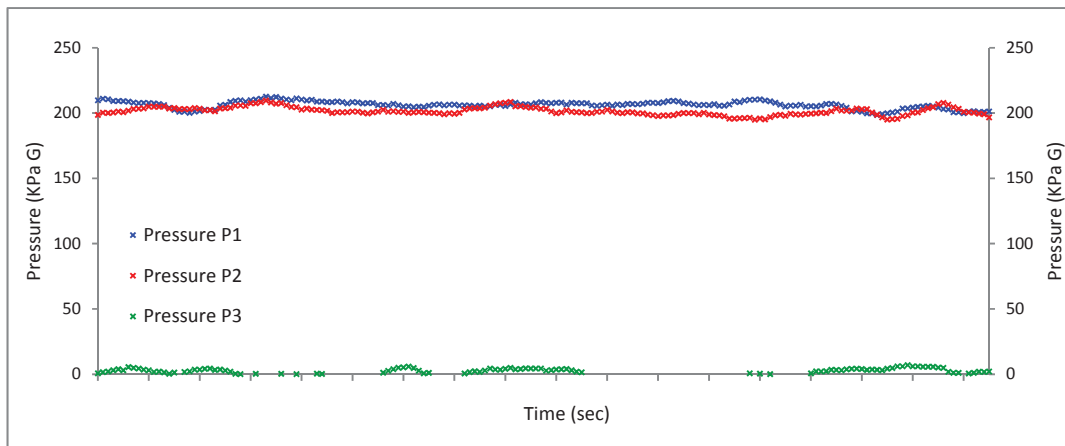


Figure 4-8: Experimental pressure measurements for VPM-1

Actual gas temperature measurement is not a trivial task and requires very accurate measuring instruments. One way of estimating the actual gas temperature is by determining the pipe wall temperature during the steady-state flow process and calculating the gas temperature assuming a recovery factor (McAdams, Nicolai, and Keenan 1946). In order to evaluate this, the process has to be adiabatic so that no heat transfer takes place with the surrounding. A T-type thermocouple was attached to the pipe wall at the exit of the vent pipe. The thermocouple was attached using an adjustable ring so that a firm contact exists between the pipe wall and thermocouple. The temperature readings were recorded at a nominal sampling rate. After performing noise reductions on these temperature readings, these measurements were summarized in figure 4-6. The final temperature recorded on achieving steady-state was 16.56 °C. The surface pipe wall temperatures at every 1m surface were measured by a non-contact dual laser thermometer. The



temperatures recorded by temperature gun are also summarized in figure 4-6. The predicted gas temperature values for the predicted stagnation temperatures were used in determining the adiabatic wall temperature. The predicted adiabatic wall temperatures are represented in figure 4-6 and compared to the measured surface pipe wall temperatures. The percentage differences between predicted and temperature gun measurements were calculated to be 0.0% at the inlet and -4.53% (equivalent to  $-0.73^{\circ}\text{C}$ ) at the exit of the vent pipe. The percent difference between predicted and thermocouple temperature measurement was calculated to be 2.26% which is equivalent to  $-0.37^{\circ}\text{C}$ . Clearly, there is also a good agreement between the measured and predicted pipe wall temperatures. In particular, the minimum wall temperature at the exit of the vent pipe, which is of significance to the materials of construction of the pipe itself, is under-predicted within 2.26%. Thus, there exists a very close agreement between the vent pipe model temperature predictions and experimental analysis.

Now, that we have a close agreement between the predicted wall temperatures and the experimental values, we can say that the predicted static temperature values and actual temperature values must be in close agreement as well and are summarized in figure 4-6. A gas temperature drop of  $6.53^{\circ}\text{C}$  was predicted for an inlet pressure of 200 KPa gauge.

The standard volumetric flow rate for the gas was recorded using IFM Effector 300 flow sensor. The flow measurements were recorded for the steady-state pressure of 200 KPa gauge for the same time period as for temperatures. After performing noise reductions on these readings, these values are summarized in figure 4-7. However, it was difficult to maintain a steady-state condition in the vent pipe due to supply issues from the laboratory air compressor. This resulted in slight variations in the pressure and flow rate readings. In order to have a close comparison between the predictions and experimental values, it was decided to predict the flow rates for the corresponding experimental pressure readings. The predicted flow rates were compared to the experimental flow rate results. An average standard volumetric flow of  $22.89\text{ Nm}^3/\text{hr}$  was attained on achieving steady-state during the experiment whereas an average standard volumetric flow of  $20.46\text{ Nm}^3/\text{hr}$  was predicted by the vent pipe model. The comparison result tells us that there exists a percentage difference of -10.6% which is equivalent to  $\pm 2.43\text{ Nm}^3/\text{hr}$ . Hence the flow rate is under-predicted by the vent pipe model. However, the calculated difference is not very high and is acceptable.

Pressure measurements were recorded at the entry and exit of the vent pipe using pressure transducers. After performing noise reductions these values are summarized in figure 4-8.

However, it was not possible to determine the pressure along the vent pipe and hence the pressure profile is discussed in more detail in Hysys validation. A similar approach to experiment VPM-1 was adopted in comparing the vent pipe model predictions to experimental analysis at 300 and 400 KPa inlet gauge pressures.

#### **4.5.2 Experiment VPM-4**

Stagnation temperature measurements were taken at the entry and exit of the vent pipe. The system was allowed to attain steady-state condition by controlling the flow. The final steady-state stagnation temperature measurements were recorded. After performing noise reductions on the recorded measurements, these were summarized in figure 4-9. The experimental values were plotted for a steady-state period only. The disturbance occurring prior to achieving steady-state condition was not plotted. The stagnation temperature predictions by the vent model were compared to the experimental values. It was seen that the exit stagnation temperature achieved a steady-state value quicker than the inlet stagnation temperature. The final steady-state value for the inlet stagnation temperature was 18.59°C whereas the exit stagnation temperature value achieved was 18.35°C. The inlet stagnation temperature value obtained from experimental analysis was inputted into the vent model to predict the exit stagnation temperature value. The stagnation temperature values along the vent profile were also predicted and are summarized in figure 4-9. The predicted steady-state exit stagnation temperature was 18.41°C. This predicted value when compared to the exit experimental value results in a percent difference of 0.33% which is equivalent to  $\pm 0.06^\circ\text{C}$  and is very small. There is clearly excellent agreement between the predicted stagnation temperature and experimental stagnation temperatures. Actual gas temperature measurement was estimated in a similar manner to experiment VPM-1. After performing noise reductions on these temperature readings, these measurements were summarized in figure 4-10. The final temperature recorded on achieving steady-state was 15.33°C. The surface pipe wall temperatures at every 1m surface were measured by a non-contact dual laser thermometer. The temperatures recorded by temperature gun are also summarized in figure 4-10. The predicted gas temperature values for the predicted stagnation temperatures were used in determining the adiabatic wall temperature. The predicted adiabatic wall temperatures are represented in figure 4-10 and compared to the measured surface pipe wall temperatures. The percentage differences between predicted and temperature gun measurements were calculated to be 0.19% at the inlet and 3.88% (equivalent to 0.55°C) at the exit of the vent pipe. The percent difference between predicted and thermocouple temperature measurement was calculated to be -3.78% which is equivalent to -0.58°C.

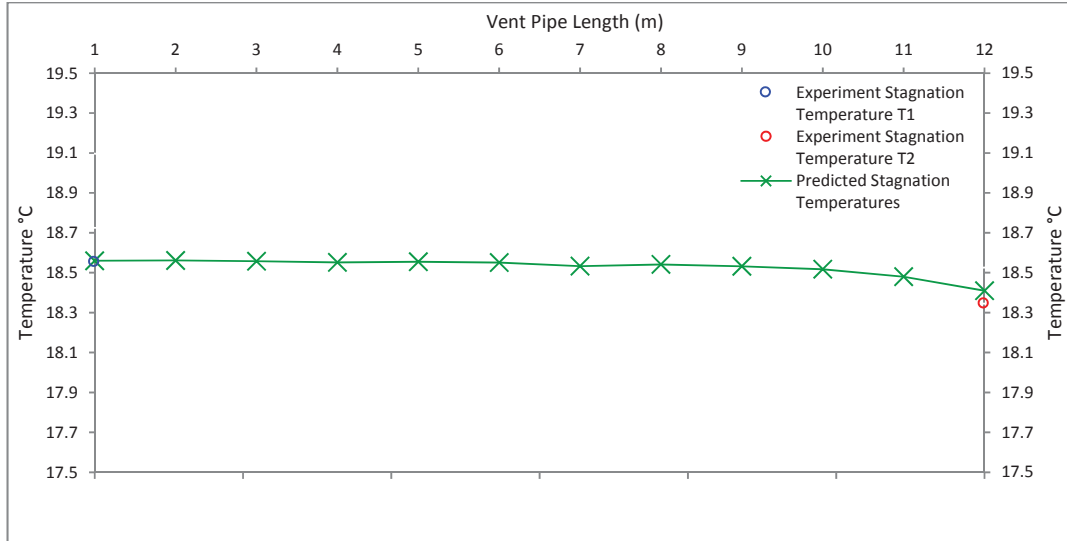


Figure 4-9: Comparison of model predicted stagnation temperature with experimental stagnation temperature for VPM-4

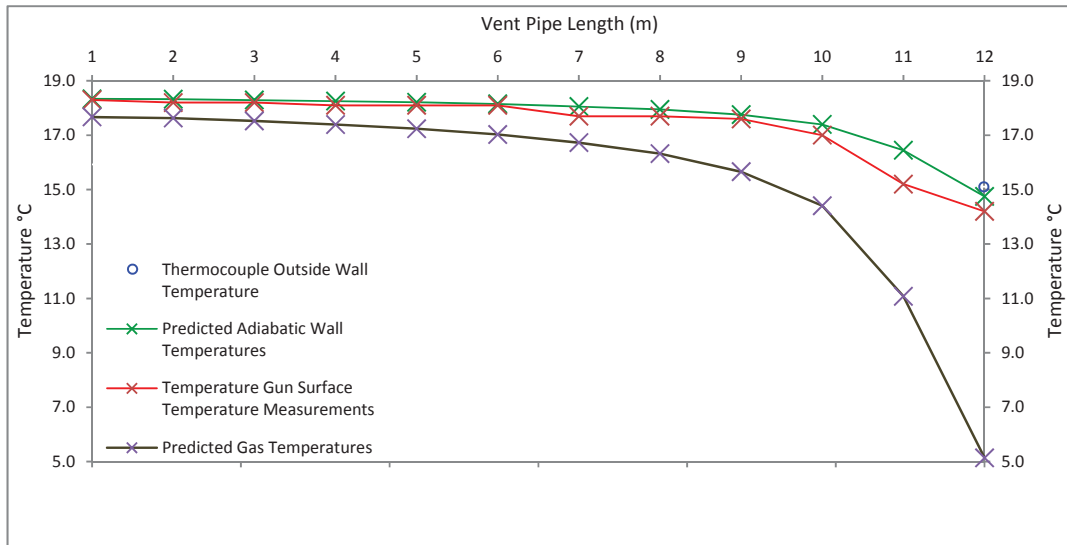


Figure 4-10: Comparison of model predicted wall temperature with experimental wall temperature for VPM-4

Clearly, there is also a good agreement between the measured and predicted pipe wall temperatures. In particular, the minimum wall temperature at the exit of the vent pipe, which is of significance to the materials of construction of the pipe itself, is under-predicted within -3.78% which is equivalent to  $-0.58^{\circ}\text{C}$ . The percent difference is relatively small and is acceptable. Once again there is a good agreement between the vent pipe model temperature

predictions and experimental analysis. Now, that we have a close agreement between the predicted wall temperatures and the experimental values, we can say that the predicted static temperature values and actual temperature values must be in close agreement as well and are summarized in figure 4-9. A gas temperature drop of 12.53 °C was predicted for a pressure drop of 300 KPa gauge.

The standard volumetric flow measurements were recorded for the steady-state pressure of 300 KPa gauge for the same time period as for temperatures. After performing noise reductions on these readings, these values are summarized in figure 4-11. It was difficult to maintain a steady-state condition in the vent pipe due to supply issues from the laboratory air compressor. This resulted in slight variations in the pressure and flow rate readings.

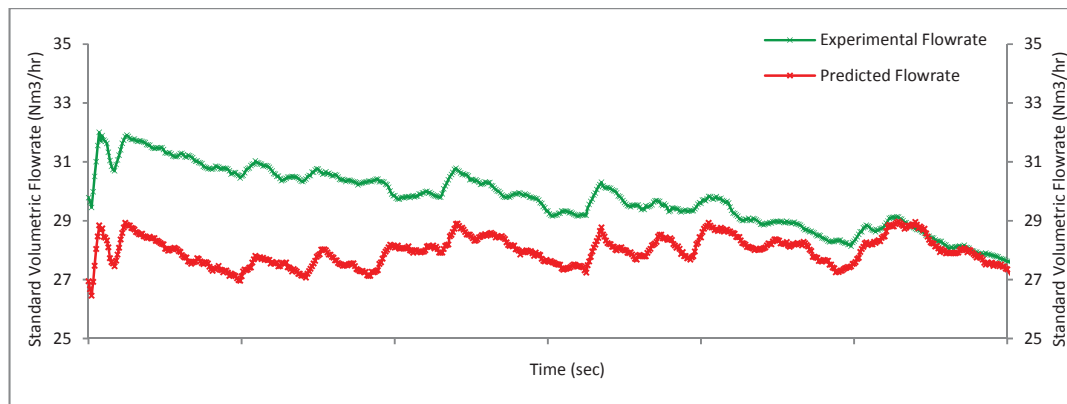


Figure 4-11: Comparison of model predicted standard volumetric flowrate with experimental standard volumetric flow for VPM-4

In order to have a close comparison between the predictions and experimental values, it was decided to predict the flowrates for the corresponding experimental pressure readings. The predicted flowrates were compared to the experimental flowrate results. An average standard volumetric flow of 29.86 Nm<sup>3</sup>/hr was attained on achieving steady-state during the experiment whereas an average standard volumetric flow of 27.98 Nm<sup>3</sup>/hr was predicted by the vent pipe model. The comparison result tells us that there exists a percentage difference of -6.3% which is equivalent to  $\pm 1.88$  Nm<sup>3</sup>/hr. Hence the flowrate is under-predicted by the vent pipe model. However, the calculated difference is not very high and is acceptable. Pressure measurements were recorded at the entry and exit of the vent pipe using pressure transducers. After performing noise reductions these values are summarized in figure 4-12. However, it was not possible to determine the pressure along the vent pipe and hence the pressure profile is discussed in more detail in Hysys validation.

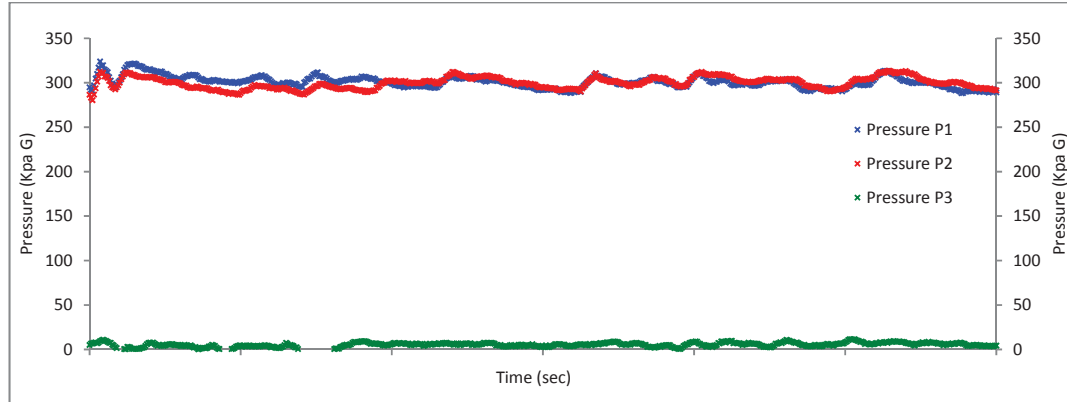


Figure 4-12: Experimental pressure for VPM-4

### 4.5.3 Experiment VPM-7

Stagnation temperature measurements were taken at the entry and exit of the vent pipe. The system was allowed to attain steady-state condition by controlling the flow. The final steady-state stagnation temperature measurements were recorded. After performing noise reductions on the recorded measurements, these were summarized in figure 4-13. The experimental values were plotted for a steady-state period only. The disturbance occurring prior to achieving steady-state condition was not plotted. The stagnation temperature predictions by the vent model were compared to the experimental values. It was seen that the exit stagnation temperature achieved a steady-state value quicker than the inlet stagnation temperature. The final steady-state value for the inlet stagnation temperature was  $18.55^{\circ}\text{C}$  whereas the exit stagnation temperature value achieved was  $18.16^{\circ}\text{C}$ . The inlet stagnation temperature value obtained from experimental analysis was inputted into the vent model to predict the exit stagnation temperature value. The stagnation temperature values along the vent profile were also predicted and are summarized in figure 4-13. The predicted steady-state exit stagnation temperature was  $18.27^{\circ}\text{C}$ . This predicted value when compared to the exit experimental value results in a percent difference of 0.6% which is equivalent to  $\pm 0.11^{\circ}\text{C}$  and is very small. There is clearly excellent agreement between the predicted stagnation temperature and experimental stagnation temperatures. Actual gas temperature measurement was estimated in a similar manner to experiment VPM-1 and VPM-4. After performing noise reductions on these temperature readings, these measurements were summarized in figure 4-14. The final temperature recorded on achieving steady-state was  $12.39^{\circ}\text{C}$ . The surface pipe wall temperatures at every 1m surface were measured by a non-contact dual laser thermometer. The temperatures recorded by temperature gun are also summarized in figure 4-14. The predicted gas temperature values for the predicted stagnation temperatures were used in determining the adiabatic wall temperature.

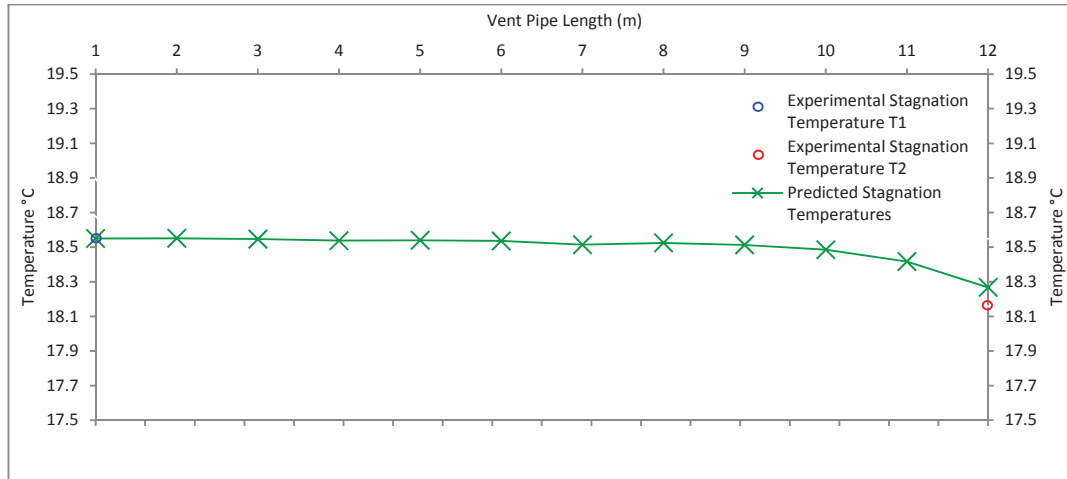


Figure 4-13: Comparison of model predicted stagnation temperature with experiment stagnation temperature for VPM-7

The predicted adiabatic wall temperatures are represented in figure 4-14 and compared to the measured surface pipe wall temperatures. The percentage differences between predicted and temperature gun measurements were calculated to be 0.49% at the inlet and 9.79% (equivalent to 1.13°C) at the exit of the vent pipe. The percent difference between predicted and thermocouple temperature measurement was calculated to be 1.91% which is equivalent to 0.24°C.

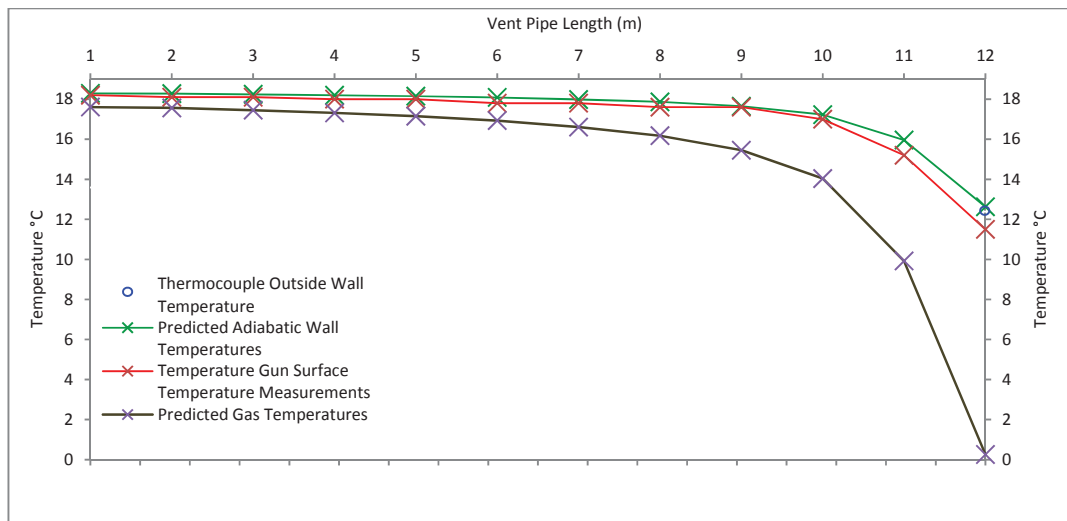


Figure 4-14: Comparison of model predicted stagnation temperature with experiment stagnation temperature for VPM-7

Again, there is good agreement between the measured and predicted pipe wall temperatures. In particular, the minimum wall temperature at the exit of the vent pipe, which is of significance to

the materials of construction of the pipe itself, is over-predicted within -1.91% which is equivalent to 0.24°C. Thus, there exists a good agreement between the vent pipe model temperature predictions and experimental analysis.

Now, that we have a close agreement between the predicted wall temperatures and the experimental values, we can say that the predicted static temperature values and actual temperature values must be in close agreement as well and are summarized in figure 4-14. A gas temperature drop of 17.35 °C was predicted for a pressure drop of 400 KPa gauge.

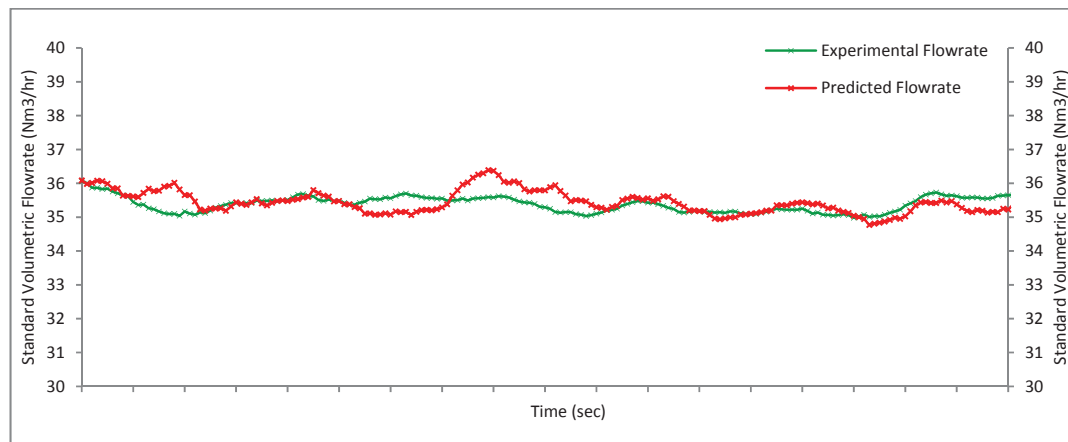


Figure 4-15: Comparison of model predicted standard volumetric flowrate with experiment flowrate for VPM-7

The standard volumetric flow measurements were recorded for the steady-state pressure of 400 KPa gauge for the same time period as for temperatures. After performing noise reductions on these readings, these values are summarized in figure 4-15. It was difficult to maintain a steady-state condition in the vent pipe due to supply issues from the laboratory air compressor as the pressure vent on increasing. This resulted in slight variations in the pressure and flowrate readings. In order to have a close comparison between the predictions and experimental values, it was decided to predict the flowrates for the corresponding experimental pressure readings. The predicted flowrates were compared to the experimental flowrate results. An average standard volumetric flow of 35.44 Nm<sup>3</sup>/hr was attained on achieving steady-state during the experiment whereas an average standard volumetric flow of 35.40 Nm<sup>3</sup>/hr was predicted by the vent pipe model. The comparison result tells us that there exists a percentage difference of -0.11%. Hence, an excellent agreement exists between the predicted and experimental flow rates at 400 KPa gauge pressure. In particular, maximum flow which is of significance in determining

the choke conditions for designing of flare systems and velocities is accurately predicted by the vent pipe model within 0.11% which is equivalent to  $\pm 0.04 \text{ Nm}^3/\text{hr}$ .

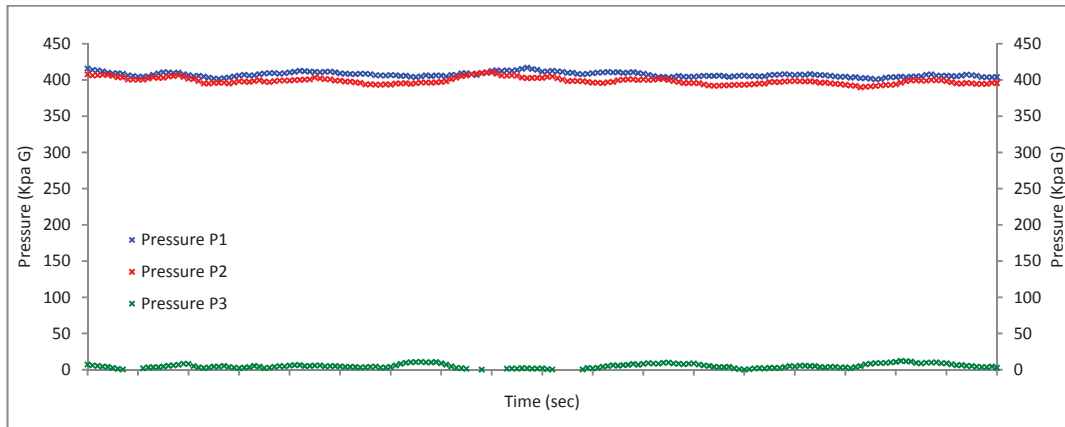


Figure 4-16: Experiment pressure measurements for VPM-7

Pressure measurements were recorded at the entry and exit of the vent pipe using pressure transducers. After performing noise reductions these values are summarized in figure 4-16. However, it was not possible to determine the pressure along the vent pipe and hence the pressure profile is discussed in more detail in Hysys validation.



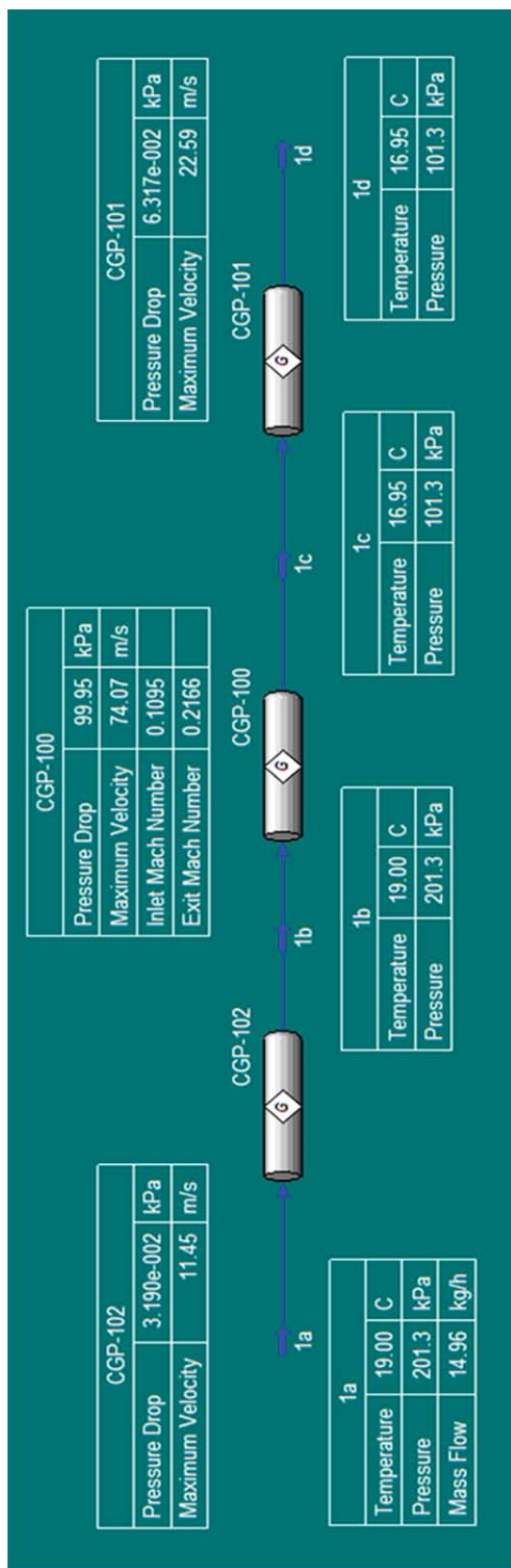


Figure 4-17: Aspen Hysys Simulation Flowsheet

## **4.6 Validation with Hysys**

In order to assess the predicted performance of the developed vent pipe model, complete process simulations were performed. Despite some expected differences between a process simulation and real-life operation, process simulators are commonly used to provide reliable information on process operation, owing to their vast component libraries, comprehensive thermodynamic packages and advanced computational methods (West, Posarac, and Ellis 2008). Predictions made using the vent pipe model have been compared with simulations performed for air, carbon-dioxide, methane and a multicomponent mixture of hydrocarbons (Kirk-Burnnand 2009). HYSYS was selected as a process simulator for both its simulation capabilities and its ability to incorporate calculations using the spreadsheet tool. It differs from other process simulators such as ASPEN PLUS in two respects: interactive interpretation of the commands/units as they entered and bi-directional information flow (Pareek 2008). Steady-state simulations were performed in Hysys version 7.1. The first step in developing the process simulation was selecting the chemical components for the process, as well as a thermodynamic model. Additionally, the unit components and input conditions for the venting process must be selected and specified. The unit operations and input conditions were selected based on the vent pipe model to ensure that the venting process simulated in HYSYS could be compared in a consistent manner. Since no polar compounds are present, Peng-Robinson model was selected as the property package for the simulation because of its simplicity and accuracy (Peng and Robinson 1976). A number of cubic equations of states are available but Peng-Robinson thermodynamic model is selected because of its wide use in development of different mathematical models. Another equation known for its accuracy is the Soave-Redlich-Kwong (Soave 1972). However, the performance of Peng-Robinson equation is better than Soave-Redlich-Kwong equation in all cases tested and shows its greatest advantage in the prediction of vapor pressure of pure substances, liquid phase densities and equilibrium ratios of mixtures. In regions where engineering calculations are frequently required the Peng-Robinson equation gives better agreement between predictions and experimental PVT data (Peng and Robinson 1976). No heat transfer approach with the surrounding was considered. The Hysys process flow-sheet for the vent pipe model is represented in figure 4-17 where the CGP-100 is the vent pipe section.

### **4.6.1 Comparison with Hysys Simulation for Air**

The vent pipe model's predicted results for compressible gas such as air are compared with the simulated results of Aspen Hysys. The predicted mass flow rates, pressure profile, temperature

profile, Mach number profile, density profile and velocity profile for air from the vent pipe model and Hysys are analyzed on an excel spreadsheet and various graphs are plotted. Remember that we are specifically interested in the exit conditions of the vent pipe. However, the different parameter profiles are discussed as well. The vent pipe design specifications used in the vent model and Aspen Hysys model puts restriction on the flow and results in a choking condition at the end of the vent pipe with sonic conditions. This sonic condition for air was calculated at ~750 K Pa gauge pressure. Due to limitations imposed in Aspen Hysys, the vent pipe flow sheet did not converge which resulted in increasing the back pressure. The following two cases are evaluated here: Air Case 1- Pressure range of 100-500 K Pa gauge (atmospheric blowdown) and Air Case 2- Pressure range of 600-1000 K Pa gauge (back pressure). The comparison percentage differences are calculated in both cases for Hysys simulations and Vent pipe model. Enthalpy and Entropy along the vent profile are also assessed which helped in understanding the fanno line.

#### **4.6.1.1 Air Case 1: Pressure range 100-500 KPa gauge**

The predicted and simulated results for mass flow rates at steady-state conditions in the pressure range 100-500 KPa gauge are in close agreement. The comparison percentage difference calculated in table G 11-1 on mass flow rates, predicted by the vent model, are at minimal. The minimum percentage difference calculated for mass flow rate was 0.25% and maximum percentage difference was calculated at 0.568%. Figure 4-18 shows the pressure profile for the vent model predictions and Aspen Hysys simulated results for air at steady-state mass flow conditions in the pressure range 100-500 K Pa gauge. The pressures at the inlet and exit conditions were calculated in both cases and were found to be in close agreement. Obviously, the percentage comparison difference at the inlet of the vent pipe was 0% whereas that calculated at the exit of vent was 0.025%. This could be due to minor calculation discrepancy. Overall an excellent agreement in the mass flow rate and exit pressure prevails. The pressure profile along the vent pipe was analyzed. The vent pipe was divided into twelve sections and the pressures at entry / exit of each section was calculated. The predicted results were compared with Hysys simulated results. Initially, the pressure profile follows a linear path and then decreases exponentially attaining exit conditions (atmospheric). The mass flowrate in all cases (from 100-500 K Pa gauge vent pipe profiles) should be constant prevailing steady-state conditions. The predicted pressure readings along the vent length compares well with Hysys and are within  $\pm 0.6\%$  of the simulated Hysys values for the first ten sections.

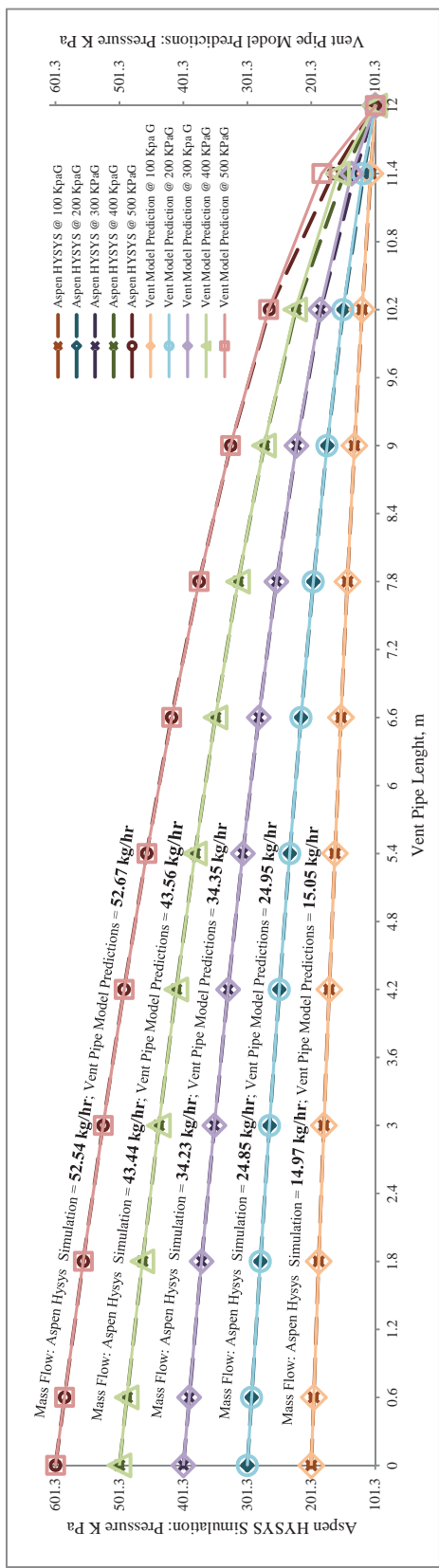


Figure 4-18: Predicted pressure comparison of vent pipe model with Hysys simulation for air in the pressure range 100-500 KPa gauge

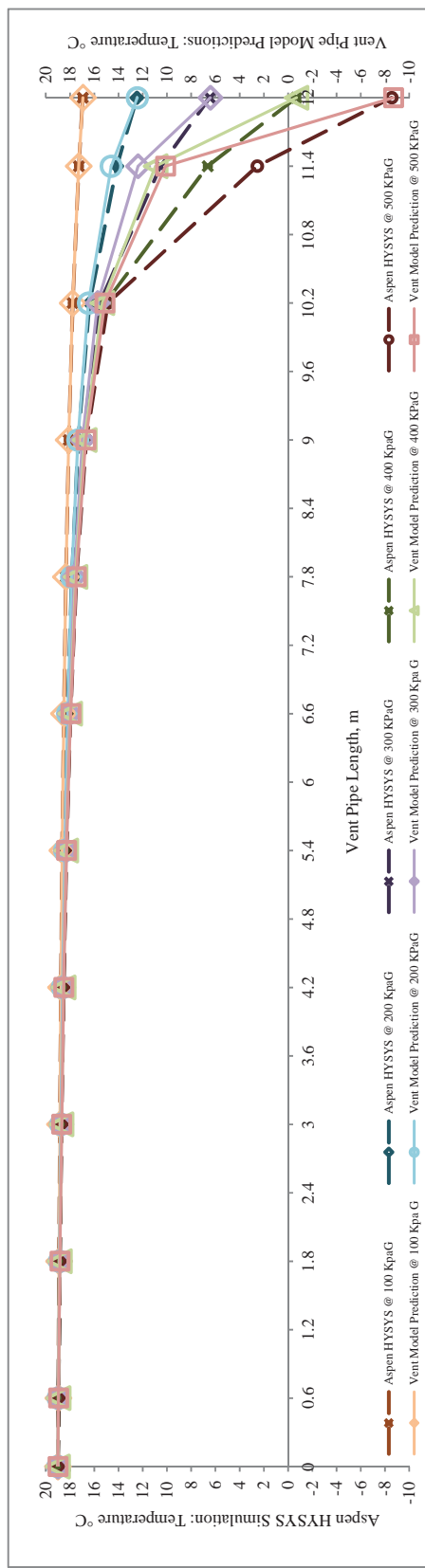


Figure 4-19: Predicted temperature comparison of vent pipe model with Hysys simulation for air in the pressure range 100-500 KPa gauge

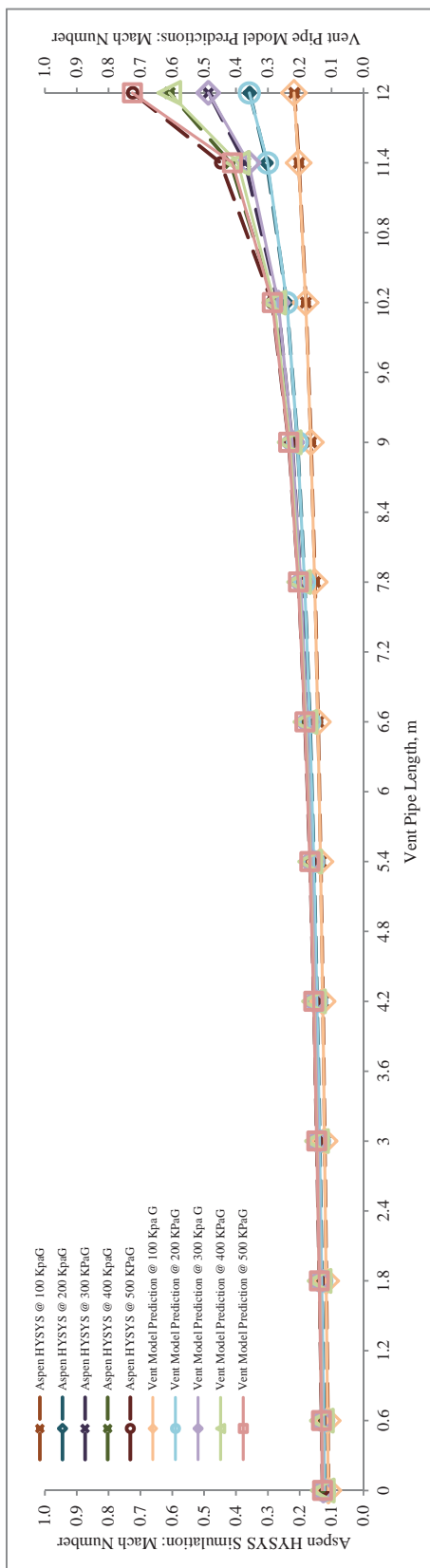


Figure 4-20: Predicted mach no. comparison of vent pipe model with Hysys simulation for air in pressure range 100-500 KPa gauge

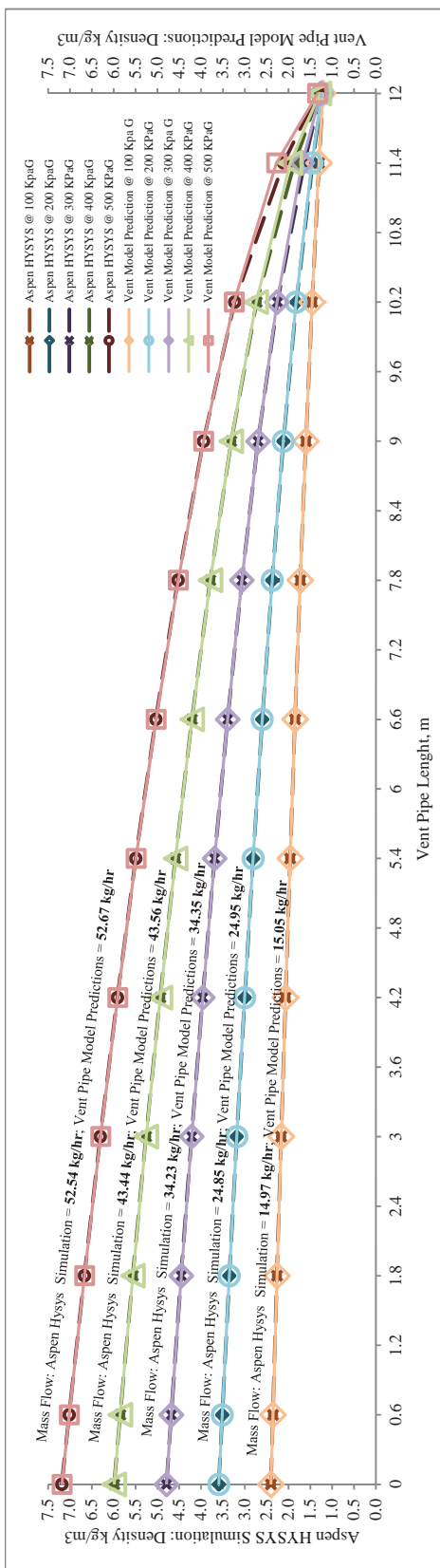


Figure 4-21: Predicted density comparison of vent pipe model with Hysys simulation for air in the pressure range 100-500 KPa gauge

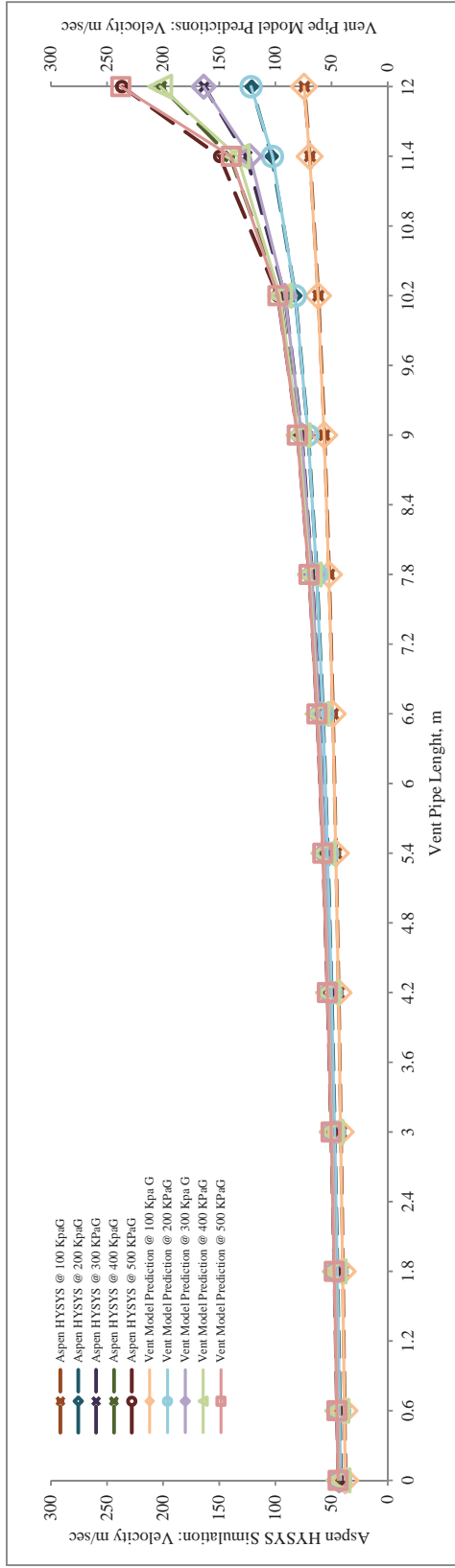


Figure 4-22: Predicted velocity comparison of vent pipe model with Hysys simulation for air in the pressure range 100-500 KPa gauge

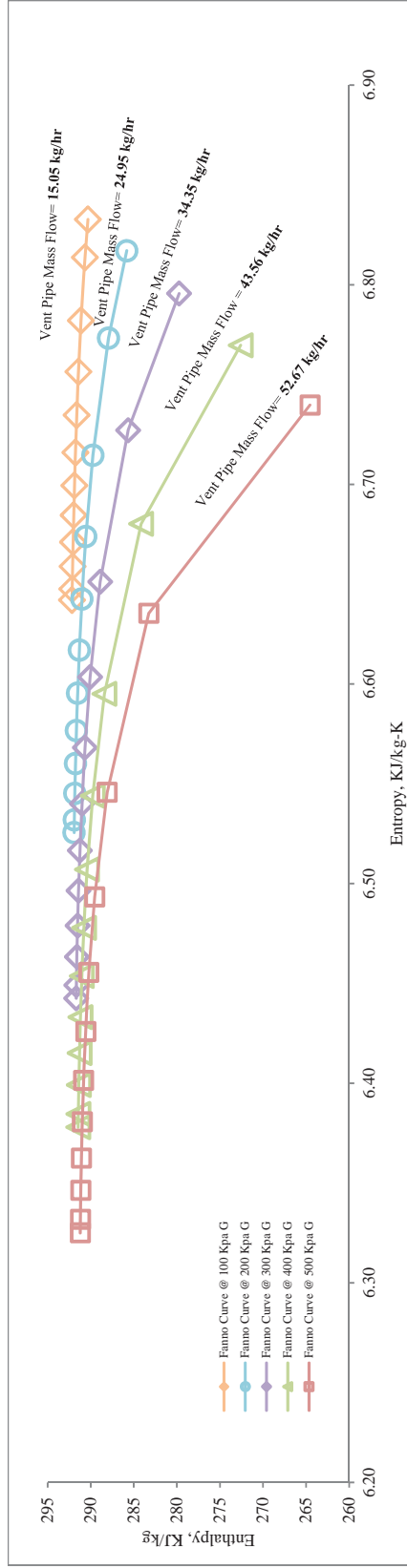


Figure 4-23: Predicted Enthalpy-Entropy (Fanno curve) of vent pipe model for air in pressure range 100-500 KPa gauge

The mystical cases are the last two sections. Although, the exit condition (atmospheric pressure) is obtained at the end of the vent pipe, the pressure drop in the 11<sup>th</sup> section of the vent pipe is significantly high in Hysys simulation then predicted by the model. The reason for existence of such a pressure profile in the last two sections is unclear at this stage.

The model predictions and Hysys simulated temperatures along the vent pipe were plotted and percent comparison differences were calculated. Figure 4-19 shows the temperature profile for the vent model predictions and Aspen Hysys simulated results for air at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. Once again looking at the Figure 4-19, it can be said that the exit temperature readings in all cases are in close agreement with a minimum difference of -0.72% and a maximum difference of 1.67%. The temperature profile along the vent pipe again follows a linear profile initially and then decreases exponentially to attain a final exit temperature. The model predicted temperatures in the first ten sections of the vent pipe match with the Hysys simulated temperature readings and are within  $\pm 1.67\%$ . A similar temperature profile as in case of pressure is obtained in the last two sections of the vent pipe. The reason for existence of such a temperature profile is unclear at this stage.

Mach number, density and velocity along the vent pipe were assessed and plotted. Figure 4-20 shows the Mach number profile for the vent model predictions and Aspen Hysys simulated results for air at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. Based on the assessment performed, it can be said that the Mach number along the vent profile is increasing towards the exit of the vent pipe and approaching towards sonic velocity. The exit Mach number readings in first ten sections are in close agreement with a minimum difference of 0.13% and a maximum difference of 0.63%.

Figure 4-21 shows the density profile for the vent model predictions and Aspen Hysys simulated results for air at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. A fall in density of fluid is noticed along the vent profile. The graph is very similar to pressure Figure 4-18 and temperature Figure 4-19 which shows decreasing linearity and an exponential fall. The exit density readings in first ten sections are in close agreement with a minimum difference of -0.2% and a maximum difference of 0.02%.

Figure 4-22 shows the velocity profile for the vent model predictions and Aspen Hysys simulated results for air at steady-state mass flow conditions in the pressure range 100-500

KPa gauge. Once again, it can be said that the exit velocity readings in all cases are in close agreement with a minimum difference of 0.4% and a maximum difference of 0.61%. The velocity profile developed is completely opposite to temperature profile and very similar to Mach number profile. Overall the results were found to be in very close agreement for all parameters in case 1. The percent difference between the vent model and Hysys was comparatively high in the 11<sup>th</sup> section of the vent pipe.

Figure 4-23 represents the enthalpy and entropy along the vent profile for the pressure range 100-500 K Pa gauge. The various curves formed are known as 'Fanno Curve' or 'Fanno Line'. As can be seen from the Figure 4-23, the enthalpy is decreasing along the vent profile and a simultaneous increase in entropy is noticed. As discussed in model development, friction is an important parameter which brings about the changes in the flow conditions. To define a flow in a region or duct, the effects of friction must be monitored. In our case, friction is causing an increase in the velocity and Mach number with a simultaneous decrease in enthalpy and pressure. The fanno line represents the effects of friction on the flow parameters. In Figure 3-3, the maximum Mach number which could be obtained at the end of the vent will be unity representing a case of adiabatic sonic flow. At this point flow is choked. On comparison of Figure 4-23 with Figure 3-3, it can be said that the fanno curve in Figure 4-23 represents the upper part of the general fanno curve. This region represents the subsonic flow region. Thus for case 1, the qualitative character of the flow is markedly influenced by subsonic flow conditions.

#### **4.6.1.2 Air Case 2: Pressure range 600-1000 KPa gauge**

Simulations performed in Aspen Hysys at pressures > 600 K Pa gauge did not converge to achieve atmospheric pressure at the exit of the vent pipe. This could be a restriction in Hysys. However, no further investigations were performed on this matter. In order to simulate the Hysys model, the back pressure (pressure at the exit of the vent) was increased by a relative amount such that the vent exit pressure equals to the back pressure. This was done by adjusting the steady-state mass flow condition. Trial and error methods were performed in order to solve the Hysys model at minimal back pressure (above atmosphere). The exit pressures obtained from the Hysys simulations were inputted in the vent pipe model and relevant predictions were calculated. The results obtained were tabulated in table G 11-2 and pressure profile, temperature profile, Mach number profiles, density profile and velocity



profile along the vent pipe were plotted. Similar results were obtained as in case1 and are discussed here.

The vent model predictions and Aspen Hysys simulated results for mass flow in the pressure range 600-1000 K Pa gauge are found to be in very close agreement. A minimum of 0.08% and a maximum of 0.22% of comparison difference were calculated. Figure 4-24 shows the pressure profile for the vent model predictions and Aspen Hysys simulated results for air at steady-state mass flow conditions in the pressure range 600-1000 K Pa gauge. The pressures at the inlet and exit conditions were calculated and were found to be in close agreement. The pressure profile along the vent pipe was analyzed in the same way as in case-1. Similar results representative to case-1 were obtained. The percentage comparison difference was well within limits for the first ten sections and was calculated to be  $\pm 0.47\%$  better than case-1. Figure 4-25 shows the temperature profile for the vent model predictions and Aspen Hysys simulated results for air at steady-state mass flow conditions in the pressure range 600-1000 KPa gauge. The temperature profile developed along the vent pipe was of the same pattern as case-1 representing a decreasing linearity followed by an exponential decrease to attain exit conditions. The percentage comparison difference calculated was  $\pm 1.71\%$  for the first ten sections of the vent pipe. Mach number, density and velocity profile were also plotted and are represented in Figure 4-26, Figure 4-27 and Figure 4-28. The density profile developed is very similar to that of the pressure drop profile which confirms the existence of relationship between them. The profiles developed represent a linear and exponential increase in Mach number and velocity and are opposite to the temperature profile. Enthalpy-Entropy plots representing the fanno curve for the pressure range 600-1000 K Pa gauge are plotted in Figure 4-29. Once again the flow is characterized to be as subsonic with a decrease in enthalpy and an increase in entropy proving the irreversibility of the process.

The mystical condition developed in the last two sections of the vent pipe in case 1 was also seen in case 2. This condition can be explained by the fanno line equation stated in model development. As discussed in the previous section of model development, a decrease in density is always registered according to the fanno equation. The mass flow per unit area must remain constant and in order to compensate for this the velocity in this region increases. As can be seen in the 11<sup>th</sup> section, the difference in the density of air is high when compared to the other sections (refer table 4-1 and table 4-2). However, this does not solve

our problem. After a careful consideration, it was concluded that this discrepancy could be generated because of calculations performed with different equation of states used in the vent model and Aspen Hysys. The GERG-2004 (Kunz et al. 2007) equation of state was used in calculating the thermophysical properties in vent model whereas Peng-Robinson (Peng and Robinson 1976) equation of state was used in calculating the thermophysical properties in Aspen Hysys simulation. The reason for the profile difference must be a result of limitations imposed by the equations of state. According to (Setzmann and Wagner 1991), the density values calculated from the Peng-Robinson equation of state deviate from the reference equation of state by up to +5% at pressures below 30MPa. However, this research was conducted for Methane gas. (Kunz et al. 2007) mentioned that the calculated values for the speed of sound show deviations of more than  $\pm 10\%$  in the same temperature and pressure ranges. This can affect our density, velocity and Mach number profiles. It was also reported that the suitability of the Peng-Robinson equation of state for use in technical applications which require high accuracy predictions of the properties of natural gases quickly revealed serious deficiencies. The GERG-2004 equation of state was developed with a view to overcome such difficulties. Hence the vent model predictions can be proved to be more accurate than the simulated results from Aspen Hysys.

Overall it can be concluded that the vent pipe model's predictions for air are in very close agreement with Aspen Hysys simulated results.

In order to investigate that the vent model predictions hold true not only for compressible gas such as air but also for other gases, it was decided to perform simulations in Aspen Hysys incorporating supercritical and hydrocarbon gases such as carbon-dioxide and methane. The predicted and simulated pressure, temperature, Mach number, density and velocity profiles were assessed. The percentage comparison difference is calculated in all cases. The results for these gases are discussed here.

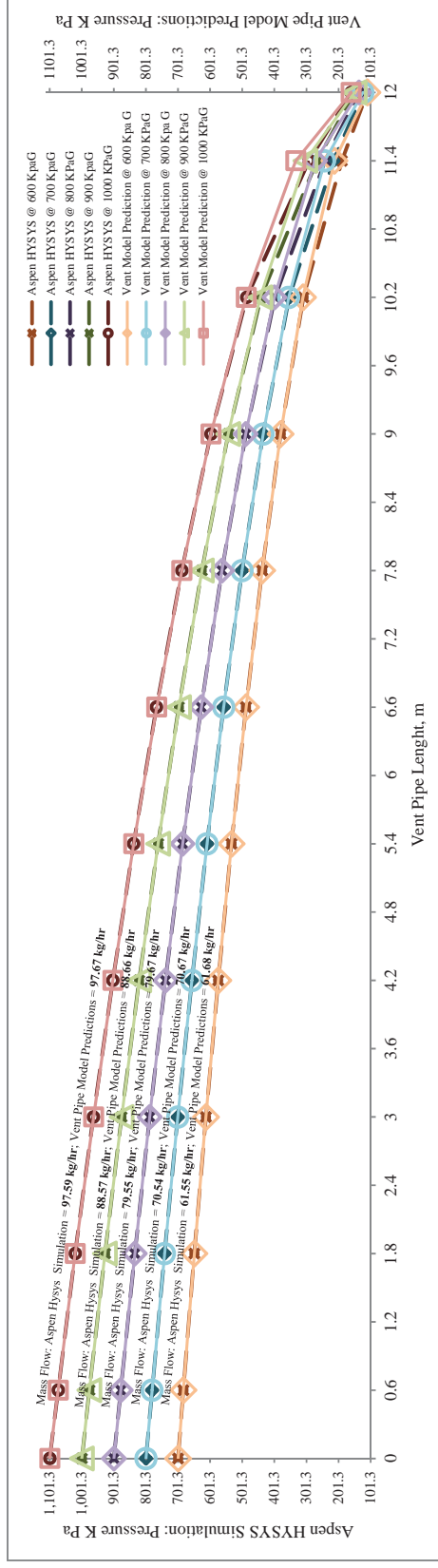


Figure 4-24: Predicted pressure comparison of vent pipe model with Hysys for air in the pressure range 600-1000 KPa gauge

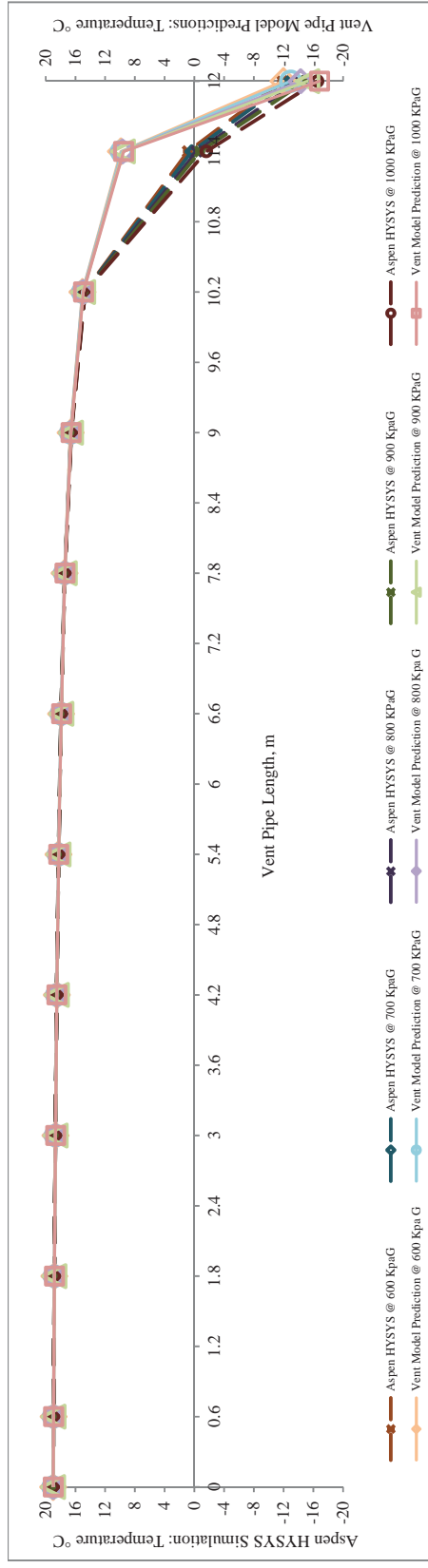


Figure 4-25: Predicted temperature comparison of vent pipe model with Hysys simulation for air in the pressure range 600-1000 KPa gauge

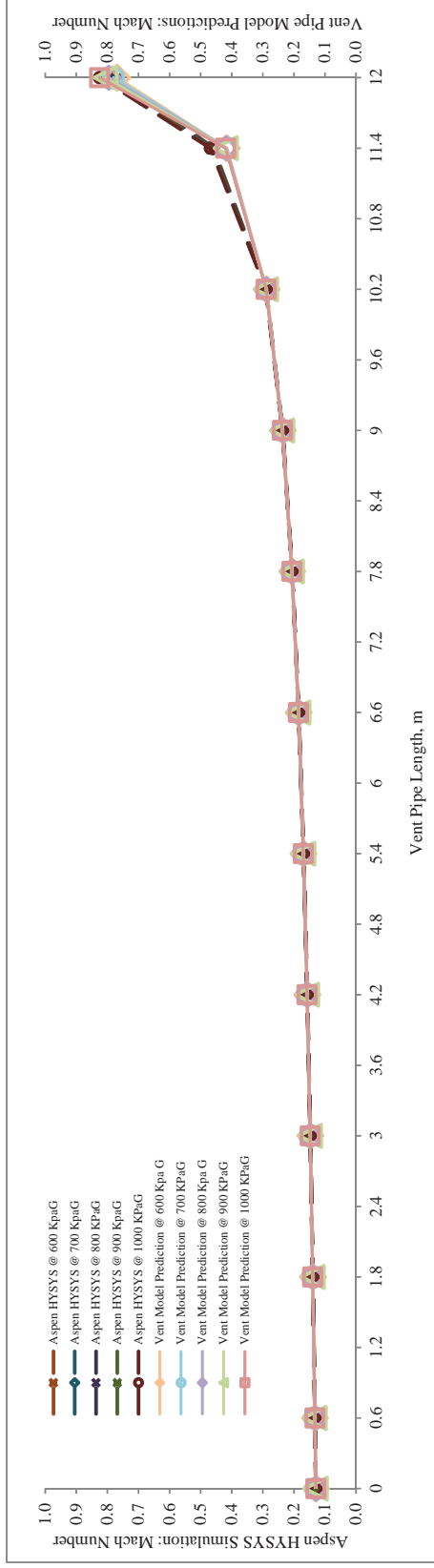


Figure 4-26: Predicted mach no. comparison of vent pipe model with Hysys simulation for air in the pressure range 600-1000 KPa gauge

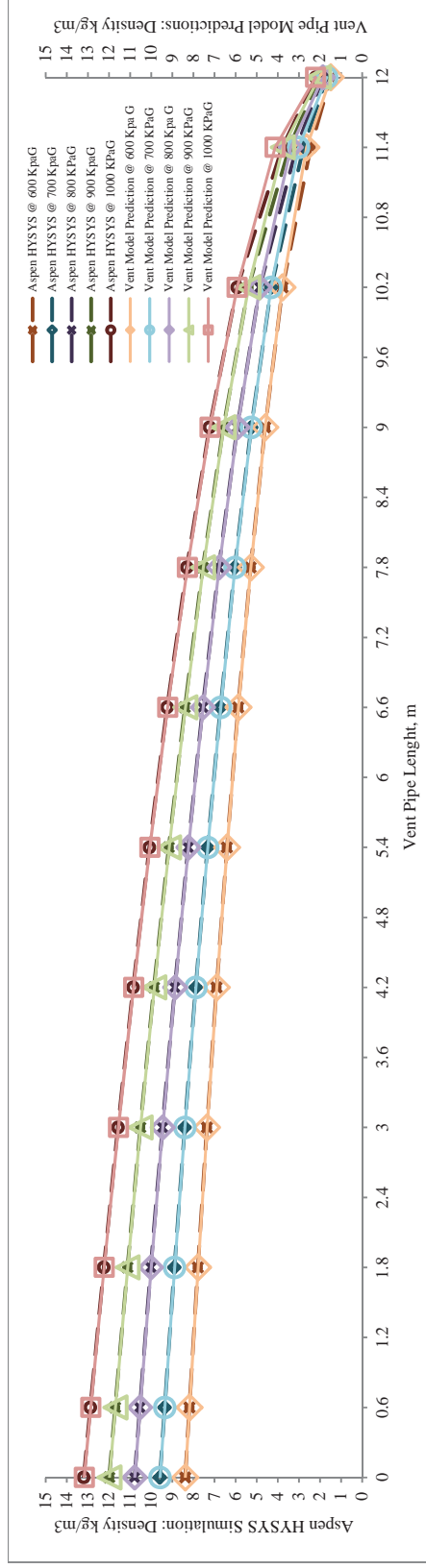


Figure 4-27: Predicted density comparison of vent pipe model with Hysys simulation for air in the pressure range 600-1000 KPa gauge

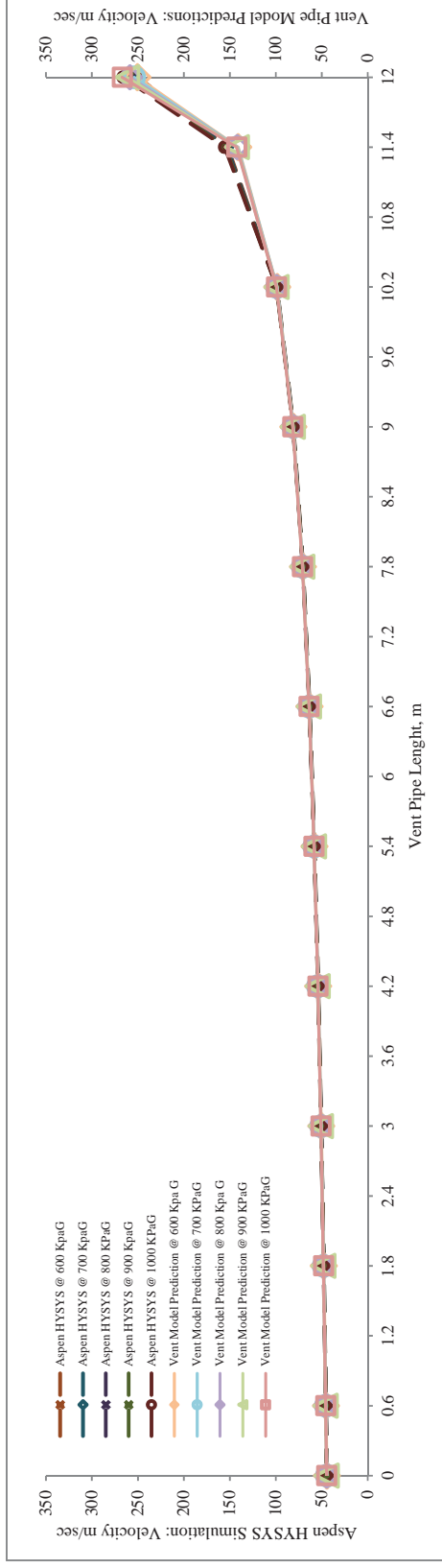


Figure 4-28: Predicted velocity comparison of vent pipe model with Hysys simulation for air in the pressure range 600-1000 KPa gauge.

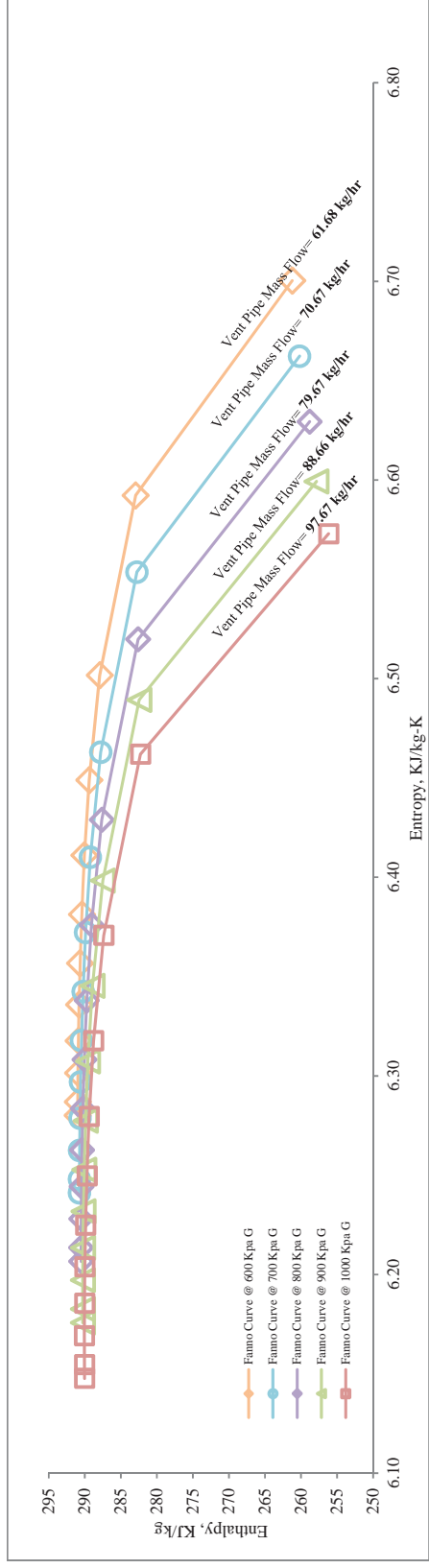


Figure 4-29: Predicted Enthalpy-Entropy (Fanno curve) of vent pipe model for air in the pressure range 600-1000 KPa gauge

## 4.6.2 Comparison with Hysys Simulation for Carbon-dioxide

The results from vent pipe model predictions and Aspen Hysys simulations for carbon-dioxide gas are explained here. The vent pipe Hysys flow sheet did not converge to complete atmospheric pressure after 600 K Pa gauge inlet pressure. Suspected reason for this could be the limitations with Hysys. Hence it was decided to increase the back pressure in order to solve the Hysys flow sheet. The following two cases are evaluated here: CO<sub>2</sub> Case 1- Pressure range of 100-500 K Pa gauge (atmospheric venting); CO<sub>2</sub> Case 2-Pressure range of 600-1000 K Pa gauge (back pressure).

### 4.6.2.1 CO<sub>2</sub> Case 1: Pressure range 100-500 KPa gauge

The predicted and simulated results for mass flow rates at steady-state conditions in the pressure range 100-500 KPa gauge are in close agreement. The comparison percentage difference calculated in table G 11-3 on mass flow rates, predicted by the vent model, are at minimal. The minimum comparison percentage difference calculated for mass flow rate was -0.16% and maximum percentage difference was calculated at -0.92%. Figure 4-30 shows the pressure profile for the vent model predictions and Aspen Hysys simulated results for carbon-dioxide at steady-state mass flow conditions in the pressure range 100-500 K Pa gauge. The percentage comparison difference at the inlet and exit of the vent pipe was 0% whereas at the exit of vent was 0.03%. This could be due to minor calculation discrepancy. Overall an excellent agreement in the mass flow rate and exit pressure prevails. The pressure profile along the vent pipe for carbon-dioxide was analyzed in a similar manner as analyzed for air. The predicted and simulated pressure results for carbon-dioxide at the entry & exit of each section of vent pipe were compared. It was found that the pressure profile developed was very similar to that developed in case of air. An initial decreasing linearity followed by an exponential fall to attain exit pressure condition (atmospheric) was established in the vent pipe. The predicted pressure readings along the vent length compares well and are within  $\pm 0.6\%$  of the simulated Hysys values for the first ten sections. High percent differences in the pressure drop are seen in the last two sections of the vent pipe. The reason for existence of such a pressure profile in the last two sections is unclear at this stage.

Figure 4-31 shows the temperature profile for the vent model predictions and Aspen Hysys simulated results for carbon-dioxide at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. A similar temperature profile pattern as seen with air was recognized in case of carbon-dioxide.

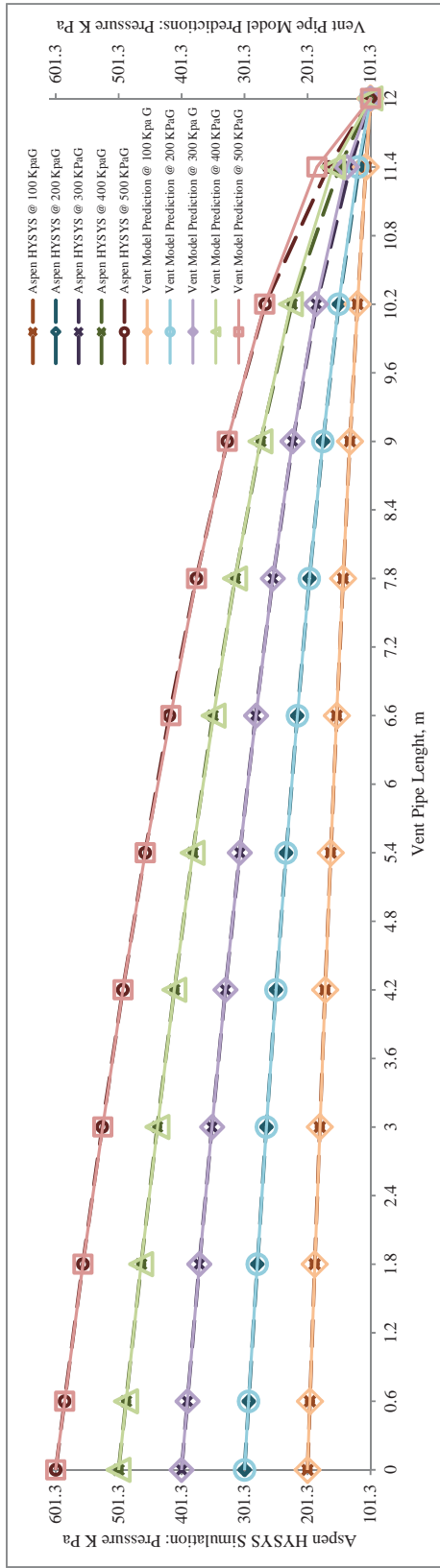


Figure 4-30: Predicted pressure comparison of vent pipe model with Hysys simulation for CO<sub>2</sub> in pressure range 100-500 KPa gauge

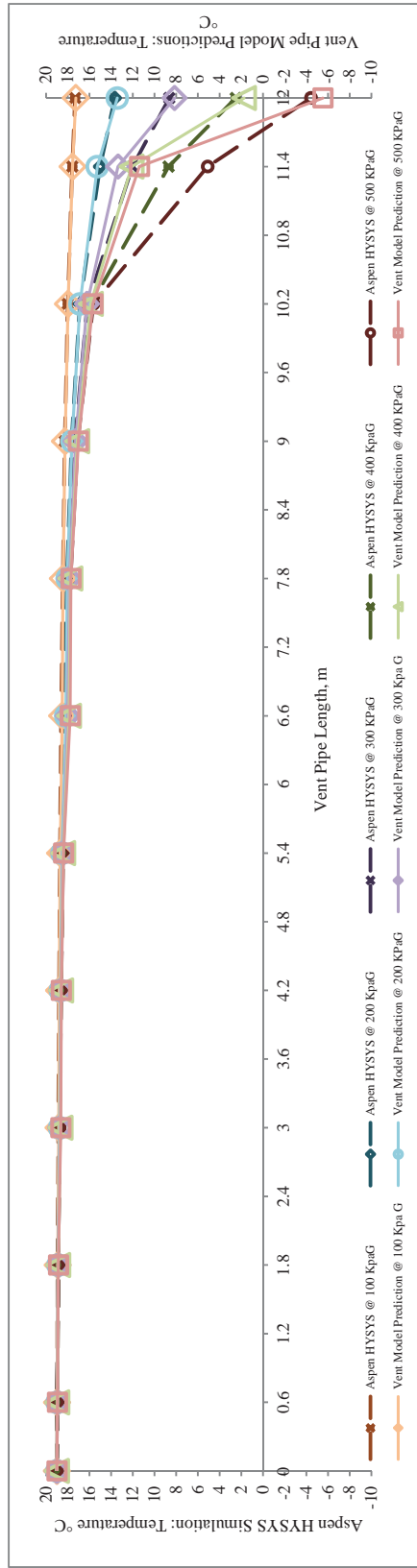


Figure 4-31: Predicted temperature comparison of vent pipe model with Hysys simulation for CO<sub>2</sub> in pressure range 100-500 KPa gauge

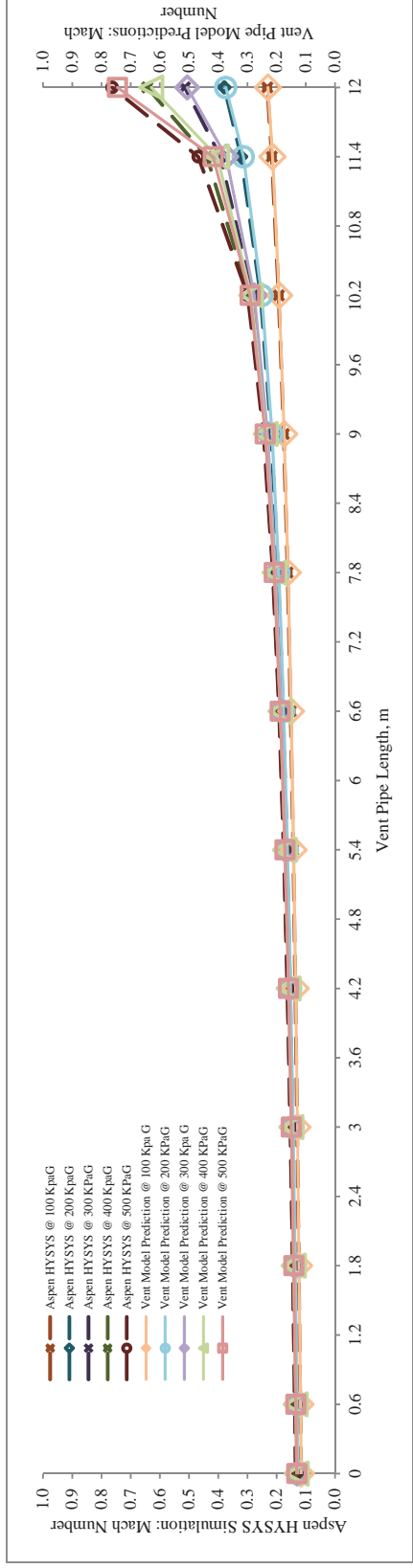


Figure 4-32: Predicted Mach no. comparison of vent pipe model with Hysys simulation for CO<sub>2</sub> in pressure range 100-500 KPa gauge

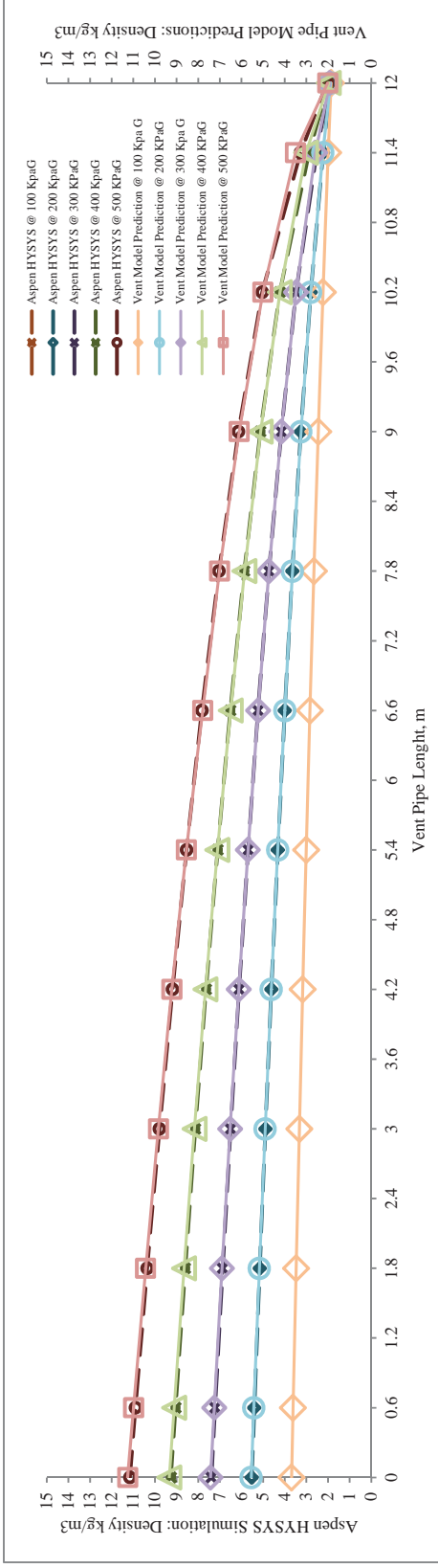


Figure 4-33: Predicted density comparison of vent pipe model with Hysys simulation for CO<sub>2</sub> in pressure range 100-500 KPa gauge



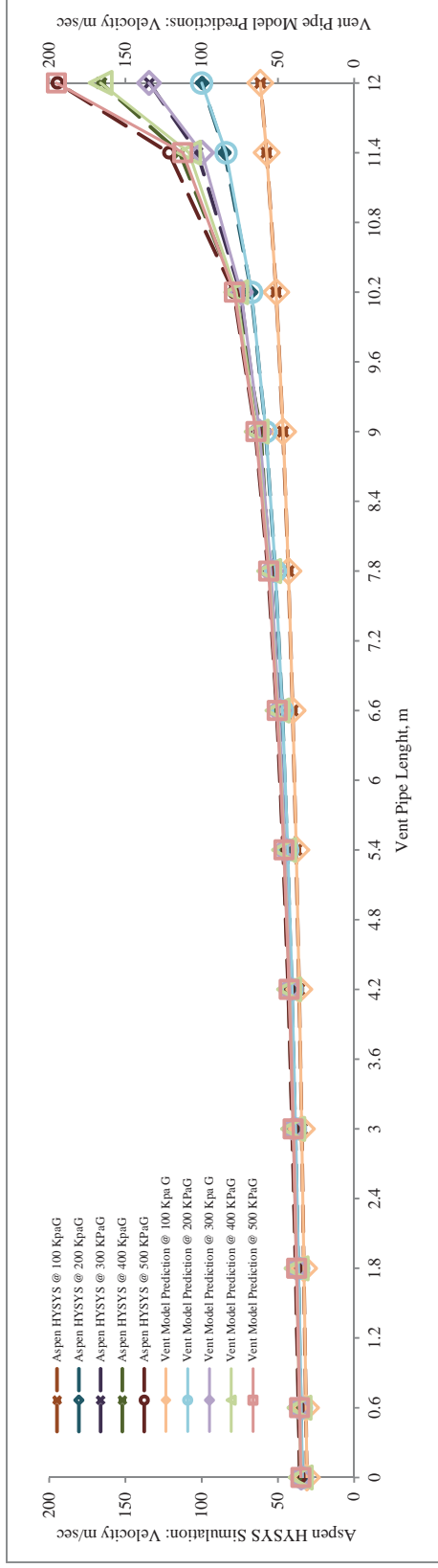


Figure 4-34: Predicted velocity comparison of vent pipe model with Hysys simulation for CO<sub>2</sub> in pressure range 100-500 KPa gauge

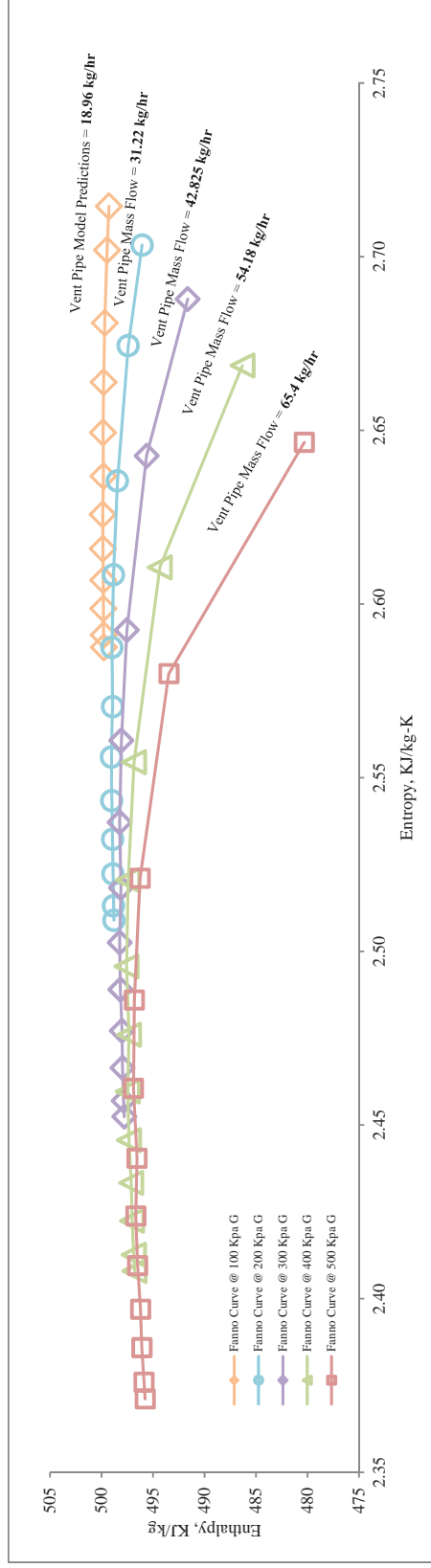


Figure 4-35: Predicted Enthalpy-Entropy (Fanno curve) of vent pipe model for CO<sub>2</sub> in the pressure range 100-500 KPa gauge

However, the temperature percentage differences were found to be of slight variant at the exit of the vent pipe. The calculated temperature differences increased with the increase in pressure. The model predicted temperatures in the first ten sections of the vent pipe match with Hysys simulations and are in close agreement. The percentage temperature differences in the 11<sup>th</sup> section of the pipe have been decreased when compared to the temperature profile of air. This decrease in temperature in the 11<sup>th</sup> section could have been compensated into the exit temperature, thus, increasing our final comparison percentage difference. A temperature percentage difference of -30.24% at 400 K Pa gauge and 24.65% at 500 K Pa gauge was calculated. Percentage differences below 400 K Pa gauge are in close agreement.

Mach number, density and velocity profiles along the vent pipe were assessed and plotted. Figure 4-32 shows the Mach number profile for the vent model predictions and Aspen Hysys simulated results for carbon-dioxide at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. Based on the assessment performed, it can be said that the Mach number along the vent profile is increasing towards the exit of the vent pipe and approaching towards sonic velocity. The exit Mach number readings in all cases are in close agreement with a minimum difference of -0.97% and a maximum difference of -2.41%.

Figure 4-33 shows the density profile for the vent model predictions and Aspen Hysys simulated results for carbon-dioxide at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. A fall in density of fluid is noticed along the vent profile. The graph is very similar to pressure Figure 4-30 and temperature Figure 4-31 which shows decreasing linearity and an exponential fall. The exit density readings in all cases are in close agreement with a minimum difference of -0.32% and a maximum difference of -1.24%.

Figure 4-34 shows the velocity profile for the vent model predictions and Aspen Hysys simulated results for carbon-dioxide at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. The minimum and maximum comparison difference calculated for the exit velocity was 0.15% and 0.35%. The velocity profile pattern developed is a horizontal mirror image of temperature profile and very similar to Mach number profile. Overall the results were found to be in very close agreement for all parameters in case 1.

Figure 4-35 shows the enthalpy-entropy diagram representing the fanno curve for the vent pipe model. The friction in the pipe results in a decrease in enthalpy with a simultaneous increase in entropy towards the exit of the vent pipe is indicated, thus, defining the flow as subsonic.

#### 4.6.2.2 CO<sub>2</sub> Case 2: Pressure range 600-1000 KPa gauge

In the case of air, simulations performed in Aspen Hysys at pressures > 600 K Pa gauge did not converge to achieve atmospheric pressure at the exit of the vent pipe. An identical situation was seen when simulating the vent pipe for carbon-dioxide gas in Hysys. In order to simulate the Hysys model, the back pressure (pressure at the exit of the vent) was increased by a relative amount such that the vent exit pressure equals to the back pressure. This was performed by adjusting the steady-state mass flow condition. Trial and error methods were performed in order to solve the Hysys model at minimal back pressure (above atmosphere). The exit pressures obtained from the Hysys simulations were inputted in the vent pipe model and relevant predictions were calculated. The results obtained were tabulated in table G 11-4 and pressure profile, temperature profile, Mach number profiles, density profile and velocity profile along the vent pipe were plotted.

The vent model predictions and Aspen Hysys simulated results for mass flow in the pressure range 600-1000 K Pa gauge are found to be in close agreement with a minimum and maximum difference of -1.13% and -2.02%. Figure 4-36 shows the pressure profile for the vent model predictions and Aspen Hysys simulated results for carbon-dioxide at steady-state mass flow conditions in the pressure range 600-1000 K Pa gauge. The predicted pressures at the inlet and exit conditions were found to be in close agreement with minimal difference. This minimal difference could be because of minor calculation error. A difference of  $\pm 0.44\%$  was calculated on analyzing the pressure profile for the first ten sections along the vent length. The predicted and simulated temperature profile for the first ten sections agreed closely and is represented in figure 4-37. The predicted and simulated Mach number, density and velocity profiles along the vent pipe were plotted in figure 4-38, figure 4-39 and figure 4-40. Similar results to CO<sub>2</sub> case-1 were obtained. Enthalpy-entropy curve were plotted in figure 4-41 which defined the flow in the vent to be subsonic.

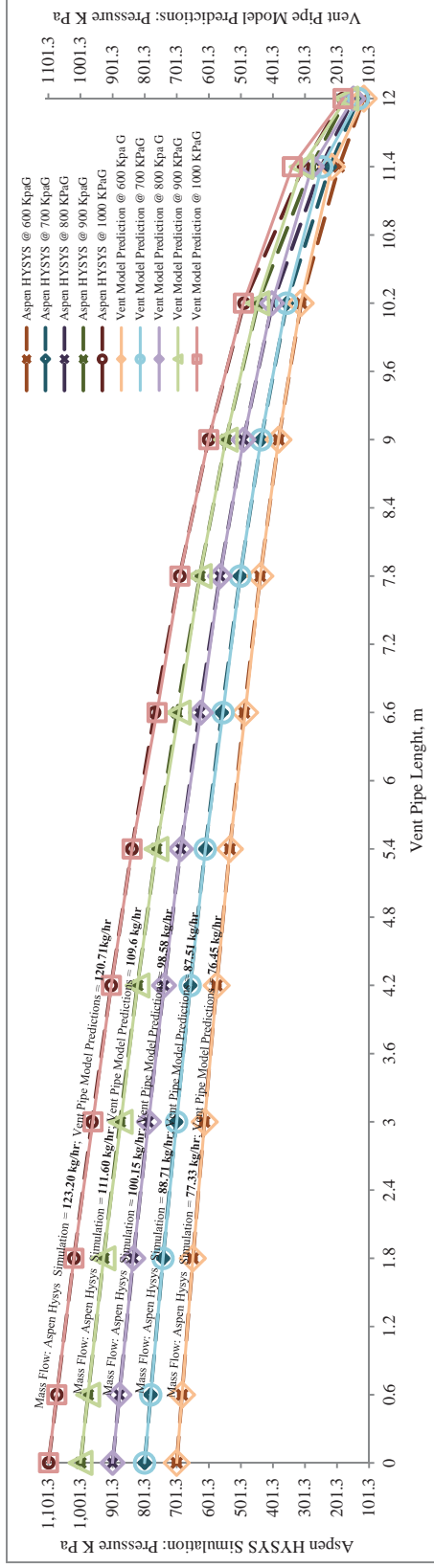


Figure 4-36: Predicted pressure comparison of vent pipe model with Hysys simulation for CO2 in pressure range 600-1000 KPa gauge

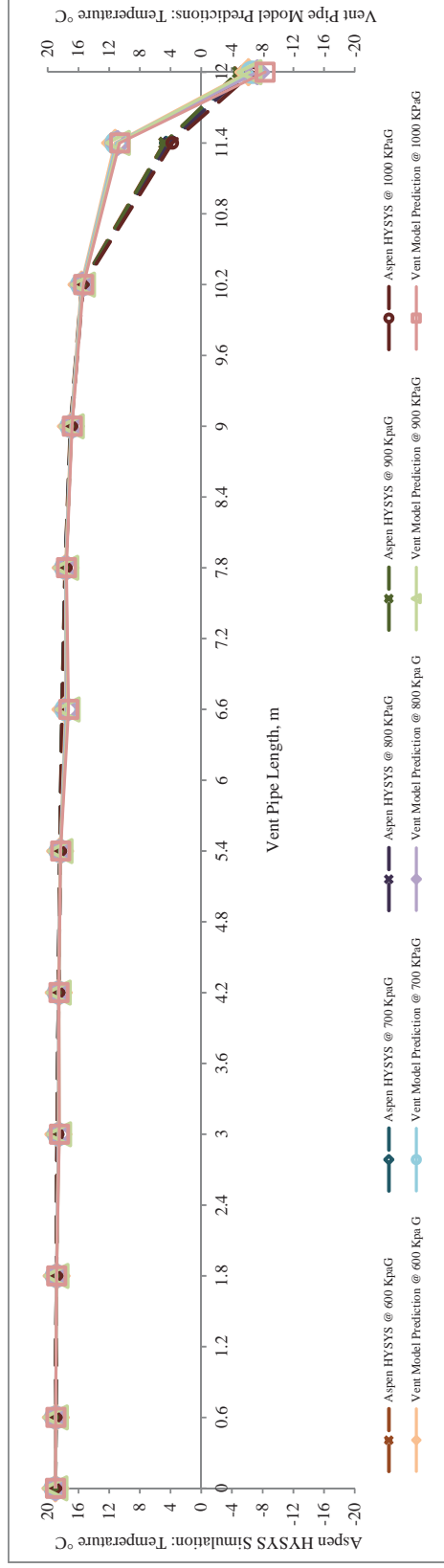


Figure 4-37: Predicted temperature comparison of vent pipe model with Hysys simulation for CO2 in pressure range 600-1000 KPa gauge

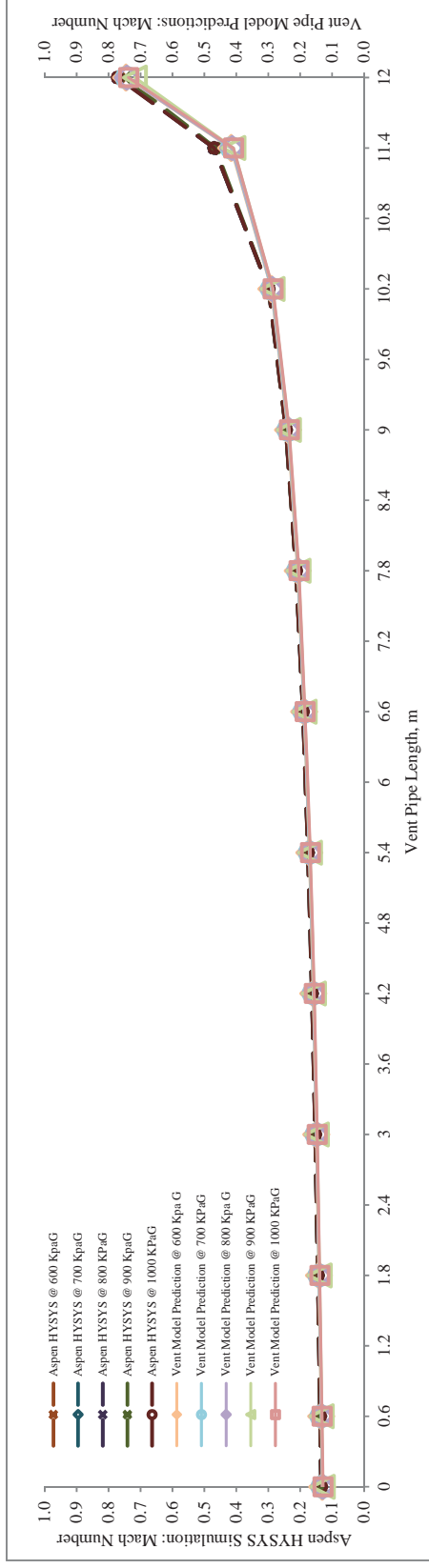


Figure 4-38: Predicted Mach no. comparison of vent pipe model with Hysys simulation for CO<sub>2</sub> in pressure range 600-1000 KPa gauge

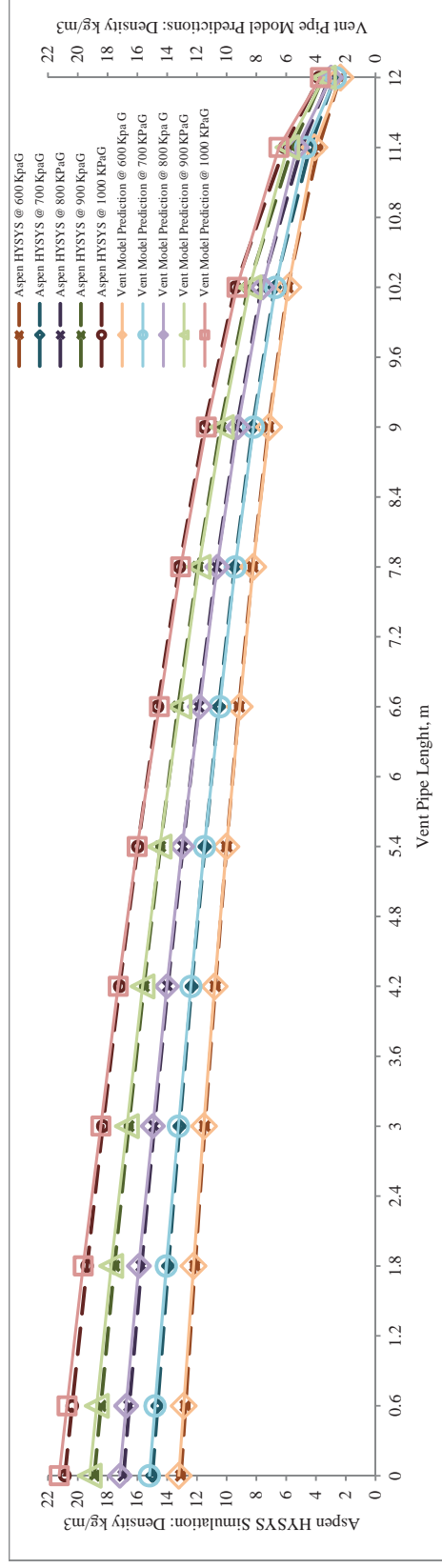


Figure 4-39: Predicted density comparison of vent pipe model with Hysys simulation for CO<sub>2</sub> in pressure range 600-1000 KPa gauge

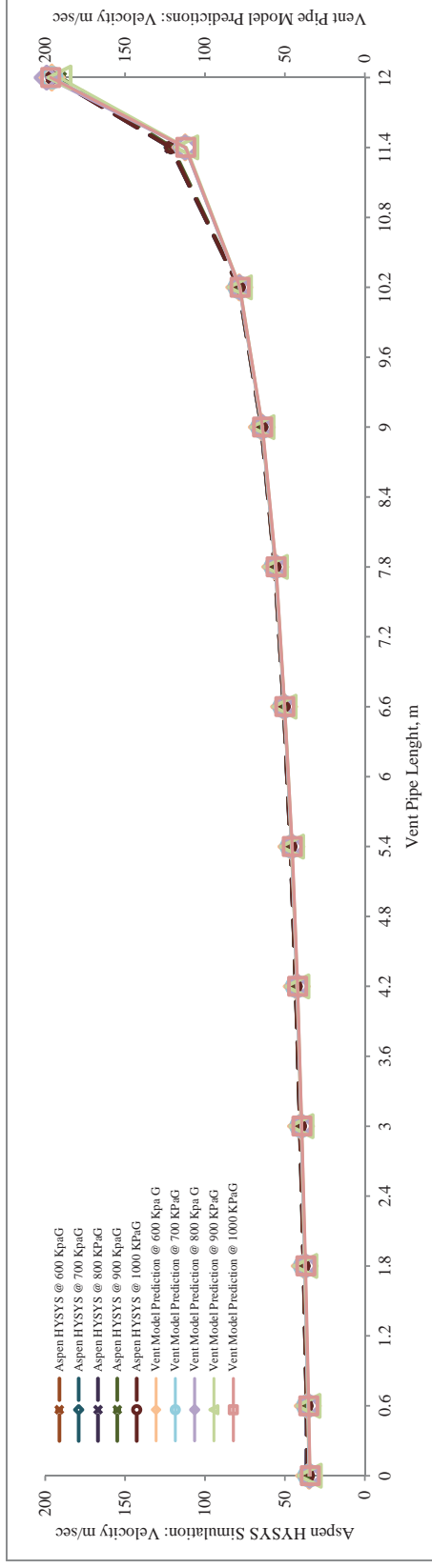


Figure 4-40: Predicted velocity comparison of vent pipe model with Hysys simulation for CO<sub>2</sub> in pressure range 600-1000 KPa gauge

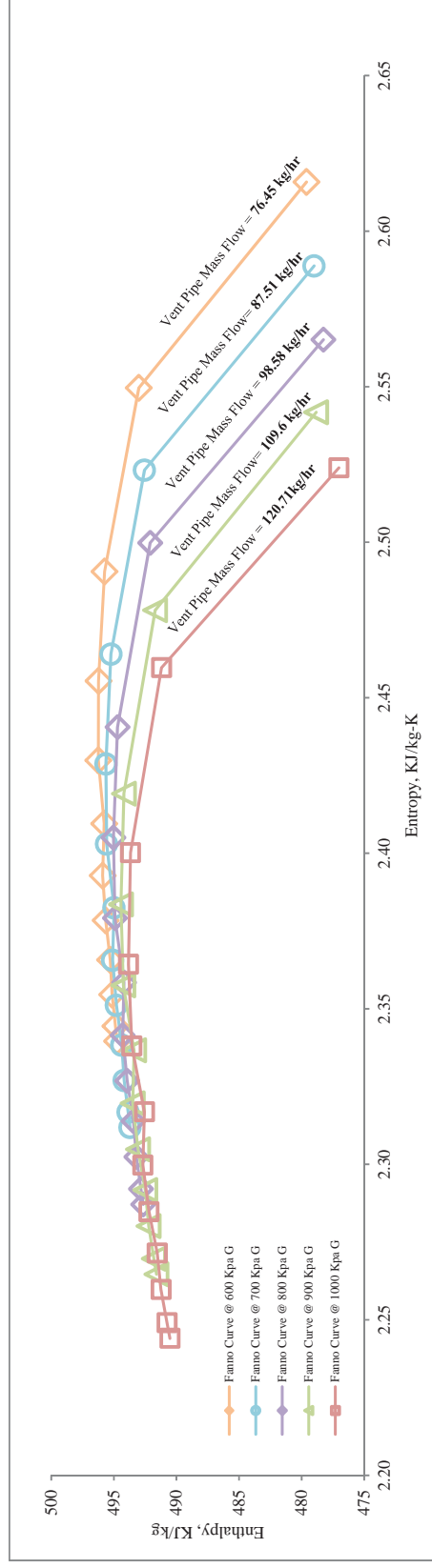


Figure 4-41: Predicted Enthalpy-Entropy (Fanno curve) of vent pipe model for CO<sub>2</sub> in the pressure range 600-1000 KPa gauge

### 4.6.3 Comparison with Hysys Simulation for Methane

The vent pipe model predictions for hydrocarbon gas such as methane were also evaluated. The results were compared to the simulated results from Aspen Hysys. Previous results for air and carbon-dioxide gases were evaluated on case by case basis due to convergence issue present in Hysys simulation. A similar situation was encountered here. The following cases were evaluated: CH<sub>4</sub> Case-1: Pressure ranges 100-500 K Pa gauge and CH<sub>4</sub> case-2: Pressure range 600-1000 K Pa gauge.

#### 4.6.3.1 CH<sub>4</sub> Case 1: Pressure range 100-500 KPa gauge

The predicted and simulated results for methane mass flow rates in the pressure range 100-500 KPa gauge are found to be in close agreement, thus maintaining steady-state conditions. The mass flow rate comparison percentage differences calculated in table G 11-5 are at minimal. The minimum comparison percentage difference calculated for mass flow rate was -0.02% and maximum percentage difference was calculated to be 0.3%. Figure 4-42 shows the pressure profile for the vent model predictions and Aspen Hysys simulated results for methane at steady-state mass flow conditions in the pressure range 100-500 K Pa gauge. On comparing the exit pressure values from the vent model predictions, a minimal percentage difference of 0.03% is calculated. This could be due to minor calculation discrepancy. The predicted pressure values in the first ten sections of the vent pipe compares well with the simulated results and are within  $\pm 0.64\%$ . The pressure drop in the 11<sup>th</sup> section of the vent pipe is high (10.92%) in case of Hysys resulting in a high percentage difference. The reason for existence of such a pressure profile in the last two sections is unclear at this stage.

The model predictions and Hysys simulated temperatures along the vent pipe were plotted and percent comparison differences were calculated. Figure 4-43 shows the temperature profile for the vent model predictions and Aspen Hysys simulated results for methane at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. The predicted exit temperature comparison percentage difference for methane is less when compared to carbon-dioxide. A minimum difference of -0.16% and a maximum difference of -9.14% were calculated for the exit temperature. The graph follows a linear decrease with an exponential fall pattern to attain the final exit temperature is seen. The model predicted temperatures in the first ten sections of the vent pipe match with the Hysys simulated temperature readings and are within  $\pm 1.15\%$  better than air and carbon-dioxide.

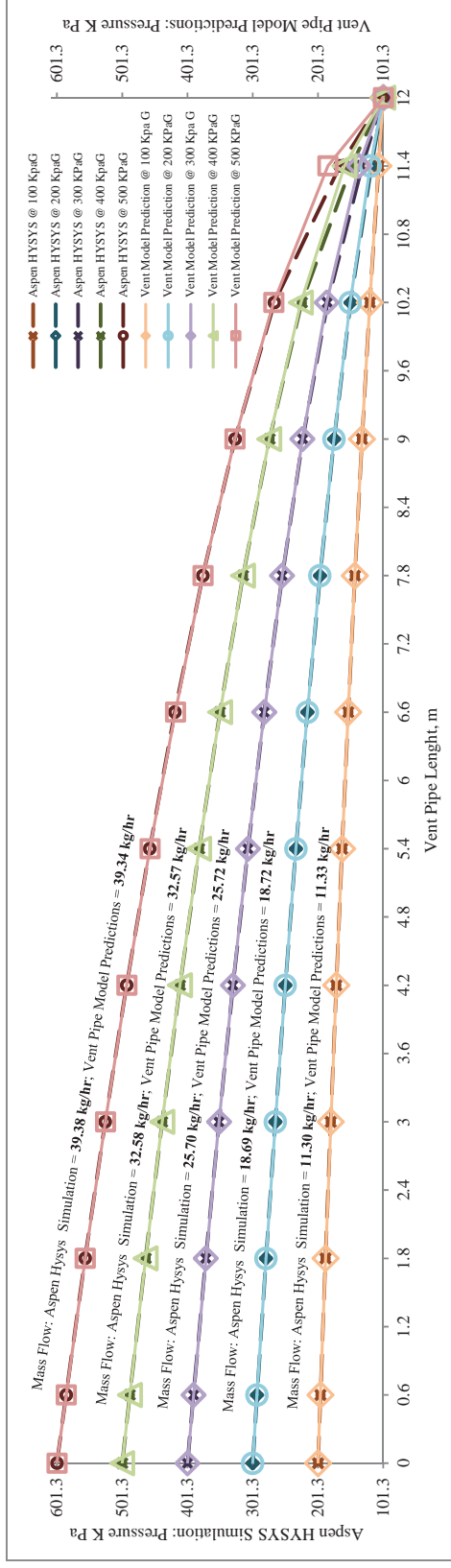


Figure 4-42: Predicted pressure comparison of vent pipe with Hysys simulation for methane in pressure range 100-500 KPa gauge

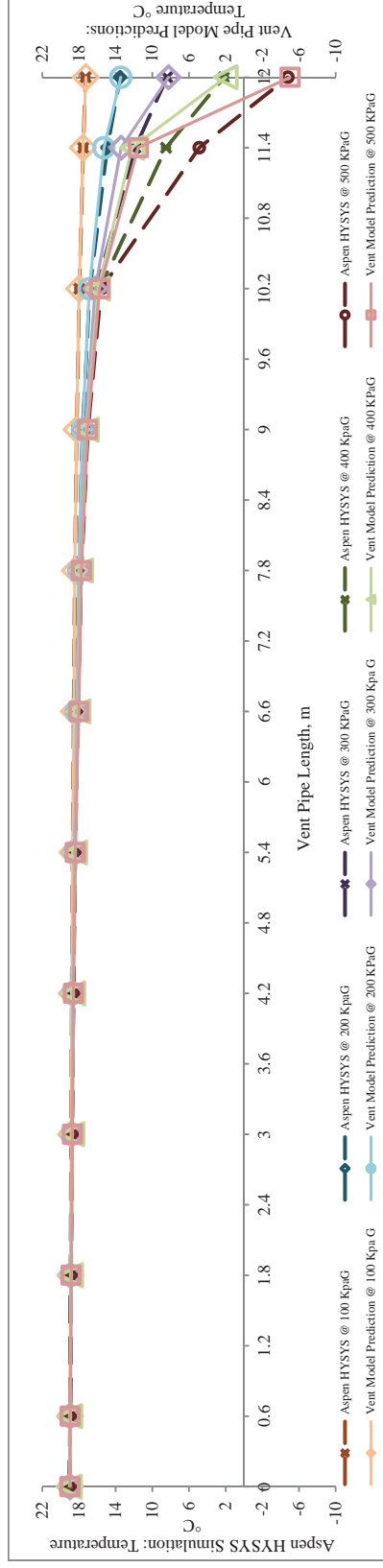


Figure 4-43: Predicted temperature comparison of vent pipe with Hysys simulation for methane in pressure range 100-500 KPa gauge



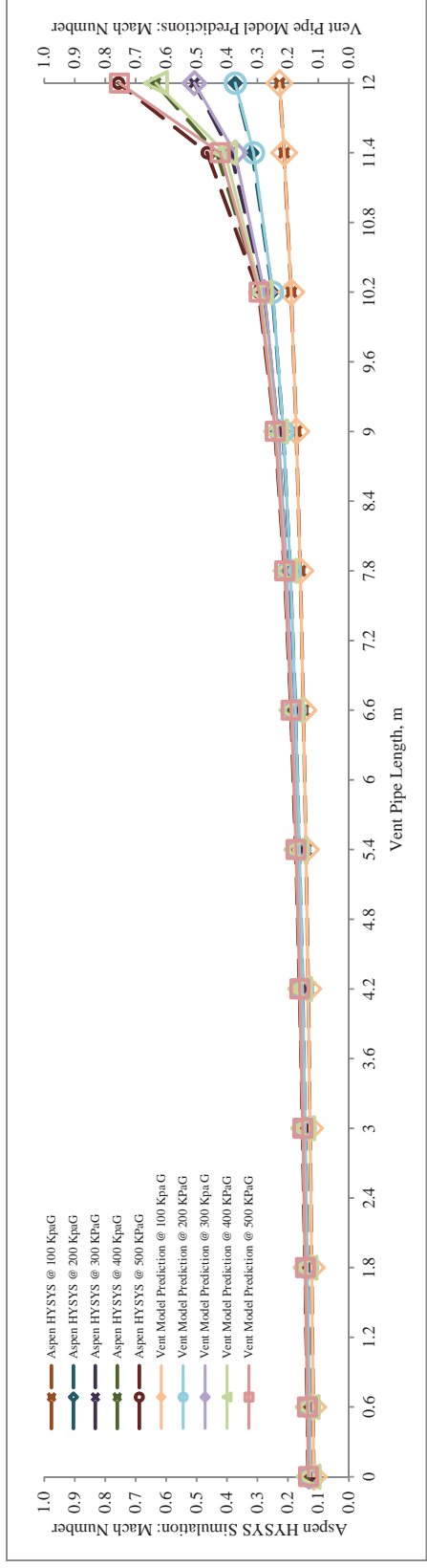


Figure 4-44: Predicted Mach no. comparison of vent pipe model with Hysys simulation for methane in pressure range 100-500 KPa gauge

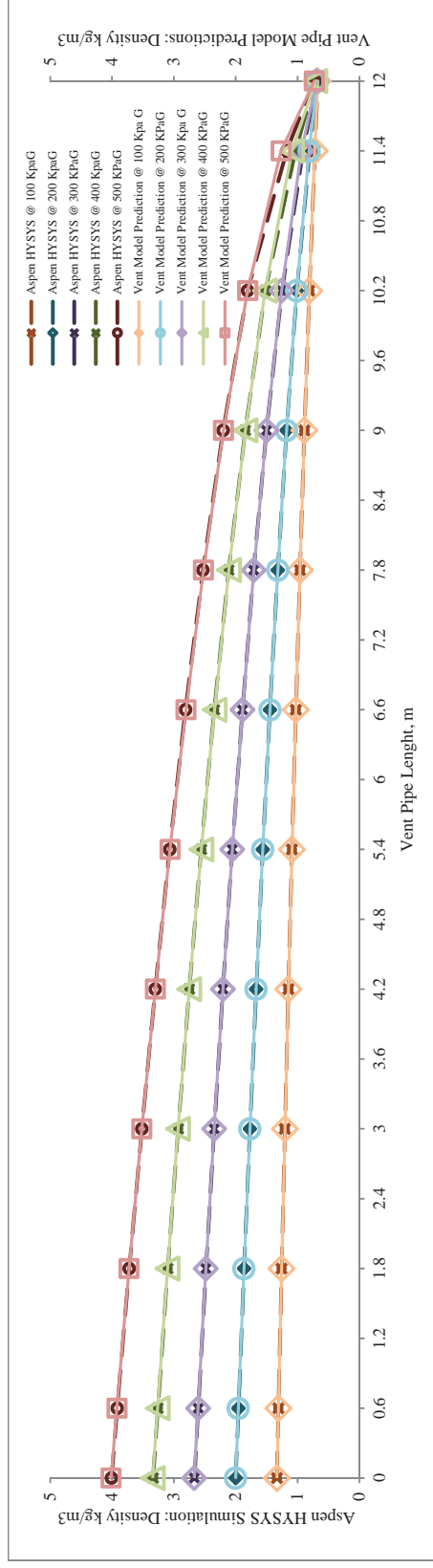


Figure 4-45: Predicted density comparison of vent pipe model with Hysys simulation for methane in pressure range 100-500 KPa gauge

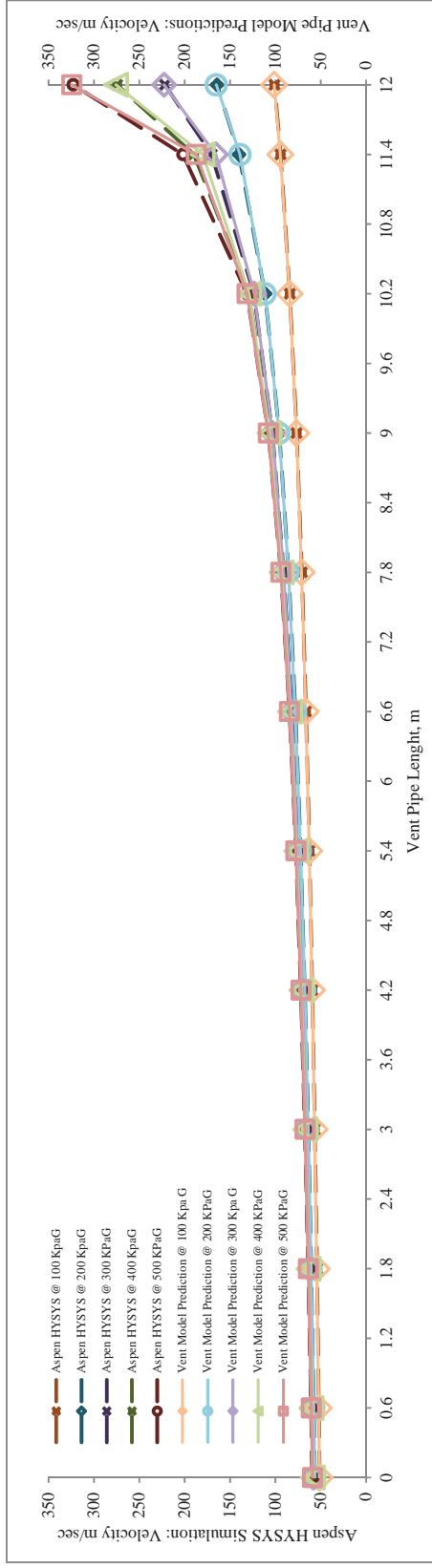


Figure 4-46: Predicted velocity comparison of vent pipe model with Hysys simulation for methane in pressure range 100-500 KPa gauge

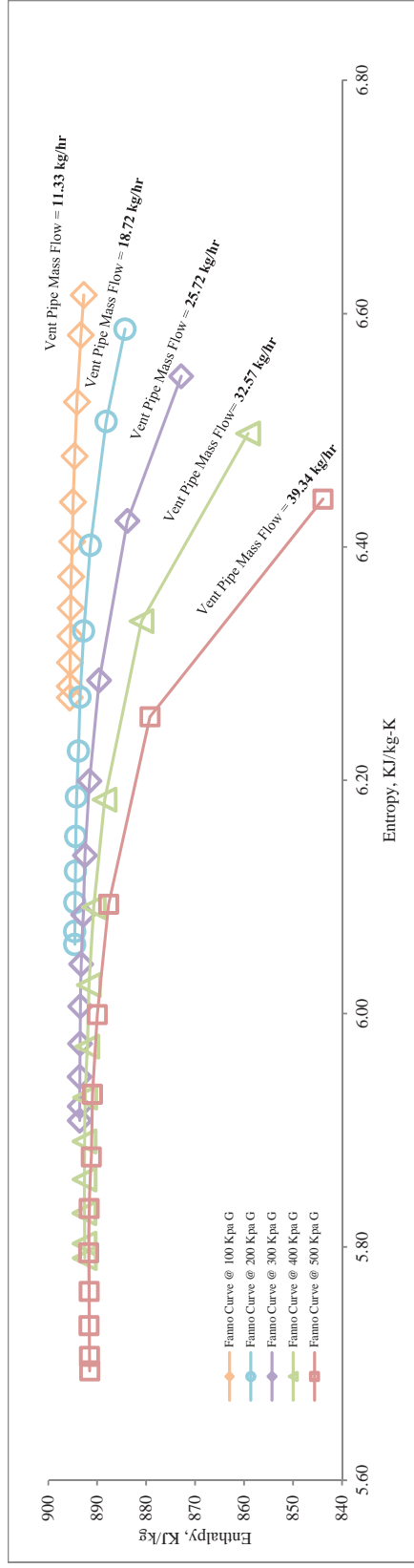


Figure 4-47: Predicted Enthalpy-Entropy (Fanno curve) of vent pipe model for methane in pressure range 100-500 KPa gauge

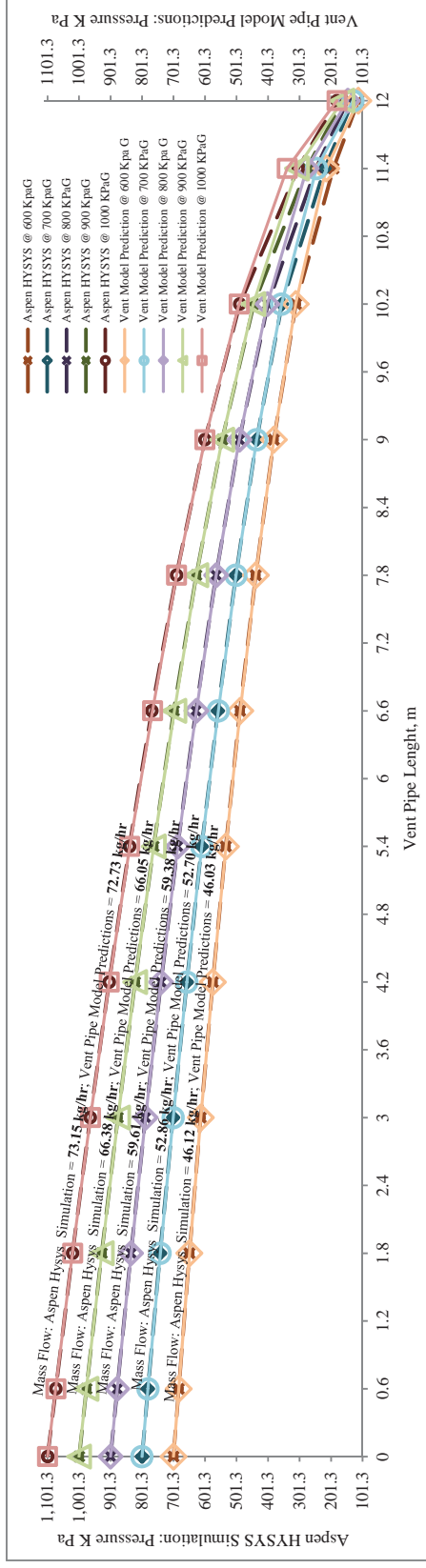


Figure 4-48: Predicted pressure comparison of vent pipe model with Hysys simulation for methane in pressure range 600-1000 KPa gauge

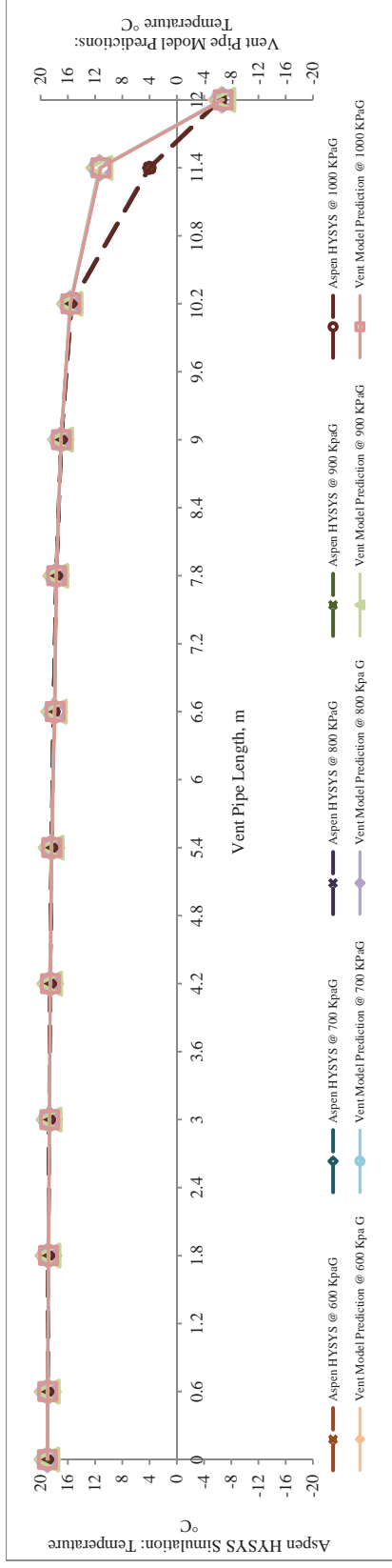


Figure 4-49: Predicted temperature comparison of vent pipe model with Hysys simulation for methane in pressure range 600-1000 KPa gauge

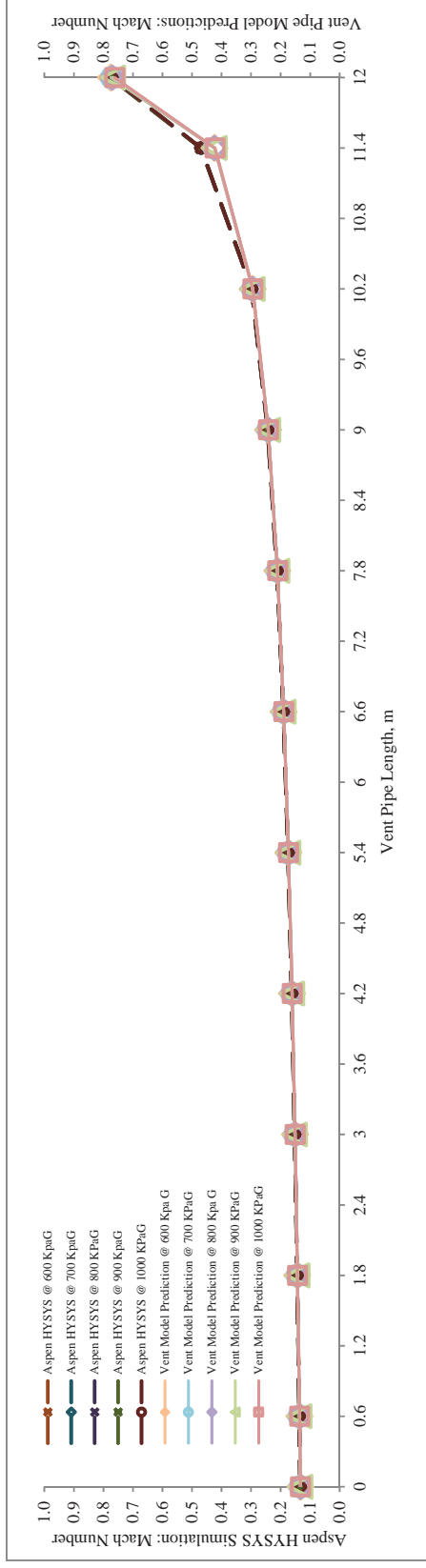


Figure 4-50: Predicted Mach no. comparison of vent pipe model with Hysys simulation for methane in pressure range 600-1000 KPa gauge

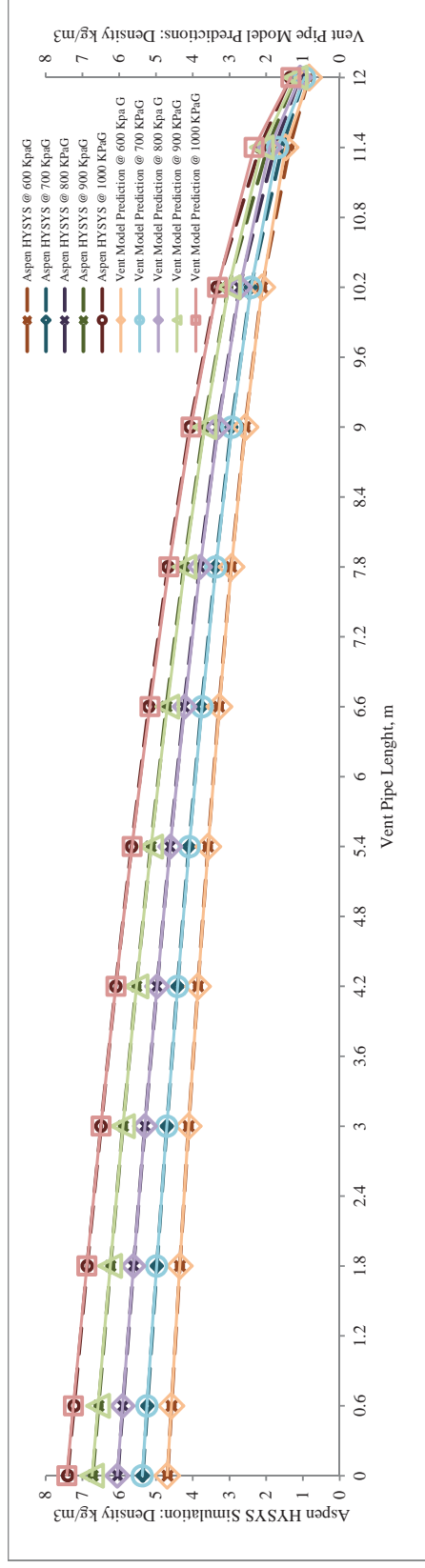


Figure 4-51: Predicted density comparison of vent pipe model with Hysys simulation for methane in pressure range 600-1000 KPa gauge

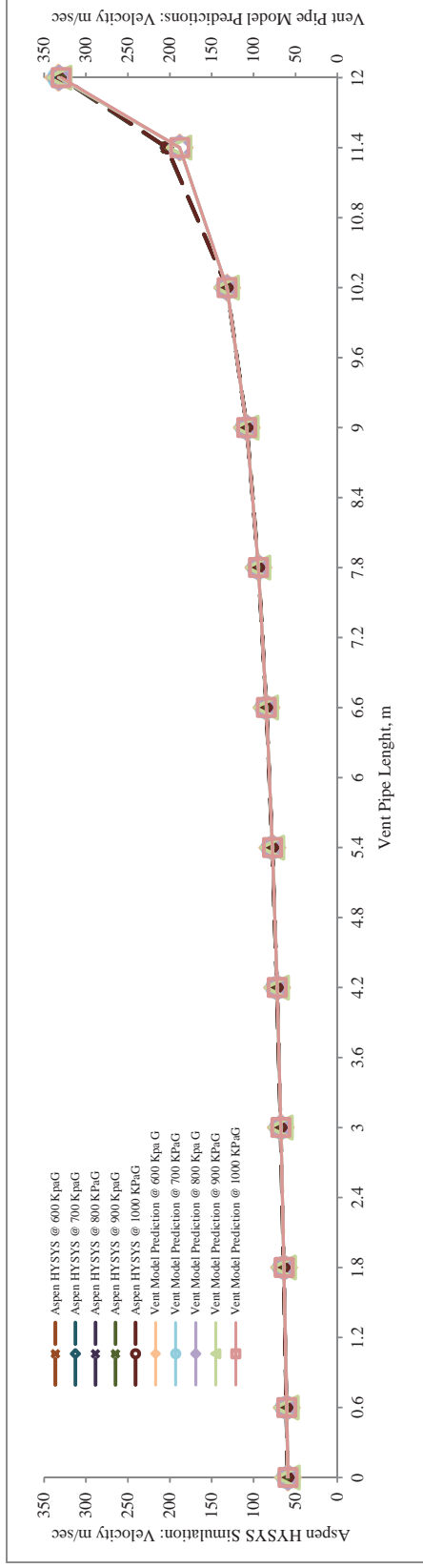


Figure 4-52: Predicted velocity comparison of vent pipe model with Hysys simulation for methane in pressure range 600-1000 KPa gauge

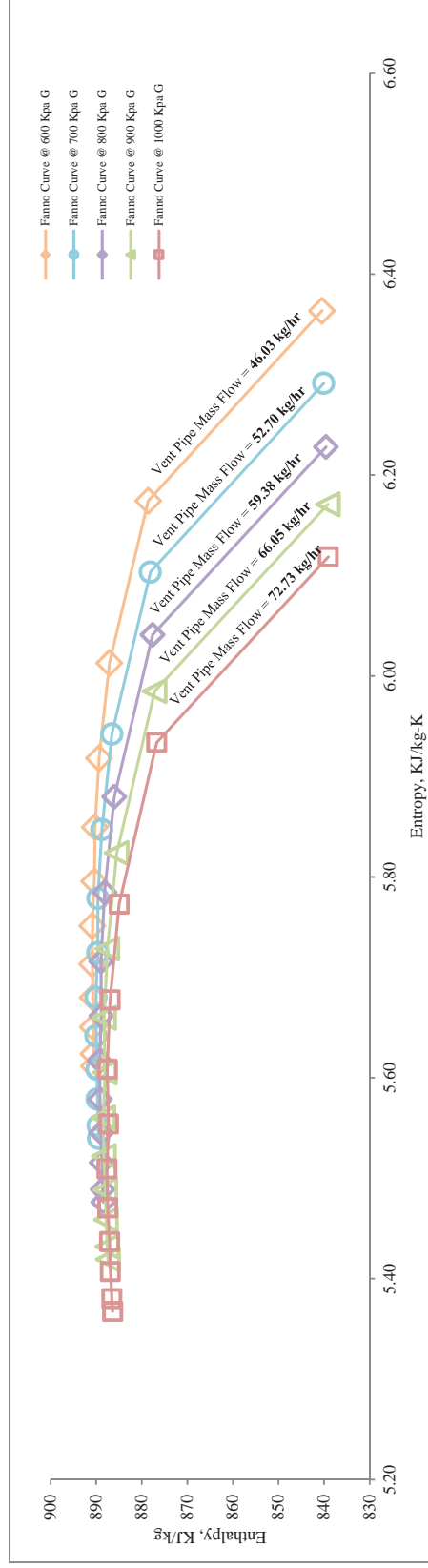


Figure 4-53: Predicted Enthalpy-Entropy (Fanno curve) of vent pipe model for methane in pressure range 600-1000 KPa gauge

A maximum percentage difference of 136.33% is calculated in the 11<sup>th</sup> section of the vent pipe. The reason for existence of such a temperature profile is unclear at this stage.

Mach number, density and velocity along the vent pipe were assessed and plotted. Figure 4-44, Figure 4-45 and Figure 4-46 show the Mach number, density and velocity profiles for the vent model predictions and Aspen Hysys simulated results for methane at steady-state mass flow conditions in the pressure range 100-500 KPa gauge. Referring to the relevant graphs, it can be said that the density along the vent profile is decreasing towards the exit of the vent pipe and the graph pattern resembles the same as the pressure graph. The Mach number and velocity profiles attain the exit conditions exponentially preceded by a linear rise. The predicted results are in close agreement for Mach number, velocity and density profile of the Hysys simulated results. Enthalpy-Entropy diagram (fanno curve) was plotted to explain the effects of flow conditions developed in the vent pipe and to define the flow in the vent pipe. Figure 4-47 represents the fanno curves in the pressure ranges 100-500 K Pa gauge. A decrease in enthalpy and pressure with a simultaneous increase in entropy defines the flow to be subsonic for the predicted results.

#### **4.6.3.2 CH<sub>4</sub> Case 2: Pressure range 600-1000 KPa gauge**

The vent model predictions and Hysys simulated results with comparison differences are tabulated in table G 11-6. Mass flow predictions agreed well with the Hysys simulated results for the pressure range 600-1000 K Pa gauge. The minimum and maximum comparison percentage difference calculated was -0.2% and 0.58% for the mass flow. The predicted and simulated results of pressure profile for the vent pipe flowing with methane were plotted and are represented in Figure 4-48. A close agreement in the pressure results is seen at the exit and in the first ten sections of the vent pipe. The percentage difference in the 11<sup>th</sup> section is high compared to the other sections of the vent pipe and is ~11.6%. The pressure profile pattern developed for methane is very similar to air and carbon-dioxide gases evaluated before. The temperature predictions and simulated results for methane were evaluated and the pattern developed was very similar to air and carbon-dioxide gas. This is represented in Figure 4-49. A minimum percentage comparison difference of 4.08% and a maximum of 6.15% were calculated at the exit of the vent pipe. The temperature profile developed along the vent pipe was of the same pattern as CH<sub>4</sub> case-1 representing a decreasing linearity followed by an exponential decrease to attain exit conditions. Predicted and simulated Mach numbers, density and velocity were also plotted in Figure 4-50, Figure

4-51 and Figure 4-52 for methane and were found to be in close agreement with each other. Enthalpy-Entropy diagram (Figure 4-53) characterized the flow to be subsonic. A decrease in enthalpy and increase in entropy was noticed.

#### **4.6.4 Comparison with Hysys Simulation for DBNGP Mixture:**

The evaluations performed for compressible gases such as air, carbon-dioxide and methane indicate that the vent model predictions and the Aspen Hysys simulated results are in good agreement for single component gas phase steady-state adiabatic conditions. In order to test the performance of the vent pipe model flowing with a multi-component gas, an evaluation was performed on multi-component DBNGP (Kirk-Burnnand 2009) gas mixture. The evaluations were performed in the pressure range 100-1000 KPa gauge on a similar case by case basis as performed with air, carbon-dioxide and methane.

##### **4.6.4.1 DBNGP<sub>mixture</sub> Case 1: Pressure range 100-500 KPa gauge**

The vent model predictions and Hysys simulated results with comparison differences are tabulated in table G 11-7. The mass flow rate predictions are in excellent agreement with Hysys simulated results. A minimum percentage difference of 0.04% and a maximum difference of -0.23% were calculated. These percentage differences are under acceptable limits. The pressure and temperature predictions hold in good agreement too. The pressure and temperature profile are plotted in figure 4-54 and figure 4-55. The predicted pressures for the first ten sections along the vent are within  $\pm 0.6\%$  of the comparison difference whereas the predicted temperatures are within  $\pm 1.09\%$  of the comparison difference in the same sections. The predicted exit conditions for pressure are in good agreement. An increase in temperature difference is noticed at pressure 400 and 500 KPa gauge. This calculated difference of is still acceptable. Predicted Mach number, densities and velocities along the vent pipe were compared with Hysys results and are plotted in Figure 4-56, Figure 4-57 and Figure 4-58. Except for the 11<sup>th</sup> section of the vent, the results are in good agreement for the first ten sections of the vent pipe and at the exit conditions. The percentage difference increases in section 11 and the reason for this is discussed when performing evaluations with air. Fanno lines were plotted in Figure 4-59 for the pressure ranging between 100-500 KPa gauge and flow was characterized to be subsonic. A decrease in enthalpy with a simultaneous increase in entropy was seen.

#### 4.6.4.2 DBNGP<sub>mixture</sub> Case 2: Pressure range 600-1000 KPa gauge

Hysys simulations performed at pressures > 600 KPa gauge did not converge the flow sheet with DBNGP gas mixture which resulted in an increase in back pressure. The vent model predictions and Hysys simulated results with comparison difference are tabulated in table G 11-8. Overall the predicted results were in close agreement with the Hysys simulated results. The minimum and maximum difference calculated when comparing the mass flow was -0.33% and -0.72%. The pressure and temperature profiles plotted for predicted and Hysys simulated results in Figure 4-60 and Figure 4-61 resemble very closely to the profile patterns developed for single component gases such as air, carbon-dioxide and methane. The percentage differences are within  $\pm 0.35\%$  for pressure and  $\pm 1.08\%$  for temperature in the first ten sections of the vent pipe. The exit pressure predictions are very closely agreeable with Hysys simulations. However, differences for exit temperatures are slightly higher than within the profile but are within acceptable ranges. Figure 4-62, Figure 4-63 and Figure 4-64 which represent the Mach number, density and velocity profiles for model predicted and Hysys simulated results show similar resemblance to air, carbon-dioxide and methane. Flow was characterized to be subsonic as per the fanno curve plotted in Figure 4-65.



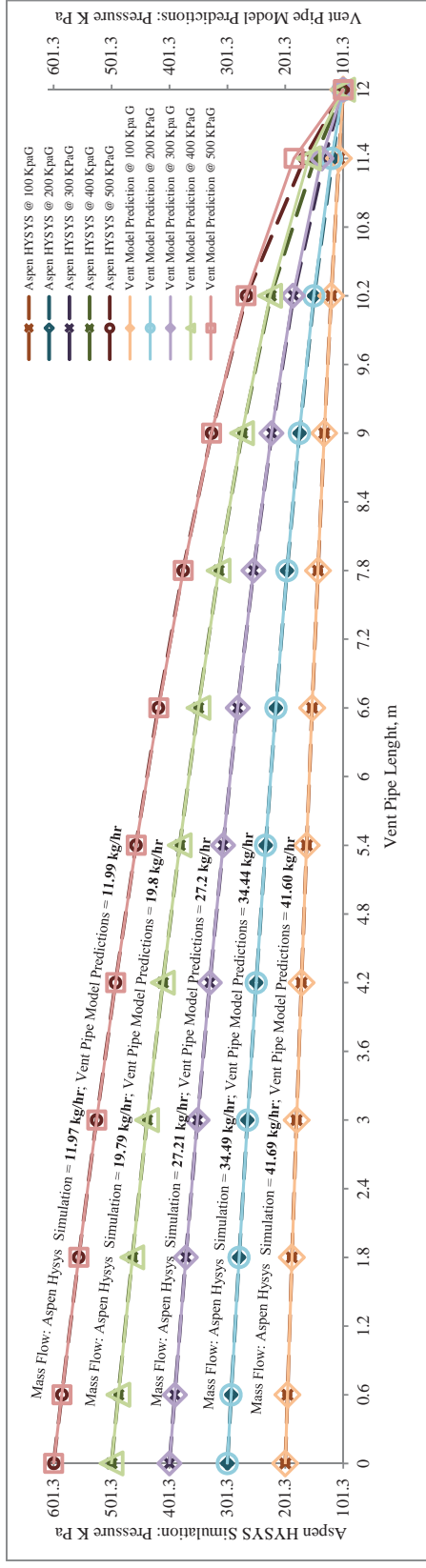


Figure 4-54: Predicted pressure comparison of vent pipe model with Hyysys simulation for DBNGP in pressure range 100-500 KPa gauge

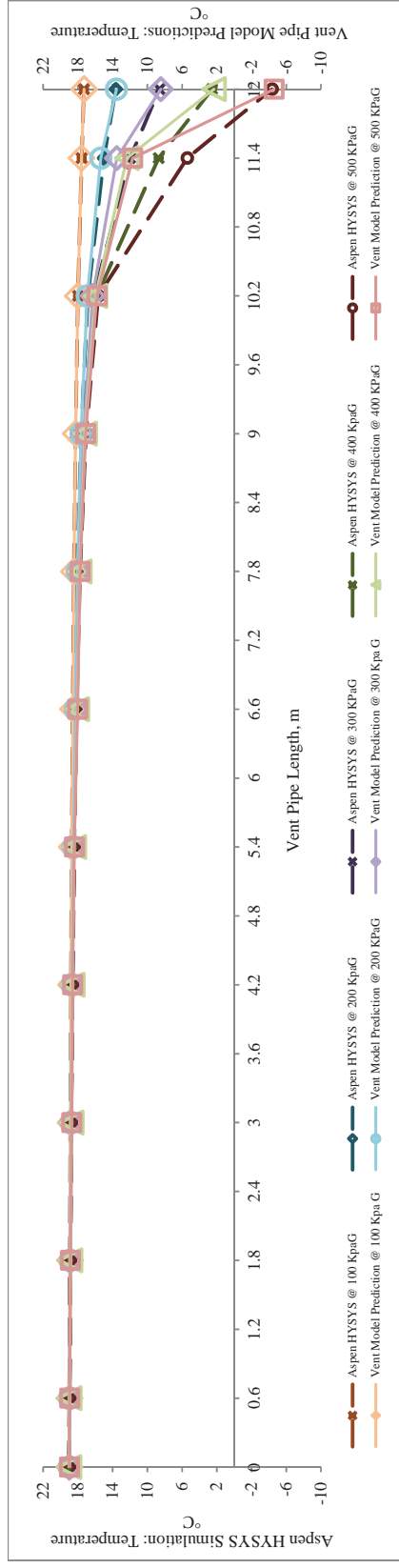


Figure 4-55: Predicted temperature comparison of vent pipe model with Hyysys simulation for DBNGP in pressure range 100-500 KPa gauge

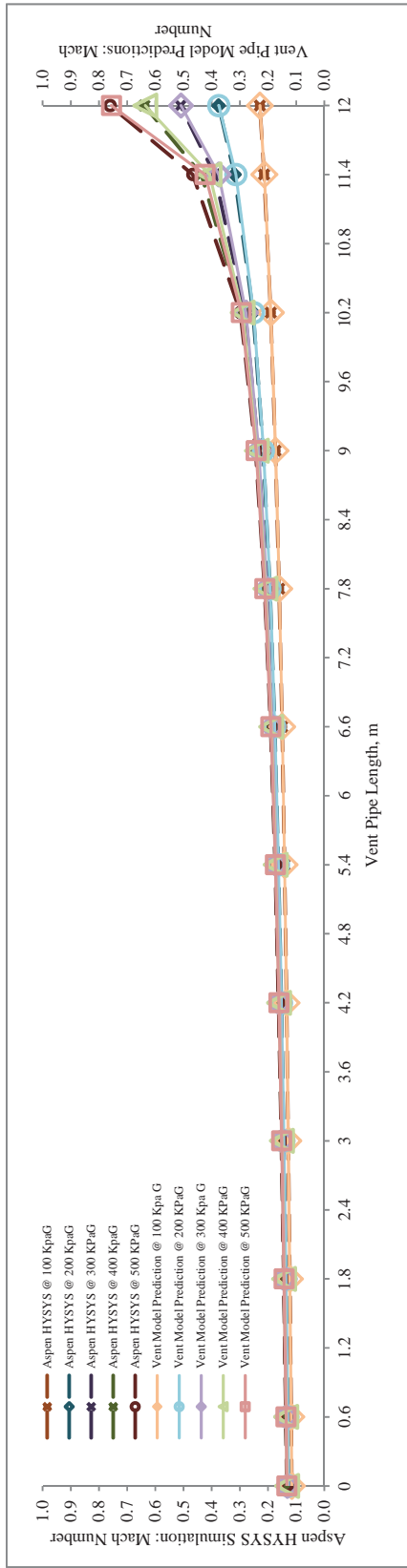


Figure 4-56: Predicted Mach no. comparison of vent pipe model with Hysys simulation for DBNGP in pressure range 100-500 KPa gauge

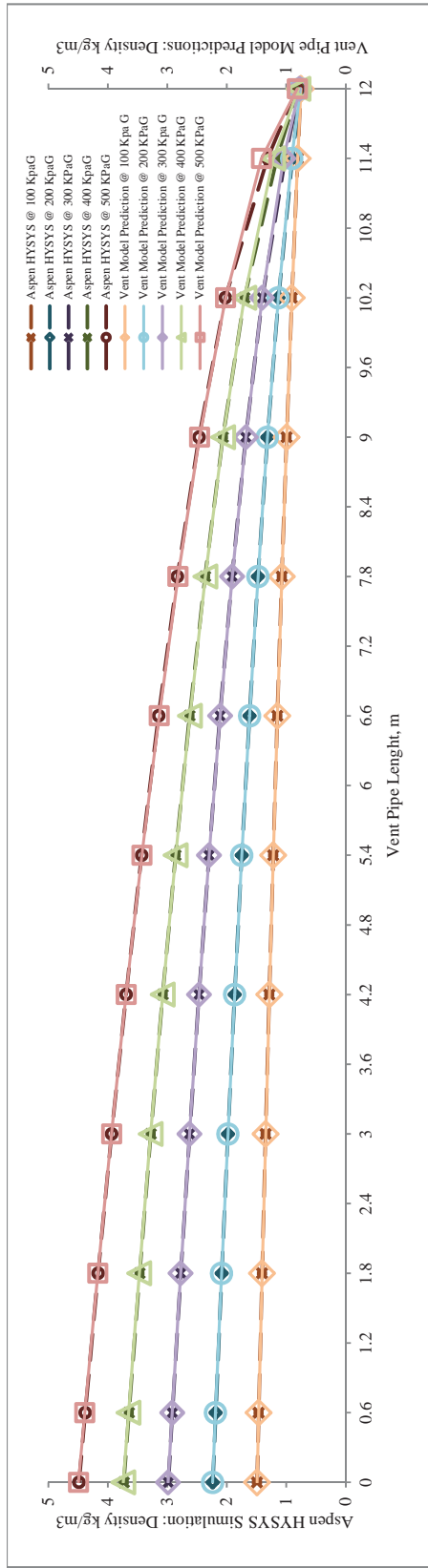


Figure 4-57: Predicted density comparison of vent pipe model with Hysys simulation for DBNGP in pressure range 100-500 KPa gauge

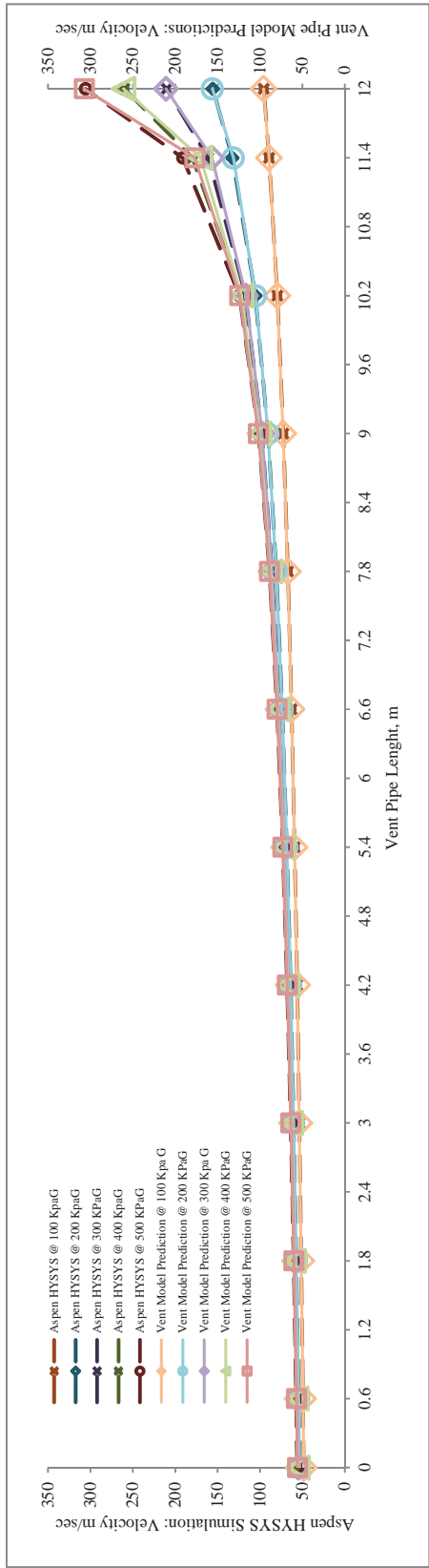


Figure 4-58: Predicted velocity comparison of vent pipe model with Hysys simulation for DBNGP in pressure range 100-500 KPa gauge

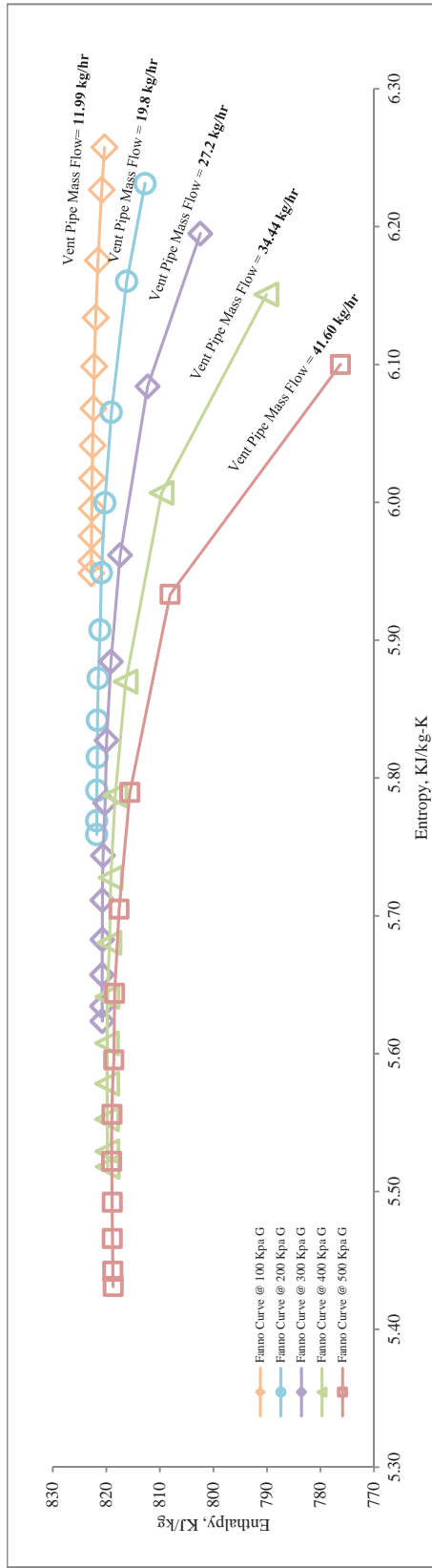


Figure 4-59: Predicted Enthalpy-Entropy (Fanno curve) of vent pipe model for DBNGP in pressure range 100-500 KPa gauge

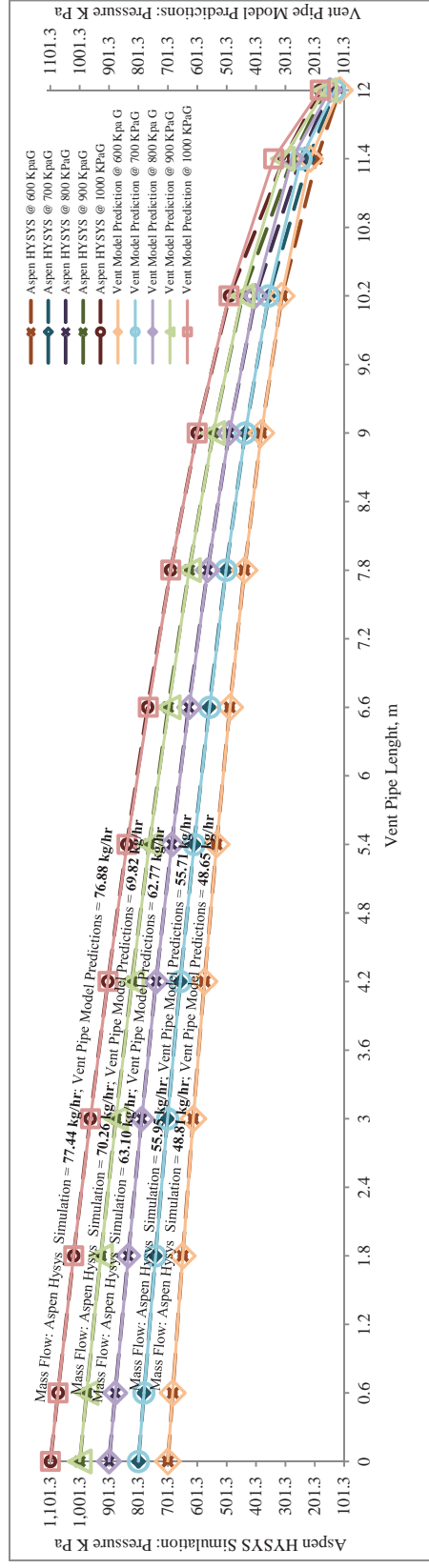


Figure 4-60: Predicted pressure comparison of vent pipe model with Hysys simulation for DBNGP in pressure range 600-1000 KPa gauge

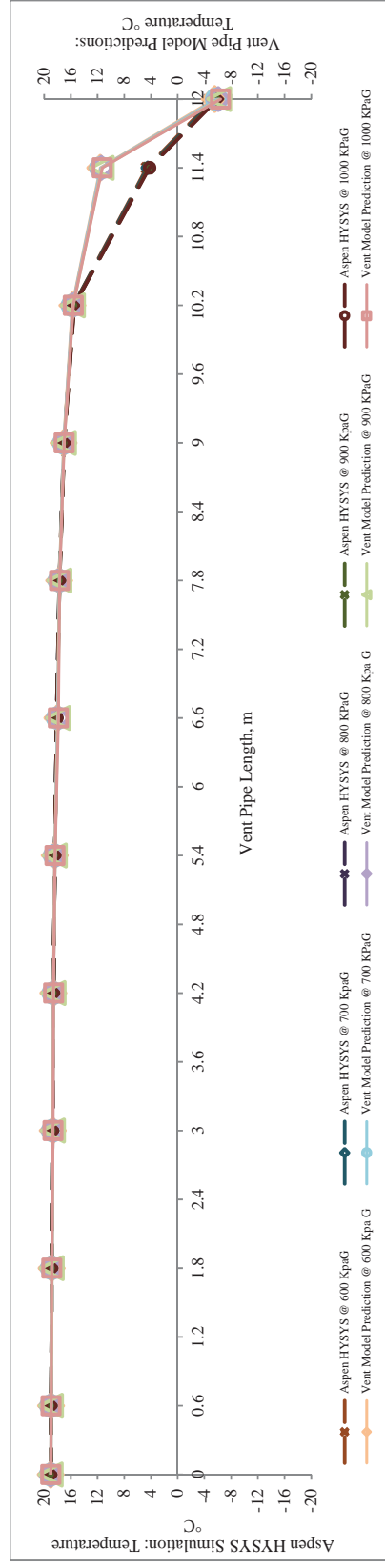


Figure 4-61: Predicted temperature comparison of vent pipe model with Hysys simulation for DBNGP in pressure range 600-1000 KPa gauge

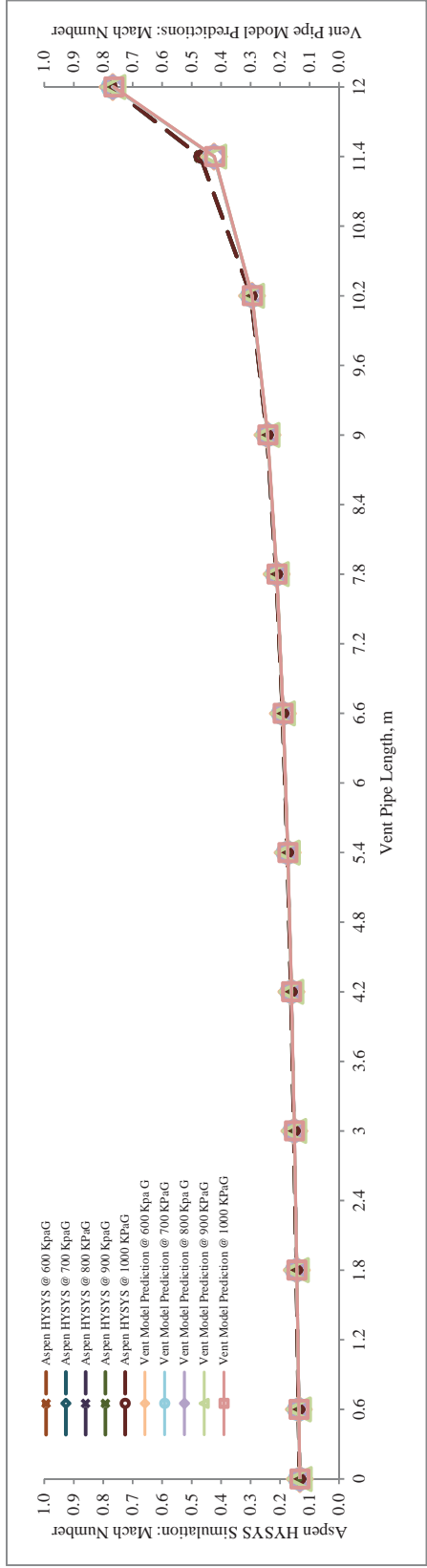


Figure 4-62: Predicted Mach no. comparison of vent pipe model with Hysys simulation for DBNGP in pressure range 600-1000 KPa gauge

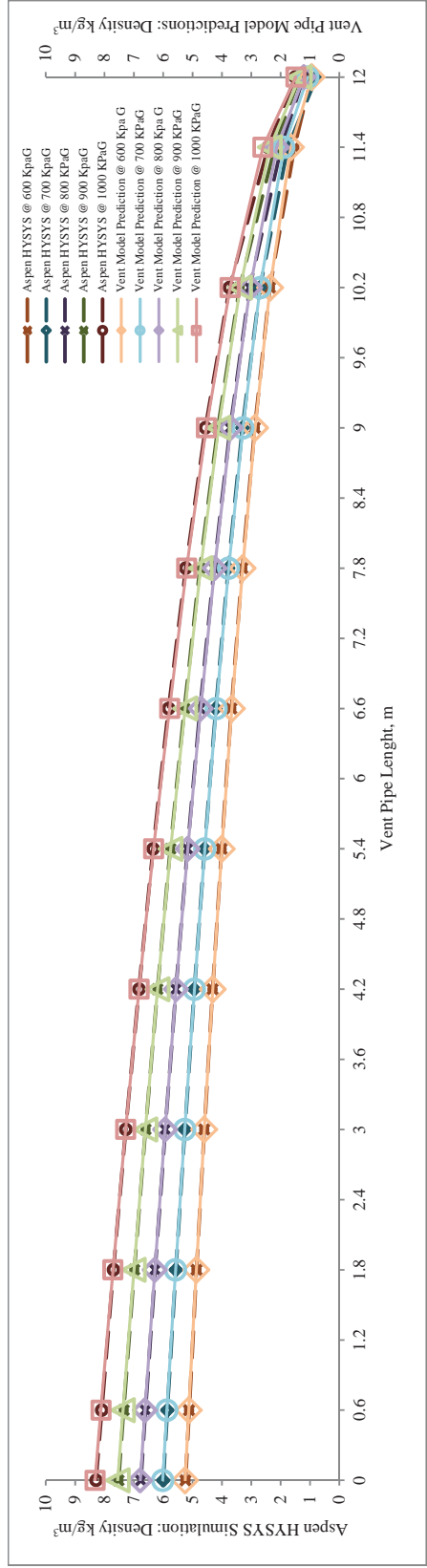


Figure 4-63: Predicted density comparison of vent pipe model with Hysys simulation for DBNGP in pressure range 600-1000 KPa gauge

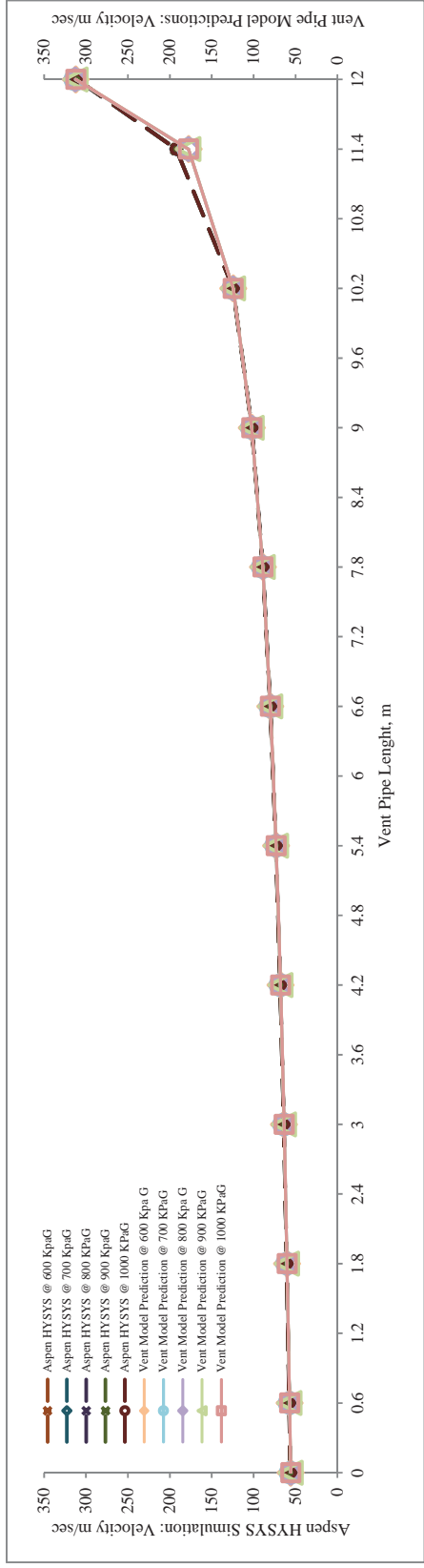


Figure 4-64: Predicted velocity comparison of vent pipe model with Hysys simulation for DBNGP in pressure range 600-1000 KPa gauge

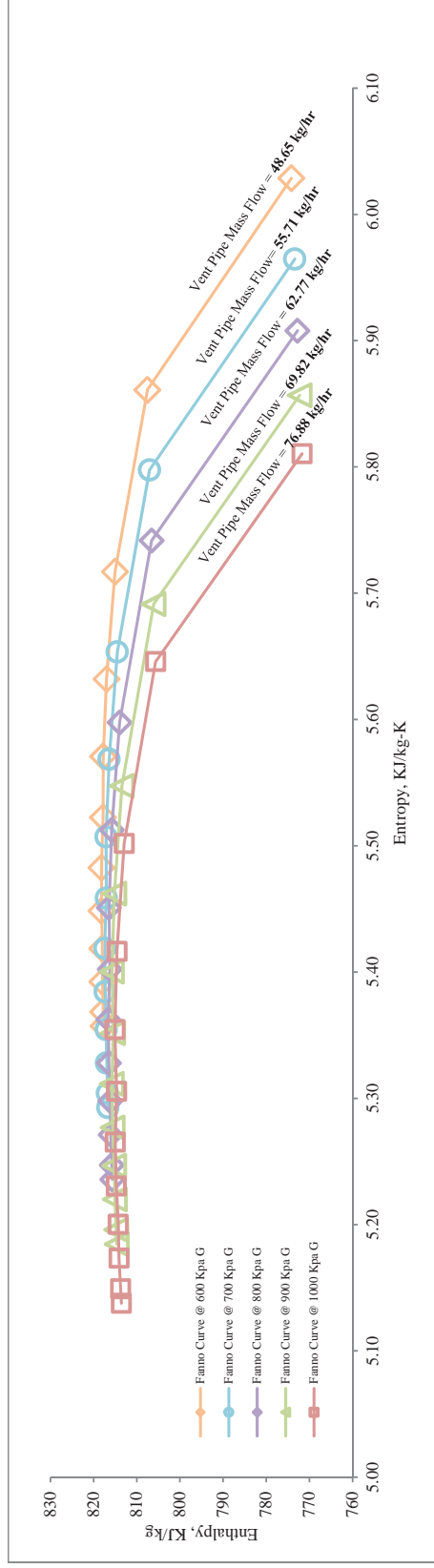


Figure 4-65: Predicted Enthalpy-Entropy (Fanno curve) of vent pipe model for DBNGP in pressure range 600-1000 KPa gauge

## **Chapter 5**

### **Conclusions and Recommendations for Future Work**

#### **5.1 Conclusions**

A thorough investigation has been conducted into compressible fluid (single-phase gas) behavior taking place in a vent pipe. The factors affecting the compressible fluid behavior and their influence on the compressible fluid parameters have been discussed. Friction is found to be the chief factor bringing about the changes in compressible fluid flow properties. This has been well explained by Fanno process. Based on the investigations performed and to satisfy the need of a model for venting through associated vent piping with pressure vessels / pipelines, a steady-state vent pipe model to predict the compressible fluid flow conditions during blowdown of pressure vessels / pipelines was developed. A fluid dynamic and thermodynamic approach was used in developing the model. The vent pipe model is described best as a model encountering adiabatic frictional flow conditions. The vent pipe model predicts the flowing gas properties such as pressure, temperature, mass flow / standard volumetric flow, temperature of the pipe wall at the exit along with stagnation properties and critical properties. The use of REFPROP, which incorporates the GERG 2004 equation of state, makes the simulation with the vent pipe model highly competent. All thermophysical properties are determined using REFPROP. The vent pipe model has been validated by comparing its predictions to experimental analysis and process simulation software, Aspen Hysys. Overall, it can be stated that the vent pipe model's predictions are in good agreement with experimental and Aspen Hysys results. The vent pipe model contains no disposable parameters and no adjustments have been made during validation to ensure the good agreement.

##### **5.1.1 Comparison of Vent Pipe Model Predictions with Experimental Analysis**

A test rig was designed and constructed for experimental analysis which incorporated the use of fast acting pressure, temperature and flowrate instruments. Steady state experiments were conducted with air in the pressure range of 200 – 400 KPa gauge and the results have been discussed. It follows from the three sets of comparisons (VPM-1, VPM-4 and VPM-7) reported here that the vent pipe model predicts results in very close agreement with the

experimental measurements. This agreement permits confidence to be placed in the predictions made using the vent pipe model. One of the most important parameters when designing venting systems is the temperature of the vent pipe. This parameter helps in estimating the minimum temperature that could be attained at the exit of the pipe wall during venting. The adiabatic wall temperature was predicted based on the recovery factor approach where the recovery factor was taken to be same as the Prandtl number. Comparison of the predicted wall temperature using recovery factor approach has provided a very close agreement. Based on experimental comparison, the standard volumetric flow rates, the stagnation temperatures and minimum pipe wall temperatures can be predicted using the vent pipe model with an estimated uncertainty of  $\pm 2.5 \text{ Nm}^3/\text{hr}$ ,  $\pm 0.15^\circ\text{C}$  and  $\pm 0.6^\circ\text{C}$ . However, there are certain other validity comparisons which would increase confidence in the program and are discussed in the recommendation section.

### **5.1.2 Comparison of Vent Pipe Model Predictions with Aspen Hysys**

The vent pipe predictions were compared to Aspen Hysys simulated results for single component compressible gases such as air, carbon-dioxide and methane and multi-component gases such as DBNGP mixtures in the pressure range of 100-1000 KPa gauge. The predicted results were found to be in close agreement for all parameters involved. The Mach number and velocity profile pattern developed were similar in all cases forming a horizontal mirror image to the temperature profiles for the flowing gases. Pressure greater than 600 K Pa gauge were evaluated by increasing the exit gas pressure at the end of the vent pipe due to convergence issues with Hysys. A high percentage comparison difference was seen in the 11<sup>th</sup> section of the vent pipe in all the parameters plotted for all gases. The reason for this high difference was explained during the evaluation of air and holds for all other gases evaluated here. Fanno curves were plotted. The flow was characterized to be subsonic and irreversibility of the process was confirmed. The vent pipe model predictions compares well with Hysys simulations with very small percentage differences at the exit. Based on Hysys comparison results, the two important parameters - the minimum temperature of the flowing gas at the exit and the maximum mass flow are predicted using the vent pipe model with an estimated uncertainty of at most  $\pm 0.25^\circ\text{C}$  with air,  $\pm 1.65^\circ\text{C}$  with carbon dioxide,  $\pm 0.40^\circ\text{C}$  with methane.  $\pm 0.42^\circ\text{C}$  with DBNGP gas mixture for minimum temperature of flowing gas and  $\pm 0.15 \text{ kg/hr}$  with air,  $\pm 2.5 \text{ kg/hr}$  with carbon dioxide,  $\pm 0.42$  with methane,  $\pm 0.56 \text{ kg/hr}$  with DBNGP gas mixture for maximum mass flux. Moreover, the vent pipe model predictions are calculated based on the GERG-2004 equation of state which is proved



to better than AGA8-DC92, Peng-Robinson and other equations of state (Kunz et al. 2007)(Kunz et al. 2007). Thus, it can be said that the developed vent pipe model can be successfully employed for predicting the single phase steady-state adiabatic vent pipe performance for single and multi-component gas mixtures.

Overall, a very close agreement exists between the predictions of the vent pipe model and experimental / Aspen Hysys process simulations. Based on these results we can conclude that the vent pipe model can be used in designing the vent piping systems associated with pressure vessels / pipelines. The vent pipe model can become much more robust when certain gaps in the experimental validation, in particular for higher pressure venting conditions, are filled.

## **5.2 Recommendations**

There are certain other validity comparisons which would increase the robustness of the vent pipe model and can be undertaken as a future scope of work. Some of the recommendations are as follows:

- The existing experimental evidence was performed in the pressure range from 200 – 400 KPa gauge due to issues related to laboratory compressor air supply. There is a need for further experiments to be performed at pressures higher than 400 KPa gauge. The existing experimental evidence was performed with air gas only. Due to constraints and other restrictions in fluid flow laboratory hydrocarbon or other supercritical gases could not be vented. There is a need for further experiments with hydrocarbon gases and supercritical gases.
- The vent pipe model is developed based on an adiabatic approach and will be employed mostly to short pipes. However, as discussed in this thesis, the actual behavior of the gas lies somewhere between the isothermal and adiabatic conditions. Hence, the development of an isothermal model with heat transfer will be an added advantage for accurate prediction of real gases.
- The vent pipe model is developed in visual basic in conjunction with Microsoft Excel spreadsheet. The convergence of results is delayed due to time taken by processor for performing calculations. This problem can be efficiently solved by scripting the program in FORTRAN language. The FORTRAN language is designed

for scientific usage and also has excellent logical capabilities. Also, FORTRAN is used heavily by experienced process engineers.

- The vent pipe model has been developed for single phase gases. A new model for multi-component multiphase gases can be developed in conjunction with the current single phase model.

## **Appendices**

### **Appendix A**

#### **6.1 Pressure Testing Certificate**



121 Vulcan Road  
Canning Vale WA 6155 Australia

Ph +61 8 9456 1300  
Fax +61 8 9456 1400  
Email: calibration@tridentaustralia.com.au

### Test Certificate - Pressure Test

<b>Test Cert No</b>	PT1100	<b>Date</b>	6-April-2010
<b>Client</b>	Curtin University	<b>Purchase Order</b>	

#### Test Details

Job / Sales No	J1697
Item:	1 x Vent Tube Assembly
Part Number:	N/A
Serial Number:	N/A
Operating Range	0-600 psi
Test Specification	WI-QA63
Test Description:	Hydrostatic
Test Medium	Water
Test Equipment:	Calibrated pressure gauge, PG

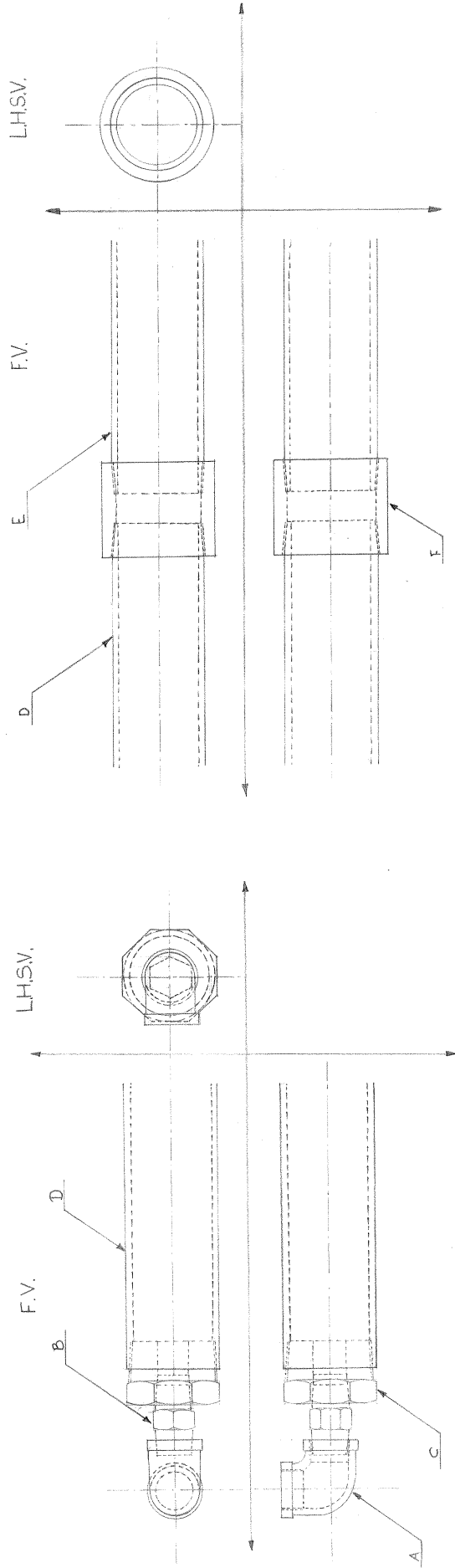
#### Test Results

Test Pressure:	600 psi	
Test Period:	30 Min	
Temperature:	Ambient	
Comments:	No Leaks	
Tested by:	Signature	Date
B Gibbon		6-April-2010

## **Appendix B**

### **7.1 Test Rig Representation and Mechanical Drawings**

Sl. No.	QTY	PART	SPECIFICATION	LIST OF MATERIALS	LENGTH	END CONNECTION	THREAD TYPE
1	1	A	20 NB 90° ELBOW 150 LB	CARBON STEEL	52	THREADED (FEMALE X FEMALE)	BSPT
2	1	B	20 NB HEXAGONAL NIPPLE 150 LB	CARBON STEEL	48	THREADED (MALE X MALE)	BSPT
3	1	C	50 X 20 NB REDUCING RUSH 150 LB	CARBON STEEL	42	THREADED (MALE X FEMALE)	20 NB BSPT; 50 NB BSPT
4	1	D	50 NB SCHEDULE 40 SEAMLESS PIPE	ASTM A106 GR. B 3000	5800	THREADED (FEMALE X MALE)	BSPT
5	1	E	50 NB SCHEDULE 40 SEAMLESS PIPE	ASTM A106 GR. B 3000	5800	THREADED (MALE X MALE)	BSPT
7	1	F	50 NB STANDARD COUPLING 150 LB	CARBON STEEL	64	THREADED (FEMALE X FEMALE)	BSPT



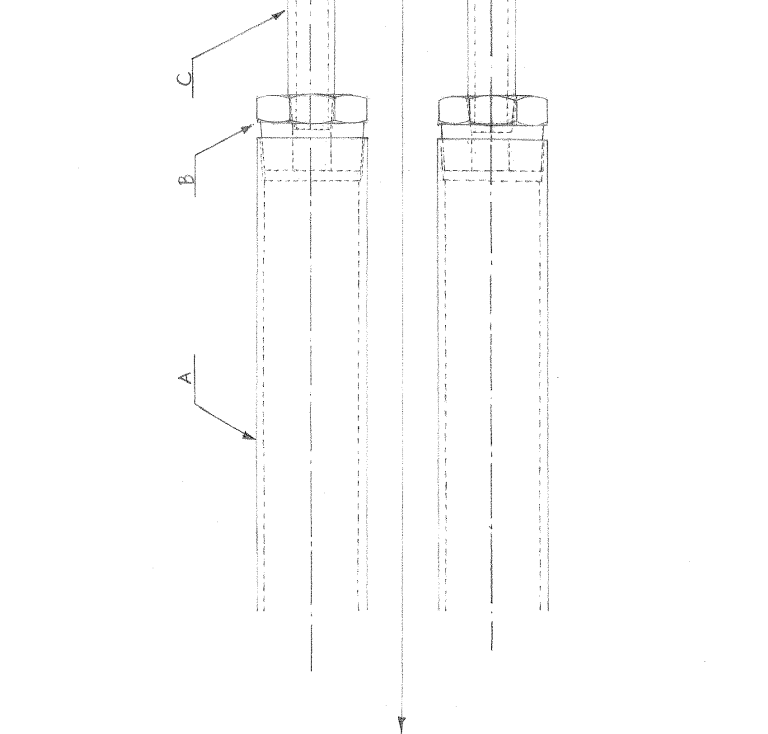
T.V.

T.V.

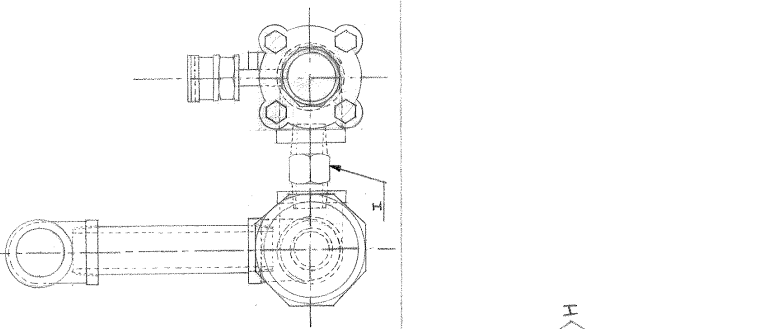
<b>NOTE:</b> ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS AND SHARP EDGES. FIRST ANGLE PROJECTION	PROJECT: INVESTIGATION INTO COMPRESSIBLE FLUID BEHAVIOUR IN A VENT PIPE DURING BLOWDOWN DRAWN: FARHAN RAJIVATE CHECKED: [ ] APPROVED: [ ]	DATE: 19/7/2010 DATE: [ ] DATE: [ ] DATE: [ ]	CURTIN University of Technology KENT STREET, BENTLEY, WA 6102
	TITLE: VENT PIPE INSTRUMENTATION AND FITTINGS ARRANGEMENT FOR TEST RIG	SCALE: 1:2 SHEET: 1 OF 2	[ ] [ ] [ ] [ ]

Sr. No.	QTY	PART	SPECIFICATION	LIST OF MATERIALS	LENGTH	END CONNECTION	THREAD TYPE
1	1	A	50 NB SCHEDULE 40 SEAMLESS PIPE	ASTM A106 GR B 3000	5800	THREADED (MALE X FEMALE)	BSPT
2	1	B	50 X 20 NB REDUCING BU: T1 150 LB	CARBON STEEL	42	THREADED (MALE X FEMALE)	20 NB BSPT; 50 NB BSPT
3	1	C	20 NB SCHEDULE 80 SEAMLESS PIPE	ASTM A106 GR B 3000	200	THREADED (MALE X MALE)	BSPT
4	2	D	20 NB TEE 150 LB	CARBON STEEL	66	THREADED (FEMALE X FEMALE)	BSPT
5	1	E	20 NB SCHEDULE 80 SEAMLESS PIPE	ASTM A106 GR B 3000	100	THREADED (MALE X MALE)	BSPT
6	1	F	20 NB BALL VALVE	BODY: A351 CF8M; BALL: S3316	86.5	THREADED (MALE X FEMALE)	NPTF
7	1	G	20 NB SCHEDULE 80 SEAMLESS PIPE	ASTM A106 GR B 3000	100	THREADED (MALE X MALE)	BSPT
8	2	H	20 NB 90° ELBOW 150 LB	CARBON STEEL	52	THREADED (FEMALE X FEMALE)	BSPT
9	1	I	20 NB HEXAGONAL NIPPLE 150 LB	CARBON STEEL	48	THREADED (MALE X MALE)	BSPT
10	1	J	20 NB SCHEDULE 80 SEAMLESS PIPE	ASTM A106 GR B 3000	100	THREADED (MALE X MALE)	NPTF; BSPT

F.V.



L.H.S.V.



T.V.

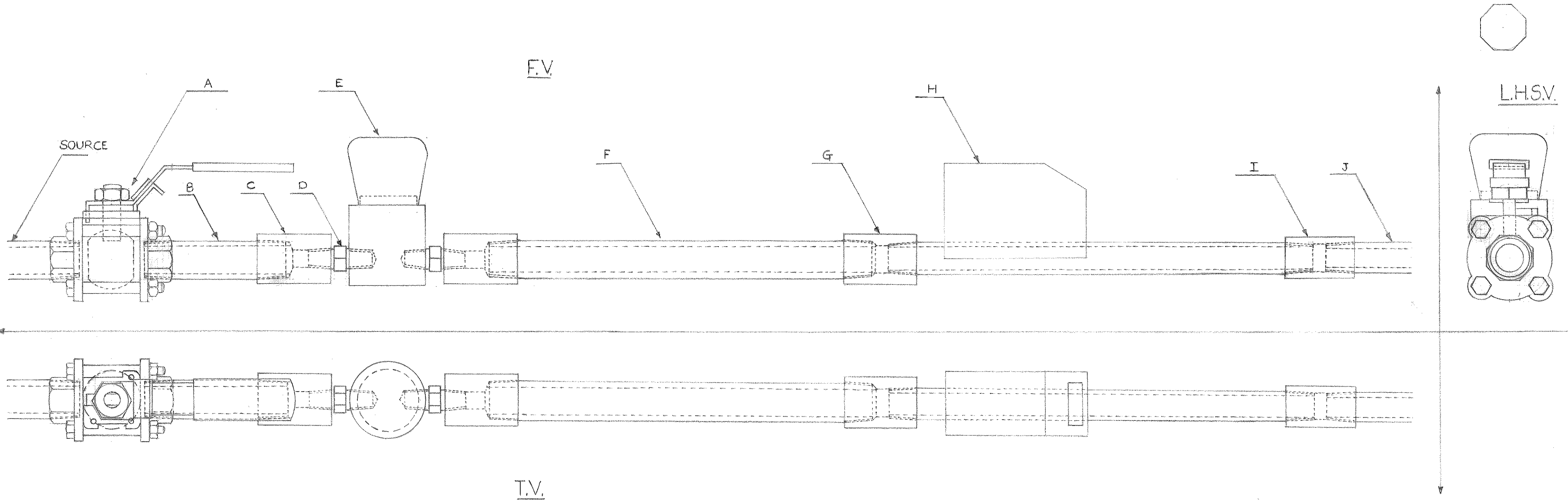



NOTE: DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED. REMOVE ALL BURRS AND SHARP EDGES. FIRST ANGLE PROJECTION		PROJECT: INVESTIGATION INTO COMPRESSIBLE FLUID BEHAVIOUR IN A VENT PIPE DURING BLOWDOWN	DRAWN: FARHAN RAJIWATE	DATE: 19/7/2010
		CHECKED:	DATE:	
		APPROVED:	DATE:	
		TITLE: VENT PIPE INSTRUMENTATION AND FITTINGS ARRANGEMENT FOR TEST RIG	SCALE: 1:2	SHEET: 2

**CURTIN**  
 University of Technology  
 KENT STREET  
 BENTLEY, WA 6102

Sr. No.	QTY	PART	SPECIFICATION	LIST OF MATERIALS	LENGTH	END CONNECTION	WELD TYPE	THREAD TYPE
1	1	SOURCE	3/4" SCH80s PIPE	ASTM A312 TP316/316L	R			
2	1	A	3/4" BALL VALVE	BODY: A351 CF8M; BALL: SS316	86.5mm	BOTH ENDS THREADED		3/4" NPTF
3	1	B	3/4" SCH80s PIPE	ASTM A312 TP316/316L	2"	BOTH ENDS THREADED		3/4" NPT
4	2	C	3/4" X 1/4" REDUCED COUPLING CLASS 3000	SS 316	2"	BOTH ENDS THREADED		3/4" NPTF; 1/4" NPTF
5	2	D	1/4" HEXAGONAL NIPPLE CLASS 3000	SS 316	1 3/4"	BOTH ENDS THREADED		1/4" NPT
6	1	E	GO PRESSURE REGULATOR (PR-1)	SS 316L	2"	BOTH ENDS THREADED		1/4" NPTF
7	1	F	3/4" SCH80s PIPE	ASTM A312 TP316/316L	10 3/4"	BOTH ENDS THREADED		
8	1	G	3/4" X 1/2" REDUCED COUPLING CLASS 3000	SS 316	2"	BOTH ENDS THREADED		3/4" NPTF; 1/2" NPTF
9	1	H	EFFECTOR 300 FLOW METER	SS304S15	11 7/8"	BOTH ENDS THREADED		
10	1	I	1/2" FULL COUPLING CLASS 3000	SS 316	1 7/8"	BOTH ENDS THREADED		1/2" NPTF
11	1	J	1/2" SCH80s PIPE (CONNECTION TO 1/2" TEE SHEET 2)	ASTM A312 TP316/316L	2"	BOTH ENDS THREADED		1/2" NPT

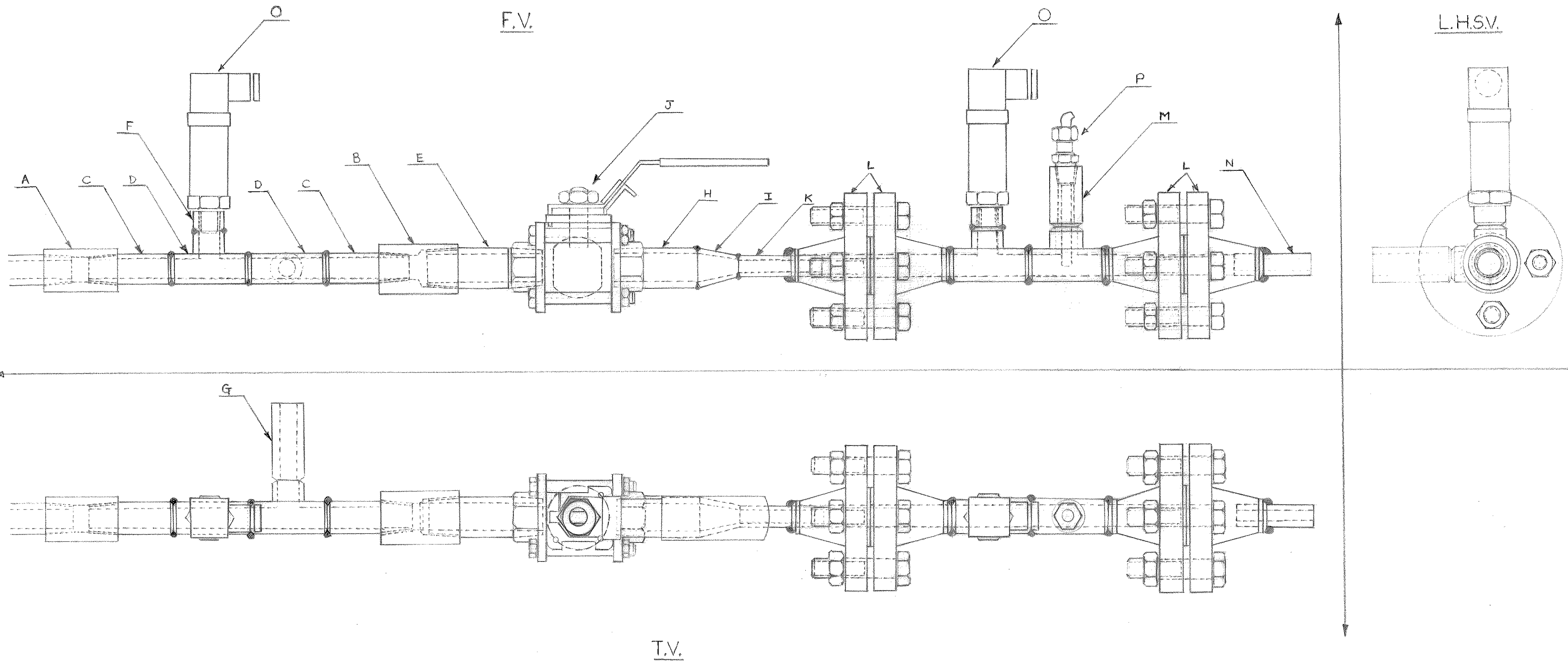
R\*- ANY LENGTH REQUIRED FOR CONNECTION TO SOURCE



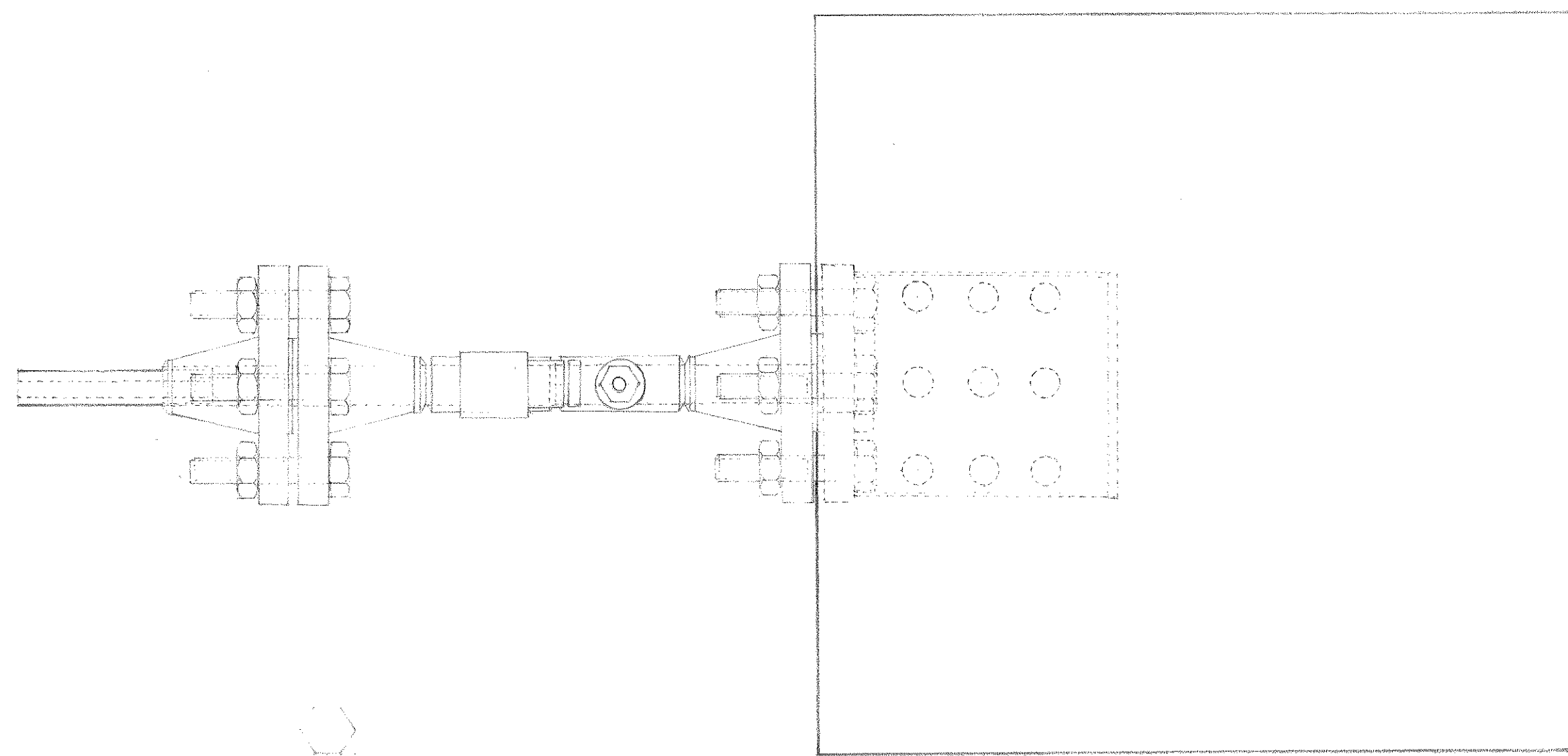
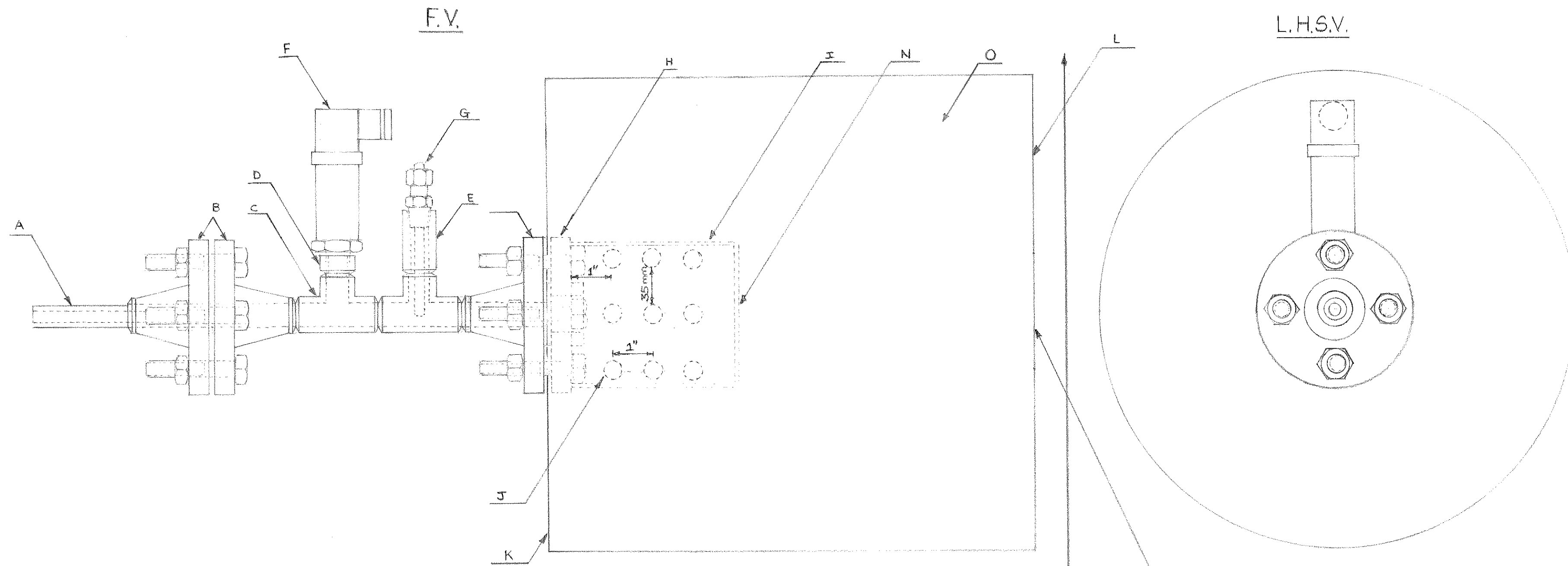
<b>NOTE:</b> ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS AND SHARP EDGES. <b>FIRST ANGLE PROJECTION</b>	<b>PROJECT:</b> INVESTIGATION INTO COMPRESSIBLE FLUID BEHAVIOUR IN A VENT PIPE DURING BLOWDOWN		 KENT STREET, BENTLEY, WA 6102	
	<b>DRAWN</b> FARHAN RAJIWATE	<b>DATE</b> 25/1/2010	<b>TITLE:</b> VENT PIPE INSTRUMENTATION AND FITTINGS ARRANGEMENT FOR TEST RIG	
	<b>CHECKED</b>	<b>DATE</b>	<b>SCALE</b> 1:2	
	<b>APPROVED</b>	<b>DATE</b>	<b>SHEET</b> 1	<b>OF</b> 3



Sr. No.	QTY	PART	SPECIFICATION	LIST OF MATERIALS	LENGTH	END CONNECTION	WELD TYPE	THREAD TYPE
1	1	A	1/2" FULL COUPLING CLASS 3000	SS 316	1 7/8"	BOTH ENDS THREADED		1/2" NPTF
2	1	B	3/4" X 1/2" REDUCED COUPLING CLASS 3000	SS 316	2"	BOTH ENDS THREADED		3/4" NPTF; 1/2" NPTF
3	2	C	1/2" SEAMLESS SCH 80s PIPE	ASTM A312 TP316/316L	2"	WELDED/THREADED	TIG	1/2" NPT
4	4	D	1/2" SCH80s BUTTWELD EQUAL TEE	ASTM A403 WP316/316L	2"	BUTTWELD	TIG	
5	1	E	3/4" SCH80s PIPE	ASTM A312 TP316/316L	2 1/2"	BOTH ENDS THREADED		3/4" NPT
6	2	F	1/2" SCH160s PIPE	ASTM A312 TP316/316L	1/2"	WELDED/THREADED	TIG	1/4" BSPPF
7	1	G	1/2" SCH160s PIPE	ASTM A312 TP316/316L	2"	WELDED/THREADED	TIG	1/2" NPTF
8	1	H	3/4" SCH80s PIPE	ASTM A403 WP316/316L	2"	WELDED/THREADED	TIG	3/4" NPT
9	1	I	3/4" X 1/4" CONCENTRIC REDUCER	SS 316	26.7mm	BOTH ENDS WELDED	TIG	
10	1	J	3/4" BALL VALVE	BODY: A351 CF8M; BALL: SS316	86.5mm	BOTH ENDS THREADED		3/4" NPTF
11	1	K	1/4" SCH80s PIPE	ASTM A312 TP316/316L	2 1/4"	BOTH ENDS WELDED	TIG	
12	4	L	1/2" SCH80s CLASS 300 R/F WELDNECK FLANGE	ASTM A182 F316L	52.3mm	WELDED	TIG	
13	1	M	1/2" SCH160s PIPE	ASTM A182 F316L	1 1/2"	WELDED/THREADED	TIG	1/4" BSPTF
14	1	N	1/4" SCH80s PIPE	ASTM A182 F316L	6000mm	WELDED/THREADED	TIG	1/4" NPT
15	2	O	PRESSURE TRANSDUCER	CERAMIC; SS316 HOUSING		THREADED		1/4" BSPP
16	1	P	RTD-PT100-3m RTD WITH PT100 OUTPUT	SS316		THREADED		1/4" BSPT



<b>NOTE:</b> ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS AND SHARP EDGES. <b>FIRST ANGLE PROJECTION</b>		<b>PROJECT: INVESTIGATION INTO COMPRESSIBLE FLUID BEHAVIOUR IN A VENT PIPE DURING BLOWDOWN</b>				KENT STREET, BENTLEY, WA 6102	
		<b>DRAWN</b> FARHAN RAJIWATE	<b>DATE</b> 25/1/2010	<b>TITLE:</b> VENT PIPE INSTRUMENTATION AND FITTINGS ARRANGEMENT FOR TEST RIG			
		<b>CHECKED</b>	<b>DATE</b>	<b>SCALE</b> 1:2	<b>SHEET</b> 2	<b>OF</b> 3	
		<b>APPROVED</b>	<b>DATE</b>				



Sr. No.	QTY	PART	SPECIFICATION	LIST OF MATERIALS	LENGTH	END CONNECTION	WELD TYPE	THREAD TYPE
1	1	A	1/4" SCH80s PIPE	ASTM A182 F316L	600mm	WELDED/THREADED	TIG	1/4" NPT
2	3	B	1/2" SCH80s CLASS 300 R/F WELDNECK FLANGE	ASTM A182 F316L	52.3mm	WELDED	TIG	
3	2	C	1/2" SCH80s BUTTWELD EQUAL TEE	ASTM A403 WP316/316L	2"	WELDED	TIG	
4	1	D	1/2" SCH160s PIPE	ASTM A312 TP316/316L	1/2"	WELDED/THREADED	TIG	1/4" BSPPF
5	1	E	1/2" SCH160s PIPE	ASTM A312 TP316/316L	2"	WELDED/THREADED	TIG	1/2" NPTF
6	1	F	PRESSURE TRANSDUCER	CERAMIC; SS316 HOUSING		THREADED		1/4" BSPP
7	1	G	RTD-PT100-3m RTD WITH PT100 OUTPUT	SS316		THREADED		1/4" BSPT
8	1	H	1/2" SCH80s CLASS 300 SLIP ON FLANGE	ASTM A182 F316L	22.4mm	WELDED	TIG	
9	1	I	3" SCH10s PIPE	ASTM A182 F316L	4"	WELDED	TIG	
10	24	J	1/2" HOLES		1/2"	DRILLED		
11	1	K	5 3/4" SHEET CONTAINER (0.9mm THICKNESS)	SS316	6"			
12	1	L	0.9mm THICKNESS PLATE	SS316	5 3/4"	WELDED	TIG	
13	1	M	2 3/4" HOLE (CONNECTION FOR MESH)	SS316	2 3/4"	CUT		
14	1	N	3 1/2" BLIND PLATE (3mm THICKNESS)	SS316	3 1/2"	WELDED	TIG	
15	1	O	ACOUSTIC FOAM	FOAM		LINED		

**NOTE:** ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED. REMOVE ALL BURRS AND SHARP EDGES.

**FIRST ANGLE PROJECTION**

**PROJECT: INVESTIGATION INTO COMPRESSIBLE FLUID BEHAVIOUR IN A VENT PIPE DURING BLOWDOWN**

<b>DRAWN</b>	FARHAN RAJIWATE	<b>DATE</b>	25/1/2010
<b>CHECKED</b>		<b>DATE</b>	
<b>APPROVED</b>		<b>DATE</b>	
<b>APPROVED</b>		<b>DATE</b>	

**TITLE:** VENT PIPE INSTRUMENTATION AND FITTINGS ARRANGEMENT FOR TEST RIG

<b>SCALE</b>	1:2	<b>SHEET</b>	3	<b>OF</b>	3
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Figure B 7-2: Photographs of test rig

## **Appendix C**

### **8.1 Commissioning and Testing Report**

**Instruments Testing:**

**PT 100 RTD      Temperature Probe T1**

**Description:**

Location                      Start of the 12 m long test rig. Temperature corresponding to the second pressure transducer (P2).

**RTD testing temperature: Water bath**

Temperature of water bath:	37 - 37.8 °C	[Range]	
Corresponding temperature of RTD:	<b>37.85 - 37.9</b> °C	[Range]	
Temperature of Mercury thermometer bulb:	37 - 38.5 °C	[Range]	Accuracy of thermometer not known
Testing time of RTD	3 min		

Temperature of water bath:	53.0 - 53.5 °C	[Range]	
Corresponding temperature of RTD:	<b>53.2 53.6</b> °C	[Range]	
Temperature of Mercury thermometer bulb:	53.0-54.5 °C	[Range]	Accuracy of thermometer not known
Testing time of RTD	3 min		

**RTD testing temperature: ICE**

Temperature of ICE:	1.5 - 2.5 °C	[Range]	As measured by thermometer.
Corresponding temperature of RTD:	<b>1.90 - 1.92</b> °C	[Range]	Thermometer immersed very close to
Testing time of RTD	2 min	40 sec	

**PT 100 RTD      Temperature Probe T2**

**Description:**

Location                      End of the 12 m long test rig. Temperature corresponding to the second pressure transducer (P3).

**RTD testing temperature: Water bath**

Temperature of water bath:	37.0 - 37.8 °C	[Range]	
Corresponding temperature of RTD:	<b>36.8 - 37.3</b> °C	[Range]	
Temperature of Mercury thermometer bulb:	37 - 38.5 °C	[Range]	Accuracy of thermometer not known
Testing time of RTD	5 min		

Temperature of water bath:	53.0 - 53.5 °C	[Range]	
Corresponding temperature of RTD:	<b>53.2 - 53.7</b> °C	[Range]	
Temperature of Mercury thermometer bulb:	53.0-54.5 °C	[Range]	Accuracy of thermometer not known
Testing time of RTD	3 min		

**RTD testing temperature: ICE**

Temperature of ICE:	1.0 - 1.5 °C	[Range]	As measured by thermometer.
Corresponding temperature of RTD:	<b>1.2 - 1.3</b> °C	[Range]	Thermometer immersed very close to
Testing time of RTD	2 min	40 sec	

Thermometer immersed very close to RTD

**PT 100 RTD      Temperature Probe T3**

**Description:**

Location                      End of the 12 m long test rig on the pipe wall.  
Results not available in Labview. Testing was conducted on 12 August 2010.



**Start-Up Procedures:**

**Safety Check:**

- 1 Ensure that all personal protective equipment (PPE) is worn correctly. PPE: Safety shoes, safety glasses, ear muffs, leather gloves.
- 2 Ensure that all instruments are online and Labview Signal Processing is running.
- 3 Ensure that both ball valves are in open position.
- 4 Close the first ball valve [confirm tags on the rig] and pressurise the buffer to 2.5 bar gauge pressure. To achieve this, open the regulator on the hose connecting the gas bottle and the test rig completely (100%). Open the valve on G size gas bottle very slowly and simultaneously, keep watching the pressure on the digital gauge to achieve 2.5 bar gauge pressure.
- 5 Once a pressure of 2.5 bar is achieved, close the valve on the G size cylinder and check for any leaks. If any leaks are detected on the buffer (especially joints) notify the area technician. Do not proceed further if leak is present.
- 6 Open the first ball valve and blowdown the gas. At the same time check the signal processing screen for instrument values.

**Testing:**

- 1 Once the safety check is performed proceed with the testing at different pressures.
- 2 Ensure that both ball valves are in open position.
- 3 Enter the desired value of pressure on the 'calibration' sheet and look for the corresponding calculated value of the current in mA. For eg: for 200 kPaG the corresponding value of current is 5.6 mA.
- 4 Ensure that the regulator connecting the G size bottle and the test rig is fully open. Open the valve on the G size gas cylinder very slowly and simultaneously keep watching the current (mA) setpoint of the second pressure transducer. Remember the aim is to achieve the current (mA). For eg. to achieve 200 kPaG, the current of 5.6 mA must be achieved.
- 5 Try to maintain the current setpoint (eg: 5.6 mA) by controlling the G size bottle valve to achieve a steady state.
- 6 Monitor the signal processing screen continuously. The test data will be logged automatically in the signal processing software.
- 7 Perform the run until a steady state is reached. (Until temperatures are stabilised at the front and end of the pipe)

**Test 1:**

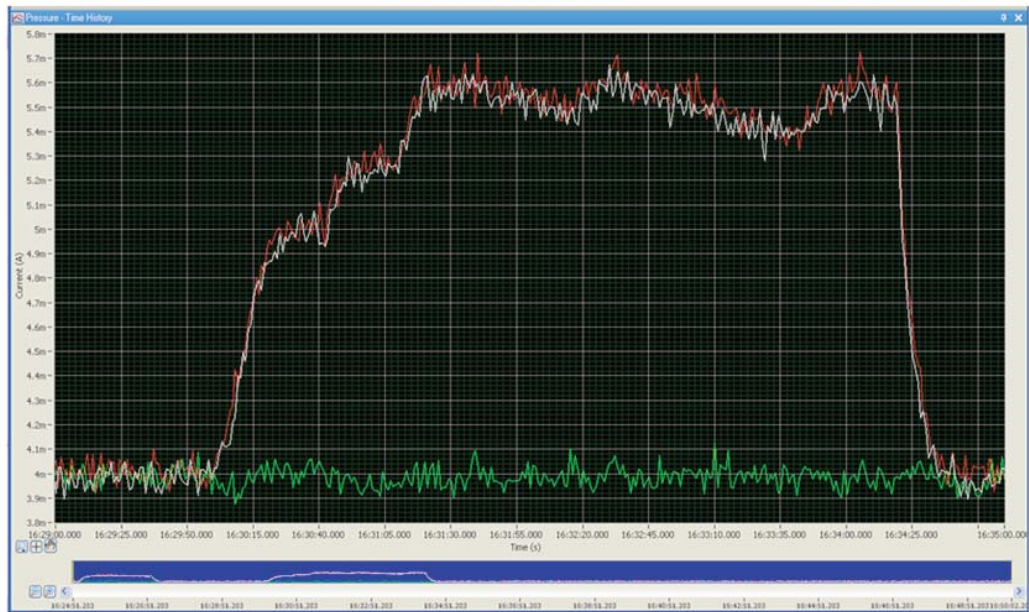
Pressure to achieve	200 kPaG		
Test Pressure	150 - 225 kPaG	[Range]	
Time for testing	6 min	0 sec	

**Pressure- Time History (Test-1)**

White: Pressure (P1)

Red: Pressure Transducer (P2)

Green: Pressure Transducer (P3)



The above trend was recorded for a time period of 6 min. The valve on the G size cylinder was opened at 16:29:50 hr which can be seen from the rising trend and reached the desired value of 5.6 mA. The increment was in series of steps until it reached the desired value. The pressure was maintained at 200 kpag (5.6 mA) by controlling the regulator and not the valve on the G size cylinder. The temperatures for the time period were recorded and are shown in fig 2.

**Temperature - Time History (Test -1)**

White: Temperature (T1) corresponding to P2    Red: Temp of gas (T2) at end of pipe    Green: Temp of pipe wall



The gas was supplied for a period of 6 min. After sometime (pass 3-4 min from the start-up), Joule-Thomson cooling started to take place at the regulator followed by isentropic cooling inside the gas bottle. The freezing of the regulator was visible and the gas bottle has started to cool. The decrease in temperature could be sensed by touching the top end (outlet end) and the bottom end of the bottle with hands. At this point, I closed the valve on the gas bottle.

As can be seen from the trend, the temperature drop at the end of the pipe and the pipe wall was not quick (reason for this I am not sure of) whereas the temperature at the start of the rig (T1) was decreasing quickly. This was obvious because JT cooling effect has started to take place.

I checked the connections for the RTD's at the end of the pipe. The connections were fine. However, out of curiosity I disconnected both the RTD's and re-did the connection. This time I put the RTD on the pipe wall to offline mode and only RTD at the end of the pipe to online mode. Also, I opened the regulator connecting the G size cylinder and the rig to 100%. The flow capacity coming out of the regulator is 500 cub. m/hr as mentioned by Andrew Arkosi (BOC representative). The test was conducted again at 200 kpag pressure. Similar operating procedures were used except that the regulator connecting the gas bottle and the test rig was 100% open.



**Test 2:**

Pressure to achieve 200 kPaG  
Test Pressure 150 - 225 kPaG [Range]  
Time for testing 6 min 40 sec

**Pressure - Time History (Test -2)**

White: Pressure Transducer (P1) Red: Pressure Transducer (P2) Green: Pressure Transducer (P3)



The pressure time trend was recorded for a period of 6 min and 40 sec. The regulator connecting the G size gas bottle and the test rig was fully open (100%) and the flow to the rig was controlled by the valve on the G size gas bottle. The pressure was in the range 150 - 225 kpag with the few hiccups while controlling the pressure. The corresponding temperature trend is plotted for the same time period and is shown in fig 4. Referring to the temperature trends, the temperature of the gas at the end of the pipe has started to drop at 0.48°C/min and the temperature at the start of the test rig was dropping at 1.5°C/min. Comparing the temperatures of gas at the start of the pipe with the previous test 1 results, the current rate of temperature drop has decreased by 0.9°C/min whereas the rate of temperature of the gas at the end of the pipe has decreased by 0.12°C/min.

**Problems Encountered during the process:**

- Flowmeter error: Short circuit output 1.
- Error while controlling the inlet pressure
- Experiment could not be complete due to emptying of gas bottle

**Current focus / Precautions:**

- Flowmeter error to be eliminated
- Monitor the inlet pressure closely so that steady state can be achieved
- Recheck the RTD's at the end of the pipe
- Provision for a standby gas bottle
- Flow to be controlled by gas bottle valve or regulator to be decided?

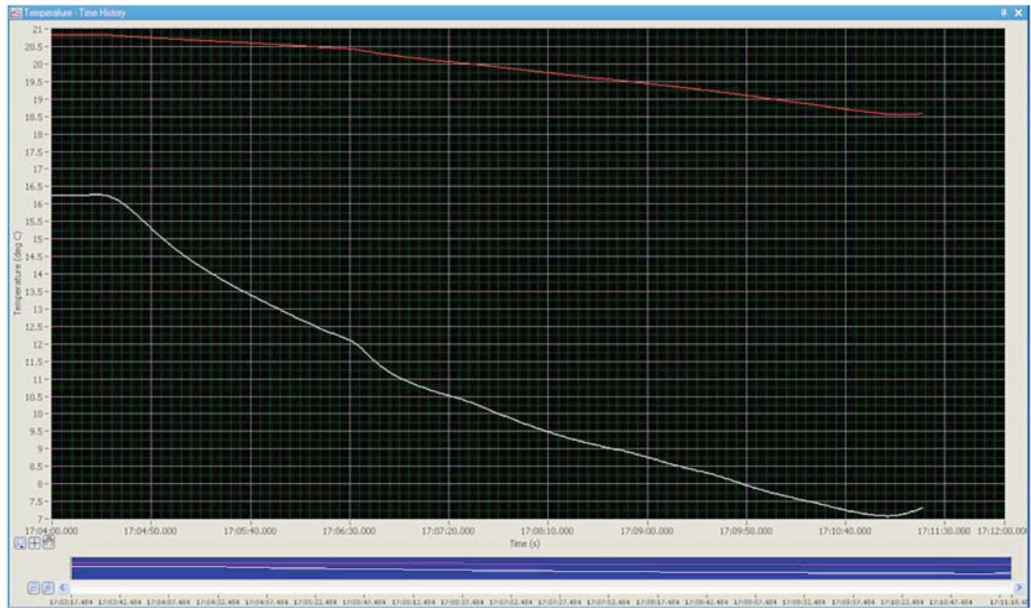
**Farhan:**  
Dennis Kirk-Burnand to recommend

**Conclusion**

At this stage, it is hard to conclude any of these results and would require more steady state runs to establish a proper set of readings.



**Temperature - Time History (Test 2) :**



## **Appendix D**

### **9.1 Visual Basic Program for Noise Reduction**

## 9.2 General Program for Eliminating Standard Deviation in Pressure, Flowrate and Temperature

```
Public Function NewmAVAR(mAVAR, ExpectedValue, N) As Double
Dim SQmAVAR, SQstddev, stddev, stddevAvg As Double
'Computing square of the mean (measured value - mA current)
SQmAVAR = WorksheetFunction.Power(mAVAR, 2)
SQstddev = SQmAVAR - WorksheetFunction.Power(ExpectedValue, 2)
'Computing Standard deviation as the noise
If SQstddev < 0 Then
    SQstddev = SQstddev * -1
    'Calculating standard deviation of a single sample
    stddev = WorksheetFunction.Power(SQstddev, 0.5)
    'Calculating the average standard deviation over a N samples
    stddevAvg = stddev / WorksheetFunction.Power(N, 0.5)
Else
    stddev = WorksheetFunction.Power(SQstddev, 0.5)
    stddevAvg = stddev / WorksheetFunction.Power(N, 0.5)
End If
If mAVAR < 4 Then
    NewmAVAR = mAVAR + stddevAvg
Else
    NewmAVAR = mAVAR - stddevAvg
End If
End Function
```

```

Public Sub NewVAR()

Dim ws, ws1 As String

Dim rangemAVAR1, rangeClear As Range

Dim AP1, mAP1, count As Variant

Dim missing As Variant

Sheet2.Activate

ws = Worksheets.Application.ActiveSheet.Name

ws1 = "VAR to Current conversion"

Set rangemAVAR1 = Worksheets(ws).Range(Range("StartmAVAR1"),
Range("StartmAVAR1").End(xlDown))

Set rangeClear = Worksheets(ws).Range("startp1clear:endp1clear")

rangeClear.ClearContents

missing = ""

count = 0

Application.StatusBar = "Converting Start-up Amp to mA"

For Each AP1 In rangemAVAR1

    If AP1.Offset(0, -8).Value > 0 Then

        AP1.Value = AP1.Offset(0, -8).Value * 1000

        AP1.Offset(0, 1).Value = AP1.Offset(0, -7).Value * 1000

        AP1.Offset(0, 2).Value = AP1.Offset(0, -6).Value * 1000

    Else

        AP1.Value = missing

        AP1.Offset(0, 1).Value = missing

        AP1.Offset(0, 2).Value = missing

    End If

Next AP1

```

```

Application.StatusBar = "Amp to mA conversion complete"

Application.StatusBar = "Progressing with Standard Deviation Calculations"

'Performing check if values present

For Each mAP1 In rangemAVAR1

    If mAP1.Offset(0, -8).Value = missing Then

        Application.StatusBar = "Zero value encountered @" & count

        Exit For

    Else

        'VAR 1

        mAP1.Offset(0,3).Value=NewmAVAR(mAP1.Value,Range("ExpectedValue").Value,
        Range("NumberofSamples").Value)

        mAP1.Offset(0,4).Value=NewmAVAR(mAP1.Offset(0,1).Value,Range("ExpectedValue").
        Value, Range("NumberofSamples").Value)

        mAP1.Offset(0,5).Value=NewmAVAR(mAP1.Offset(0,2).Value,Range("ExpectedValue").
        Value, Range("NumberofSamples").Value)

        mAP1.Offset(0,6).Value=NewmAVAR(mAP1.Offset(0,3).Value,Range("ExpectedValue").
        Value, Range("NumberofSamples").Value)

        mAP1.Offset(0,7).Value=NewmAVAR(mAP1.Offset(0,4).Value,Range("ExpectedValue").
        Value, Range("NumberofSamples").Value)

        mAP1.Offset(0,8).Value=NewmAVAR(mAP1.Offset(0,5).Value,Range("ExpectedValue").
        Value, Range("NumberofSamples").Value)

    End If

    count = count + 1

    Application.StatusBar = "Reducing the mA data point to low Standard Deviation. Currently
    at " & count

Next mAP1

Application.StatusBar = "All mA data points reduced to low Standard Deviation"

End Sub

```

### 9.3 General Program for Performing Moving Average on Pressure, Flowrate and Temperature measurements

```
Public Sub CalculateMovingAverage()
```

```
Application.Calculation = xlCalculationManual
```

```
Dim ws As String
```

```
Dim MAve, DInterval, a, b, c, d, e, f, count As Variant
```

```
Dim rangeMAveCurrent1, rangeMAveCurrent2, rangeMAveCurrent3, rangeMAverage1,  
rangeMAverage2, rangeMAverage3 As Range
```

```
ws = "VAR Noise Reduction"
```

```
DInterval = Worksheets(ws).Range("Interval").Value
```

```
Set
```

```
rangeMAveCurrent1=Worksheets(ws).Range("StartMovingAverage:EndMovingAverage")
```

```
Set
```

```
rangeMAveCurrent2=Worksheets(ws).Range("StartMovingAverage:EndMovingAverage").  
Offset(0, 1)
```

```
Set
```

```
rangeMAveCurrent3 =  
Worksheets(ws).Range("StartMovingAverage:EndMovingAverage").Offset(0, 2)
```

```
rangeMAveCurrent1.ClearContents
```

```
rangeMAveCurrent2.ClearContents
```

```
rangeMAveCurrent3.ClearContents
```

```
count = 0
```

```
For Each MAve In rangeMAveCurrent1
```

```
  If MAve.Offset(DInterval - 1, -7).Value > 0 Then
```

```
    'current 1
```

```
    a = MAve.Offset(0, -4).Address
```

```
    b = MAve.Offset(DInterval - 1, -4).Address
```

```
    'current 2
```

```
    c = MAve.Offset(0, -3).Address
```

```
    d = MAve.Offset(DInterval - 1, -3).Address
```

```
    'current 3
```

```
    e = MAve.Offset(0, -2).Address
```

```
    f = MAve.Offset(DInterval - 1, -2).Address
```

```

Set rangeMAverage1 = Worksheets(ws).Range(a, Worksheets(ws).Range(b))
Set rangeMAverage2 = Worksheets(ws).Range(c, Worksheets(ws).Range(d))
Set rangeMAverage3 = Worksheets(ws).Range(e, Worksheets(ws).Range(f))

'Starting from the top
MAve.Value = Application.WorksheetFunction.Average(rangeMAverage1)
'Starting after the interval point
MAve.Offset(DInterval-1,0).Value =
Application.WorksheetFunction.Average(rangeMAverage1)
MAve.Offset(DInterval - 1, 1).Value =
Application.WorksheetFunction.Average(rangeMAverage2)
MAve.Offset(DInterval - 1, 2).Value =
Application.WorksheetFunction.Average(rangeMAverage3)

count = count + 1
Application.StatusBar = "Performing Noise Reduction. Currently at " & count

Else
    Application.StatusBar = "VAR Noise Reduction Calculation Complete"
    Application.Calculation = xlCalculationAutomatic
    Exit Sub
    End If

    Next MAve

Application.StatusBar = "VAR Noise Reduction Calculation Complete"
Application.Calculation = xlCalculationAutomatic

MsgBox "VAR Noise Reduction Calculation Complete"

End Sub

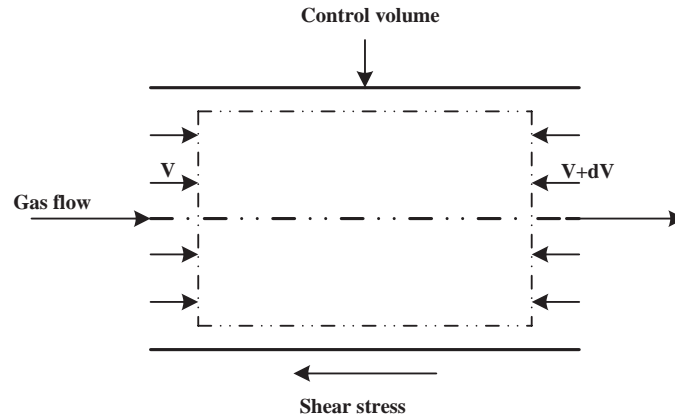
```

## **Appendix E**

### **10.1 Adiabatic frictional flow derivation**



Consider a steady one dimensional flow of a real gas with constant specific heats across a control surface, as shown in the figure below,



Above figure adapted from (Saad 1993)

Momentum equation is expressed as

$$Ap - A(p + dp) - \tau_w.P.dx = \rho Av(v + dv - v)$$

$$Ap - Ap - Adp - \tau_w.P.dx = \rho Avdv$$

$$Adp + \tau_w.P.dx + \rho Avdv = 0$$

Now, the friction factor is related to the shear stress in the flow direction in the following way:

$$f = \frac{\tau_w}{\frac{1}{2}\rho v^2} \quad \text{Where } f : \text{Friction factor; } \tau_w : \text{Shear stress; } P : \text{Wetted perimeter}$$

The wetted perimeter of the duct  $P$  in terms of hydraulic diameter is given as:

$$P = \frac{4A}{D_H} \quad \text{Where } D_H = \text{hydraulic diameter}$$

For circular ducts  $D_H=D$ , diameter of circular duct

$$\therefore Adp + \frac{f\rho v^2}{2} \cdot \frac{4A}{D} dx + \frac{\rho Av^2}{v^2} \frac{dv^2}{2} = 0$$

$$\therefore dp + \frac{4f\rho v^2}{D \times 2} dx + \frac{\rho v^2}{2} \frac{dv^2}{v^2} = 0 \dots \dots \dots 1$$

Other equations necessary for the solution

$$\text{Real Gas Equation} \quad P = Z\rho RT \quad 2$$

$$\text{Continuity Equation} \quad m = \rho v A = \text{Constant} \quad 3$$

$$\text{Energy Equation:} \quad \Delta H = -v^2/2 \quad 4$$

$$\text{Mach number} \quad M^2 = v^2/z\gamma RT \quad 5$$

$$\text{Second law of thermodynamics} \quad ds \geq 0 \quad 6$$

Dividing equation 1 by  $p$

$$\therefore \frac{dp}{p} + \frac{4f\rho v^2}{D \cdot 2p} dx + \frac{\rho v^2}{2p} \frac{dv^2}{v^2} = 0$$

Now,

$$\begin{aligned} \rho v^2 &= \rho \frac{v^2}{z\gamma RT} \times z\gamma RT \\ &= \rho M^2 \times z\gamma RT \\ &= \gamma M^2 \times \rho RT \\ &= \gamma M^2 P \end{aligned}$$

Therefore, above equation becomes

$$\therefore \frac{dp}{p} + \frac{4f\gamma M^2}{2D} dx + \frac{\gamma M^2}{2} \frac{dv^2}{v^2} = 0 \quad 7$$

From equation 4

$$\Delta H = -\frac{v^2}{2}$$

$$\therefore H + \frac{v^2}{2} = \text{Constant}$$

$$\therefore dh + \frac{2v dv}{2} = 0$$

$$\therefore dh + v dv = 0$$

$$\therefore dh = -v dv$$

$$\therefore Cp.dT = \frac{-dv^2}{2}$$

Dividing above equation by  $Cp.T$

$$\therefore \frac{dT}{T} = -\frac{dv^2}{2CpT}$$

$$\text{Now, } Cp = \frac{\gamma R}{\gamma - 1} (T_{REQ} \frac{dz}{dT} + z_{REQ}) \quad \& \quad M^2 = \frac{v^2}{z\gamma RT}$$

The term  $(T_{REQ} \frac{dz}{dT_{REQ}})$  is small and hence can be neglected.

$$\therefore \frac{dT}{T} = -\frac{dv^2}{2\left(\frac{\gamma R}{\gamma - 1}\right)zT}$$

$$\therefore \frac{dT}{T} = -\left(\frac{\gamma - 1}{2}\right) \frac{dv^2}{z\gamma RT}$$

$$\therefore \frac{dT}{T} = -\left(\frac{\gamma - 1}{2}\right) \frac{dv^2}{v^2 / M^2}$$

$$\therefore \frac{dT}{T} = -\left(\frac{\gamma - 1}{2}\right) M^2 \frac{dv^2}{v^2}$$

9

From equation 5, we have

$$M^2 = \frac{v^2}{z\gamma RT}$$

$\therefore$  Taking  $\ell n$  on both sides

$$\therefore \ln M^2 = \ln v^2 - \ln T - \ln z$$

$$\therefore \frac{dM^2}{M^2} = \frac{dv^2}{v^2} - \frac{dT}{T} - \frac{dz}{z}$$

$$\frac{dT}{T} = \frac{dv^2}{v^2} - \frac{dM^2}{M^2} - \frac{dz}{z}$$

10

From equations 8 & 9, we get

$$\frac{dv^2}{v^2} - \frac{dM^2}{M^2} = -\frac{(\gamma-1)}{2} M^2 \frac{dv^2}{v^2}$$

$$\therefore \frac{dv^2}{v^2} \left[ 1 + \left( \frac{\gamma-1}{2} \right) M^2 \right] = \frac{dM^2}{M^2}$$

$$\therefore \frac{dv^2}{v^2} = \frac{1}{1 + \left( \frac{\gamma-1}{2} \right) M^2} \left( \frac{dM^2}{M^2} \right) \dots\dots\dots 10$$

From equation 2 & 3

$$\frac{dp}{p} = \frac{d\rho}{\rho} + \frac{dT}{T} + \frac{dz}{z}$$

$$\& \frac{d\rho}{\rho} = -\frac{dv}{v}$$

$$\therefore \frac{dp}{p} = -\frac{dv}{v} + \frac{dT}{T} + \frac{dz}{z}$$

$$\therefore \frac{dp}{p} = \frac{dv^2}{v^2} \left[ -\frac{1}{2} - \frac{\gamma-1}{2} M^2 \right]$$

11

Substitute equation 11 in equation 7

$$\frac{dv^2}{v^2} \left[ -\frac{1}{2} - \frac{\gamma-1}{2} M^2 \right] + \frac{4f\gamma M^2}{2D} dx + \frac{\gamma M^2}{2} \frac{dv^2}{v^2} = 0$$

$$\therefore \frac{dv^2}{v^2} \left[ -\frac{1}{2} - \frac{\gamma-1}{2} M^2 + \frac{\gamma M^2}{2} \right] + \frac{4f\gamma M^2}{2D} dx = 0$$

$$\therefore \frac{dv^2}{v^2}(1-M^2) = \frac{4f\gamma M^2}{D} dx \quad 12$$

$$\therefore \frac{4f\gamma M^2}{D} dx = \left[ \frac{1}{1 + \left(\frac{\gamma-1}{2}\right)M^2} \frac{dM^2}{M^2} \right] (1-M^2)$$

$$\therefore \frac{4f}{D} dx = \left[ \frac{1}{\left[1 + \left(\frac{\gamma-1}{2}\right)M^2\right] \gamma M^2} \right] (1-M^2) \frac{dM^2}{M^2}$$

$$\therefore \frac{4f}{D} dx = \frac{2(1-M^2)}{\gamma M^2 \left[1 + \left(\frac{\gamma-1}{2}\right)M^2\right]} \frac{dM}{M} \quad 13$$

From equation 10

$$\frac{dv^2}{v^2} = \frac{1}{1 + \left(\frac{\gamma-1}{2}\right)M^2} \frac{dM^2}{M^2}$$

$$\therefore \frac{dv}{v} = \frac{1}{1 + \left(\frac{\gamma-1}{2}\right)M^2} \frac{dM}{M} \quad 14$$

Now,

$$\therefore \frac{dv}{v} = -\frac{d\rho}{\rho} = \frac{1}{1 + \left(\frac{\gamma-1}{2}\right)M^2} \frac{dM}{M} \quad 15$$

From equation 11

$$\begin{aligned} \frac{dp}{p} &= \frac{dv^2}{v^2} \left[ -\frac{1}{2} - \frac{\gamma-1}{2} M^2 \right] \\ &= \frac{2dv}{v} \left[ -\frac{1}{2} - \frac{\gamma-1}{2} M^2 \right] \end{aligned}$$

$$\therefore \frac{dp}{p} = \frac{dv^2}{v^2} [-1 - (\gamma - 1)M^2]$$

$$\therefore \frac{dp}{p} = \left[ \frac{1}{1 + \left(\frac{\gamma - 1}{2}\right)M^2} \right] \frac{dM}{M} [-1 - (\gamma - 1)M^2]$$

$$\therefore \frac{dp}{p} = \left[ \frac{-1 - (\gamma - 1)M^2}{1 + \left(\frac{\gamma - 1}{2}\right)M^2} \right] \frac{dM}{M}$$

16

From equation 8

$$\begin{aligned} \frac{dT}{T} &= -\left(\frac{\gamma - 1}{2}\right)M^2 \frac{dv^2}{v^2} \\ &= -\left(\frac{\gamma - 1}{2}\right)M^2 \frac{2dv}{v} \end{aligned}$$

$$= -\left[ \frac{(\gamma - 1)M^2}{1 + \left(\frac{\gamma - 1}{2}\right)M^2} \right] \frac{dM}{M}$$

$$\therefore \frac{dT}{T} = -\left[ \frac{(\gamma - 1)M}{1 + \left(\frac{\gamma - 1}{2}\right)M^2} \right] dM$$

17

Properties of a fluid at any section of a vent pipe may be related to properties at any other section. Equation 13 represents the changes in Mach number with displacement along the vent pipe. By integrating equation 13 within the limits  $M=M_1$  to  $M=M_2$  and  $x=0$  to  $x=L$  (Maximum vent pipe length at which Mach number is unity)

$$\int_0^L \frac{4f}{D} dx = \int_{M_1}^{M_2} \frac{2}{\gamma M^2} \frac{(1 - M^2)}{1 + \left(\frac{\gamma - 1}{2}\right)M^2} \frac{dM}{M}$$

$$= \int_{M_1}^{M_2} \frac{1}{\gamma M^4} \frac{(1-M^2)}{1 + \left(\frac{\gamma-1}{2}\right)M^2} dM^2$$

The solution of the above equation can be obtained by method of partial fractions which results in

$$\left(\frac{4fL}{D}\right) = \frac{1}{\gamma} \left( \frac{1}{M_1^2} - \frac{1}{M_2^2} \right) + \left[ \left( \frac{\gamma+1}{2\gamma} \right) \ln \left( \frac{1 + \left(\frac{\gamma-1}{2}\right)M_2^2}{1 + \left(\frac{\gamma-1}{2}\right)M_1^2} \right) \right] \quad 18$$

Friction is the chief parameter which causes the properties of any flow, whether subsonic or supersonic to approach these Mach unity characteristics. Hence,  $M_1=M$ ;  $M_2=1$  and  $L=L^*$

$$\left(\frac{4fL^*}{D}\right) = \left( \frac{1-M^2}{\gamma M^2} \right) + \left[ \left( \frac{\gamma+1}{2\gamma} \right) \ln \left( \frac{(\gamma+1)M^2}{2 \left( 1 + \left(\frac{\gamma-1}{2}\right)M^2 \right)} \right) \right] \quad 19$$

## **Appendix F**

### **11.1 Vent Pipe Model Simulations Results for Air, Carbon Dioxide, Methane and DBNGP Gas Mixture**



Gas Property Calculation for Air @ 100 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>	<b>Argon:0.0092;Oxygen:0.2096;Nitrogen:0.7812;</b>										
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 1008.07	1007.94	1007.81	1007.66	1007.51	1007.35	1007.19	1007.00	1006.80	1006.57	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 718.06	718.04	718.02	717.99	717.96	717.93	717.90	717.86	717.82	717.77	
Ratio of specific heats, $\gamma$	1.4039	1.4037	1.4036	1.4035	1.4033	1.4031	1.4030	1.4028	1.4026	1.4024	
Molecular weight, $M.W.$	$kg/mole$ 28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	
Gas constant, $R$	$J/kg \cdot K$ 287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	
<b>Standard condition</b>	<b>Standard condition</b>										
Inlet pressure, $P_{in}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{in}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	
Normal or standard flow	$m^3/hr$ 204.7552	204.7552	204.7552	204.7552	204.7552	204.7552	204.7552	204.7552	204.7552	204.7552	
Phase flow	Single	Single	Single	Single	Single	Single	Single	Single	Single	Single	
Actual inlet flow condition	$kg/hr$ 6.27	6.52	6.79	7.10	7.46	7.89	8.39	9.02	9.81	10.86	
Standard flow condition	$m^3/hr$ 12.29	12.29	12.29	12.29	12.29	12.29	12.29	12.29	12.29	12.29	
<b>Stagnation Properties</b>	<b>Stagnation Properties</b>										
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.86	292.85	292.84	292.82	292.80	292.78	292.79	292.74	292.72	292.69	
Inlet Stagnation Pressure	$KPa abs$ 203.04	195.02	187.61	179.15	170.85	161.81	152.21	141.96	130.79	118.59	
Outlet Stagnation Pressure	$KPa abs$ 195.02	187.61	179.15	170.85	161.81	152.21	141.96	130.79	118.59	107.75	
Stagnation Density, $\rho_0$	$kg/m^3$ 2.42	2.32	2.23	2.13	2.03	1.93	1.81	1.69	1.56	1.41	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 292.88	292.89	292.90	292.90	292.90	292.90	292.93	292.91	292.91	292.91	
<b>Upstream Condition</b>	<b>Upstream Condition</b>										
Inlet pressure, $P_1$	$KPa g$ 100.00	92.25	84.49	76.13	67.55	58.38	48.67	38.18	26.81	14.27	
Inlet temperature, $T_1$	$^{\circ}C$ 201.33	193.58	185.82	177.46	168.88	159.71	149.99	139.51	128.13	115.59	
Compressibility, $Z_1$	0.9995	0.9993	0.9991	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995	0.9996	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	
Density, $\rho_1$	$kg/m^3$ 2.4018	2.3098	2.2178	2.1187	2.0169	1.9083	1.7930	1.6690	1.5344	1.3861	
Velocity, $V_1$	$m/sec$ 37.7753	39.2798	40.9104	42.8241	44.9843	47.5458	50.6020	54.3612	59.1308	65.4548	
Mach number at the inlet, $M_1$	0.1101	0.1147	0.1193	0.1251	0.1313	0.1388	0.1478	0.1587	0.1728	0.1913	
Reynolds number, $Re$	3.816E+04	3.817E+04	3.818E+04	3.819E+04	3.820E+04	3.822E+04	3.824E+04	3.827E+04	3.830E+04	3.833E+04	
Friction factor, $f$	0.02718800	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	
Recovery factor, $r$	0.72144162	0.7214	0.7213	0.7213	0.7212	0.7212	0.7211	0.7211	0.7210	0.7210	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.51	19.49	19.46	19.41	19.37	19.32	19.28	19.18	19.08	18.95	
Enthalpy, $h$	$KJ/kg$ 292.17	292.12	292.06	291.98	291.89	291.78	291.65	291.43	291.17	289.78	
Entropy, $s$	$KJ/kg \cdot K$ 6.64203303	6.6531	6.6647	6.6776	6.6915	6.7071	6.7247	6.7448	6.7683	6.7965	
<b>Downstream Condition</b>	<b>Downstream Condition</b>										
Mach number at the outlet, $M_2$	0.1147	0.1193	0.1251	0.1313	0.1388	0.1478	0.1587	0.1728	0.1913	0.2180	
Absolute outlet pressure, $P_2$	$KPa g$ 193.58	185.82	177.46	168.88	159.71	149.99	139.51	128.13	115.59	101.33	
Outlet pressure (gauge)	$KPa g$ 92.253	84.491	76.132	67.551	58.383	48.668	38.183	26.806	14.266	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.94	18.86	18.76	18.65	18.51	18.37	18.12	17.83	17.41	16.76	
Compressibility, $Z_2$	0.9993	0.9993	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995	0.9996	0.9996	
Density, $\rho_2$	$kg/m^3$ 2.3098	2.2178	2.1187	2.0169	1.9083	1.7930	1.6690	1.5344	1.3861	1.2178	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.81E-05	
Actual outlet flow	$m^3/hr$ 6.5166	6.7871	7.1046	7.4630	7.8879	8.3949	9.0186	9.8099	10.8590	12.3604	
Velocity, $V_2$	$m/sec$ 39.2798	40.9104	42.8241	44.9843	47.5458	50.6020	54.3612	59.1308	65.4548	74.5043	
Reynolds number, $Re$	3.817E+04	3.818E+04	3.819E+04	3.820E+04	3.822E+04	3.824E+04	3.827E+04	3.830E+04	3.833E+04	3.842E+04	
Friction factor, $f$	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	0.0272	
Recovery factor, $r$	0.7214	0.7213	0.7213	0.7212	0.7212	0.7211	0.7211	0.7210	0.7210	0.7210	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.4932	19.4678	19.4296	19.3839	19.3341	19.2802	19.2162	19.0996	18.9660	18.7654	
Enthalpy, $h$	$KJ/kg$ 292.1247	292.0636	291.9826	291.8919	291.7759	291.6549	291.4342	291.1660	290.7783	290.1505	
Entropy, $s$	$KJ/kg \cdot K$ 6.6531	6.6647	6.6776	6.6915	6.7071	6.7247	6.7448	6.7683	6.7965	6.8321	
<b>Critical Properties at Outlet Mach 1</b>	<b>Critical Properties at Outlet Mach 1</b>										
Critical Pressure	$KPa g$ -81.08	-81.08	-81.08	-81.08	-81.08	-81.08	-81.08	-81.08	-81.08	-81.08	
Critical Temperature	$^{\circ}C$ 20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	
Max length of duct at which no shock occurs	$m$ 243.66	243.66	243.66	243.66	243.66	243.66	243.66	243.66	243.66	243.66	
<b>Drop</b>	<b>Drop</b>										
Pressure drop / Segment Length	$KPa$ 7.75	7.76	8.36	8.58	9.17	9.71	10.48	11.38	12.54	14.27	
Temperature drop / Segment Length	$^{\circ}C$ 0.06	0.08	0.10	0.11	0.14	0.14	0.24	0.29	0.42	0.66	
Total pressure drop	$KPa$ 100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
Total temperature drop	$^{\circ}C$ 2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	

Figure F 11-1: Vent pipe model predictions for air gas at 100 KPa gauge

Gas Property Calculation for Air @ 200 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>	<b>Argon:0.0092;Oxygen:0.2096;Nitrogen:0.7812;</b>										
Specific heat at constant pressure, cp:	J/kg.K 1009.78	1009.55	1009.31	1009.06	1008.79	1008.49	1008.17	1007.82	1007.41	1006.90	
Specific heat at constant volume, cv:	J/kg.K 718.33	718.29	718.24	718.20	718.15	718.10	718.04	717.96	717.88	717.75	
Ratio of specific heats, γ:	1.4057	1.4055	1.4052	1.4050	1.4047	1.4044	1.4041	1.4038	1.4033	1.4029	
Molecular weight, M.W:	kg/mole 28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	
Gas constant, R:	J/kg.K 287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	
<b>Standard condition</b>	<b>Standard condition</b>										
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	
Normal or standard flow:	m <sup>3</sup> /hr 20.3759	20.3759	20.3759	20.3759	20.3759	20.3759	20.3759	20.3759	20.3759	20.3759	
lines/min:	339.5988	339.5988	339.5988	339.5988	339.5988	339.5988	339.5988	339.5988	339.5988	339.5988	
<b>Phase flow</b>	<b>Single</b>										
Actual inlet flow condition:	kg/hr 24.97										
m <sup>3</sup> /hr:	6.94	7.26	7.63	8.07	8.58	9.22	10.02	11.09	12.61	15.05	
Standard flow condition:	m <sup>3</sup> /hr 20.38	20.38	20.38	20.38	20.38	20.38	20.38	20.38	20.38	20.38	
<b>Stagnation Properties</b>	<b>Stagnation Properties</b>										
Stagnation Temperature, T <sub>0</sub> :	°C 293.02	293.02	292.98	292.96	292.92	292.89	292.89	292.81	292.77	292.71	
Inlet Stagnation Pressure:	Kpa abs 304.49	291.18	277.24	262.87	247.47	230.72	212.74	192.90	170.69	144.49	
Outlet Stagnation Pressure:	Kpa abs 291.18	277.24	262.87	247.47	230.72	212.74	192.90	170.69	144.49	110.90	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 3.62	3.46	3.30	3.13	2.94	2.75	2.53	2.30	2.03	1.72	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 292.80	292.83	292.83	292.83	292.84	292.84	292.88	292.85	292.86	292.87	
<b>Upstream Condition</b>	<b>Upstream Condition</b>										
Inlet pressure, P <sub>1</sub> :	Kpa g 200.00	186.60	172.51	157.76	142.02	125.03	106.75	86.37	63.40	36.08	
Kpa abs:	301.33	287.92	273.84	259.08	243.35	226.38	208.08	187.70	164.73	137.40	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9161	18.7855	18.6340	18.4473	18.2064	17.9278	17.4407	16.7491	15.4787	
Compressibility, Z <sub>1</sub> :	0.9989	0.9990	0.9990	0.9991	0.9991	0.9992	0.9992	0.9992	0.9994	0.9995	
Viscosity, μ <sub>1</sub> :	Pa.sec 1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.80E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 3.5961	3.4370	3.2702	3.0954	2.9091	2.7083	2.4916	2.2512	1.9803	1.6389	
Velocity, V <sub>1</sub> :	m/sec 41.8457	43.7832	46.0163	48.6139	51.7276	55.5624	60.3943	66.8441	75.9898	90.7104	
Mach number at the inlet, M <sub>1</sub> :	0.1219	0.1276	0.1342	0.1417	0.1507	0.1620	0.1762	0.1951	0.2220	0.2656	
4fL <sub>1</sub> /D:	43.8352	39.7622	35.6917	31.6239	27.5586	23.4961	19.4362	15.3792	11.3250	7.2740	
Reynolds number, Re:	6.323E+04	6.323E+04	6.328E+04	6.332E+04	6.336E+04	6.341E+04	6.347E+04	6.356E+04	6.369E+04	6.393E+04	
Friction factor, 4f:	0.02584669	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	
Recovery factor, r:	0.7221023	0.7221	0.7220	0.7219	0.7218	0.7218	0.7217	0.7216	0.7215	0.7214	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.63	19.60	19.54	19.48	19.40	19.31	19.23	19.04	18.82	18.43	
Enthalpy, h:	KJ/kg 291.93	291.88	291.78	291.66	291.51	291.31	291.07	290.63	289.99	288.78	
Entropy, s:	KJ/kg.K 6.52553120	6.5384	6.5524	6.5679	6.5854	6.6054	6.6288	6.6569	6.6921	6.7400	
<b>Downstream Condition</b>	<b>Downstream Condition</b>										
4fL <sub>2</sub> /D:	4.0491	4.0490	4.0488	4.0486	4.0484	4.0481	4.0478	4.0473	4.0466	4.0453	
Mach number at the outlet, M <sub>2</sub> :	0.1276	0.1342	0.1417	0.1507	0.1620	0.1762	0.1951	0.2220	0.2656	0.3580	
Absolute outlet pressure, P <sub>2</sub> :	Kpa g 287.92	273.84	259.08	243.35	226.38	208.08	187.70	164.73	137.40	101.33	
Outlet pressure (gauge):	Kpa g 186.396	172.514	157.759	142.020	125.050	106.752	86.372	63.401	36.076	0.001	
Outlet temperature, T <sub>2</sub> :	°C 18.92	18.79	18.63	18.45	18.21	17.93	17.44	16.75	15.48	12.16	
Compressibility, Z <sub>2</sub> :	0.9990	0.9990	0.9991	0.9991	0.9992	0.9992	0.9993	0.9994	0.9995	0.9996	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 3.4370	3.2702	3.0954	2.9091	2.7083	2.4916	2.2512	1.9803	1.6389	1.2374	
Viscosity of gas, μ <sub>2</sub> :	Pa.sec 1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.80E-05	1.79E-05	
Actual outlet flow:	m <sup>3</sup> /hr 7.2657	7.6342	8.0651	8.5817	9.2179	10.0195	11.0895	12.6088	15.0490	20.1746	
Velocity, V <sub>2</sub> :	m/sec 43.7832	46.0163	48.6139	51.7276	55.5624	60.3943	66.8441	75.9898	90.7104	121.6062	
Reynolds number, Re:	6.323E+04	6.328E+04	6.332E+04	6.336E+04	6.341E+04	6.347E+04	6.356E+04	6.369E+04	6.393E+04	6.433E+04	
Friction factor, 4f:	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	0.0258	
Recovery factor, r:	0.7221	0.7220	0.7219	0.7218	0.7218	0.7217	0.7216	0.7215	0.7214	0.7216	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.6028	19.5653	19.5007	19.4274	19.3374	19.2334	19.0974	18.8474	18.4629	17.5043	
Enthalpy, h:	KJ/kg 291.8774	291.7792	291.6616	291.5110	291.3087	291.0718	290.6301	289.9889	288.7761	285.5286	
Entropy, s:	KJ/kg.K 6.5384	6.5524	6.5679	6.5854	6.6054	6.6288	6.6569	6.6921	6.7400	6.8161	
<b>Critical Properties at Outlet Mach 1</b>	<b>Critical Properties at Outlet Mach 1</b>										
Critical Pressure:	Kpa g -67.81										
Kpa abs:	33.52										
Critical Temperature:	°C 29.54										
Max length of duct at which no shock occurs:	m 12.99										
<b>Drop</b>	<b>Drop</b>										
Pressure drop / Segment Length:	Kpa 13.40	14.08	14.75	15.74	16.97	18.30	20.38	22.97	27.33	36.08	
Temperature drop / Segment Length:	°C 0.08	0.13	0.15	0.19	0.24	0.28	0.49	0.69	1.27	3.32	
Total pressure drop:	Kpa 200.00										
Total temperature drop:	°C 6.56										

Figure F 11-2: Vent pipe model predictions for air gas at 200 KPa gauge

Gas Property Calculation for Air @ 300 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>	Argon:0.0092;Oxygen:0.2096;Nitrogen:0.7812;										
Specific heat at constant pressure, cp:	J/kg.K 1011.49	1011.18	1010.84	1010.48	1010.10	1009.69	1009.24	1008.73	1008.13	1007.36	
Specific heat at constant volume, cv:	J/kg.K 718.59	718.54	718.48	718.42	718.35	718.28	718.19	718.09	717.97	717.78	
Ratio of specific heats, γ:	1.4076	1.4073	1.4069	1.4065	1.4061	1.4057	1.4052	1.4047	1.4041	1.4034	
Molecular weight, M.W:	kg/mole 28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	
Gas constant, R:	J/kg.K 287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	
Normal or standard flow:	m <sup>3</sup> /hr 28.0591	28.0591	28.0591	28.0591	28.0591	28.0591	28.0591	28.0591	28.0591	28.0591	
lines/min:	467.6514	467.6514	467.6514	467.6514	467.6514	467.6514	467.6514	467.6514	467.6514	467.6514	
<b>Phase flow</b>	Single										
Actual inlet flow condition:	kg/hr 34.38										
m <sup>3</sup> /hr:	7.18	7.52	7.92	8.40	8.98	9.70	10.62	11.90	13.80	17.18	
Standard flow condition:	m <sup>3</sup> /hr 28.06	28.06	28.06	28.06	28.06	28.06	28.06	28.06	28.06	28.06	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C 293.07	293.08	293.05	292.99	292.94	292.90	292.89	292.78	292.72	292.65	
°R:	19.92	19.93	19.88	19.84	19.79	19.75	19.74	19.63	19.57	19.50	
Inlet Stagnation Pressure:	Kpa abs 405.82	387.79	368.54	347.77	325.97	302.75	276.99	248.53	215.84	176.25	
Outlet Stagnation Pressure:	Kpa abs 387.79	368.54	347.77	325.97	302.75	276.99	248.53	215.84	176.25	119.50	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 4.83	4.61	4.39	4.14	3.88	3.60	3.30	2.96	2.57	2.10	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 292.62	292.66	292.66	292.67	292.67	292.68	292.74	292.70	292.71	292.73	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g 300.00	281.49	261.84	240.91	218.68	194.81	168.66	139.27	105.42	63.65	
Kpa abs:	401.33	382.82	363.17	342.23	320.00	296.13	269.99	240.60	206.75	164.98	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9090	18.7561	18.5694	18.3421	18.0549	17.7090	17.0860	16.1375	14.1760	
°R:	292.15	292.06	291.91	291.72	291.49	291.20	290.86	290.24	289.29	287.33	
Compressibility, Z <sub>1</sub> :	0.9996	0.9987	0.9987	0.9988	0.9989	0.9989	0.9990	0.9991	0.9992	0.9993	
Viscosity, μ <sub>1</sub> :	Pa.sec 1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.80E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 4.7912	4.5714	4.3387	4.0909	3.8280	3.5456	3.2362	2.8898	2.4911	2.0011	
Velocity, V <sub>1</sub> :	m/sec 43.2511	45.3307	47.7617	50.6543	54.1341	58.4444	64.0336	71.7082	83.1844	103.5520	
Mach number at the inlet, M <sub>1</sub> :	0.1260	0.1319	0.1390	0.1475	0.1577	0.1702	0.1867	0.2091	0.2430	0.3035	
4fL <sub>1</sub> /D:	40.8869	36.8954	32.9083	28.9258	24.9476	20.9740	17.0050	13.0405	9.0809	5.1263	
Reynolds number, Re:	8.700E+04	8.704E+04	8.709E+04	8.714E+04	8.721E+04	8.730E+04	8.740E+04	8.757E+04	8.782E+04	8.832E+04	
Friction factor, 4f:	0.02522425	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	
Recovery factor, r:	0.72296951	0.7228	0.7227	0.7226	0.7225	0.7225	0.7222	0.7220	0.7219	0.7219	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.67	19.64	19.57	19.49	19.39	19.28	19.18	18.93	18.61	18.02	
Enthalpy, h:	kJ/kg 291.69	291.64	291.54	291.40	291.22	290.99	290.70	290.14	289.27	287.40	
Entropy, s:	6.44253250	6.4559	6.4706	6.4872	6.5059	6.5273	6.5528	6.5840	6.6244	6.6827	
<b>Downstream Condition</b>											
4fL <sub>2</sub> /D:	3.9516	3.9515	3.9513	3.9511	3.9509	3.9507	3.9503	3.9498	3.9491	3.9475	
Mach number at the outlet, M <sub>2</sub> :	0.1319	0.1390	0.1475	0.1577	0.1702	0.1867	0.2091	0.2430	0.3035	0.4870	
Absolute outlet pressure, P <sub>2</sub> :	Kpa g 382.82	363.17	342.23	320.00	296.13	269.99	240.60	206.75	164.98	101.33	
Kpa abs:	281.493	261.840	240.906	218.679	194.809	168.662	139.272	105.423	63.652	0.000	
Outlet temperature, T <sub>2</sub> :	°C 18.91	18.76	18.57	18.34	18.05	17.71	17.09	16.14	14.18	6.08	
Compressibility, Z <sub>2</sub> :	0.9987	0.9987	0.9988	0.9989	0.9989	0.9990	0.9991	0.9992	0.9993	0.9995	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 4.5714	4.3387	4.0909	3.8280	3.5456	3.2362	2.8898	2.4911	2.0011	1.2645	
Viscosity of gas, μ <sub>2</sub> :	Pa.sec 1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.80E-05	1.76E-05	
Actual outlet flow:	m <sup>3</sup> /hr 7.5204	7.9237	8.4056	8.9809	9.6960	10.6253	11.8965	13.8004	17.1794	27.1875	
Velocity, V <sub>2</sub> :	m/sec 45.3307	47.7617	50.6543	54.1341	58.4444	64.0336	71.7082	83.1844	103.5520	163.8774	
Reynolds number, Re:	8.704E+04	8.709E+04	8.714E+04	8.721E+04	8.730E+04	8.740E+04	8.757E+04	8.782E+04	8.832E+04	9.039E+04	
Friction factor, 4f:	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	
Recovery factor, r:	0.7228	0.7227	0.7226	0.7225	0.7225	0.7222	0.7220	0.7219	0.7219	0.7225	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.6432	19.6010	19.5197	19.4235	19.3101	19.1803	19.0026	18.6622	18.0669	15.7747	
Enthalpy, h:	kJ/kg 291.6436	291.5360	291.3973	291.2209	290.9882	290.7020	290.1444	289.2702	287.3962	279.4062	
Entropy, s:	6.4559	6.4706	6.4872	6.5059	6.5273	6.5528	6.5840	6.6244	6.6827	6.7944	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa G 55.25										
Kpa abs:	46.08										
Critical Temperature:	°C 29.68										
°R:	243.47										
Max length of duct at which no shock occurs:	m 12.42										
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa 18.51	19.65	20.93	22.23	23.87	26.15	29.39	33.85	41.77	63.65	
Temperature drop / Segment Length:	°C 0.09	0.15	0.19	0.23	0.29	0.35	0.62	0.95	1.96	8.10	
Total pressure drop:	Kpa 300.00										
Total temperature drop:	°C 12.62										

Figure F 11-3: Vent pipe model predictions for air gas at 300 KPa gauge



Gas Property Calculation for Air @ 400 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>	Argon:0.0092;Oxygen:0.2096;Nitrogen:0.7812;										
Specific heat at constant pressure, cp:	J/kg.K 1013.20	1012.80	1012.38	1011.93	1011.44	1010.92	1010.34	1009.69	1008.92	1007.92	
Specific heat at constant volume, cv:	J/kg.K 718.85	718.79	718.71	718.64	718.55	718.46	718.36	718.23	718.08	717.84	
Ratio of specific heats, γ:	1.4095	1.4090	1.4086	1.4081	1.4076	1.4071	1.4065	1.4058	1.4050	1.4041	
Molecular weight, M.W:	kg/mole 28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	
Gas constant, R:	J/kg.K 287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	
Normal or standard flow:	m <sup>3</sup> /hr 35.5869	35.5869	35.5869	35.5869	35.5869	35.5869	35.5869	35.5869	35.5869	35.5869	
litres/min:	593.1155	593.1155	593.1155	593.1155	593.1155	593.1155	593.1155	593.1155	593.1155	593.1155	
<b>Phase flow</b>	Single										
Actual inlet flow condition:	kg/hr 43.60										
m <sup>3</sup> /hr:	7.28	7.64	8.06	8.55	9.16	9.91	10.89	12.26	14.34	18.23	
Standard flow condition:	m <sup>3</sup> /hr 35.59	35.59	35.59	35.59	35.59	35.59	35.59	35.59	35.59	35.59	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C 293.10	293.10	293.05	292.99	292.93	292.87	292.86	292.72	292.64	292.55	
°F:	19.95	19.95	19.90	19.84	19.78	19.72	19.71	19.57	19.49	19.40	
Inlet Stagnation Pressure:	Kpa abs 507.12	483.60	459.47	433.69	405.68	375.33	343.01	306.05	263.89	211.76	
Outlet Stagnation Pressure:	Kpa abs 483.60	459.47	433.69	405.68	375.33	343.01	306.05	263.89	211.76	130.58	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 6.04	5.76	5.47	5.16	4.83	4.47	4.08	3.63	3.14	2.52	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 292.40	292.46	292.46	292.47	292.47	292.48	292.55	292.50	292.51	292.54	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g 400.00	376.30	351.45	325.02	296.60	263.84	232.60	194.57	150.66	95.30	
Kpa abs:	501.33	477.62	452.77	426.34	397.93	367.17	333.92	295.89	251.98	196.63	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9005	18.7318	18.5302	18.2776	17.9507	17.5818	16.8701	15.7873	13.4056	
°F:	292.15	292.05	291.88	291.68	291.43	291.10	290.73	290.02	288.94	286.56	
Compressibility, Z <sub>1</sub> :	0.9983	0.9983	0.9984	0.9985	0.9986	0.9987	0.9988	0.9988	0.9990	0.9992	
Viscosity, μ <sub>1</sub> :	Pa.sec 1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 5.9870	5.7055	5.4113	5.0986	4.7625	4.3988	4.0052	3.5574	3.0404	2.3918	
Velocity, V <sub>1</sub> :	m/sec 43.8980	46.0643	48.5681	51.3475	55.1853	59.7476	65.6194	73.8798	86.4417	109.8821	
Mach number at the inlet, M <sub>1</sub> :	0.1278	0.1341	0.1413	0.1500	0.1606	0.1741	0.1912	0.2156	0.2526	0.3224	
4fL <sub>1</sub> /D:	39.5286	35.6051	31.6851	27.7684	23.8553	19.9456	16.0394	12.1368	8.2380	4.3432	
Reynolds number, Re:	1.102E+05	1.103E+05	1.104E+05	1.105E+05	1.106E+05	1.107E+05	1.108E+05	1.111E+05	1.114E+05	1.122E+05	
Friction factor, 4f:	0.02485395	0.0249	0.0249	0.0249	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	
Recovery factor, r:	0.72371972	0.7236	0.7234	0.7232	0.7231	0.7229	0.7227	0.7225	0.7223	0.7222	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.69	19.66	19.57	19.48	19.37	19.23	19.12	18.82	18.46	17.73	
Enthalpy, h:	KJ/kg 291.45	291.41	291.30	291.16	290.97	290.71	290.42	289.79	288.81	286.54	
Entropy, s:	6.37793819	6.3917	6.4066	6.4234	6.4425	6.4647	6.4909	6.5234	6.5661	6.6294	
<b>Downstream Condition</b>											
4fL <sub>2</sub> /D:	3.8936	3.8935	3.8933	3.8931	3.8929	3.8927	3.8924	3.8919	3.8912	3.8896	
Mach number at the outlet, M <sub>2</sub> :	0.1341	0.1413	0.1500	0.1606	0.1741	0.1912	0.2156	0.2526	0.3224	0.6094	
Absolute outlet pressure, P <sub>2</sub> :	Kpa a 477.62	452.77	426.34	397.93	367.17	333.92	295.89	251.98	196.63	101.32	
Outlet pressure (gauge):	Kpa g 376.297	351.448	325.018	296.604	263.841	232.597	194.569	150.659	95.303	0.000	
Outlet temperature, T <sub>2</sub> :	°C 18.90	18.73	18.53	18.28	17.95	17.58	16.87	15.79	13.41	-1.09	
Compressibility, Z <sub>2</sub> :	0.9983	0.9984	0.9985	0.9986	0.9987	0.9988	0.9989	0.9990	0.9992	0.9994	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 5.7055	5.4113	5.0986	4.7625	4.3988	4.0052	3.5574	3.0404	2.3918	1.2979	
Viscosity of gas, μ <sub>2</sub> :	Pa.sec 1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05	1.72E-05	
Actual outlet flow:	m <sup>3</sup> /hr 7.6421	8.0575	8.5518	9.1553	9.9122	10.8864	12.2568	14.3408	18.2296	33.5933	
Velocity, V <sub>2</sub> :	m/sec 46.0643	48.5681	51.3475	55.1853	59.7476	65.6194	73.8798	86.4417	109.8821	202.4808	
Reynolds number, Re:	1.103E+05	1.104E+05	1.105E+05	1.106E+05	1.107E+05	1.108E+05	1.111E+05	1.114E+05	1.122E+05	1.170E+05	
Friction factor, 4f:	0.0249	0.0249	0.0249	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	
Recovery factor, r:	0.7236	0.7234	0.7232	0.7231	0.7229	0.7227	0.7225	0.7223	0.7222	0.7237	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.6606	19.6116	19.5186	19.4096	19.2753	19.1244	18.9239	18.5219	17.8004	13.7338	
Enthalpy, h:	KJ/kg 291.4089	291.2973	291.1564	290.9689	290.7122	290.4194	289.7925	288.8068	286.5414	272.1934	
Entropy, s:	6.3917	6.4066	6.4234	6.4425	6.4647	6.4909	6.5234	6.5661	6.6294	6.7682	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa G -42.93										
Kpa abs:	58.40										
Critical Temperature:	°C 29.84										
°F:	243.31										
Max length of duct at which no shock occurs:	m 12.18										
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa 23.70	24.85	26.43	28.41	30.76	33.24	38.03	43.91	55.36	95.30	
Temperature drop / Segment Length:	°C 0.10	0.17	0.20	0.25	0.33	0.37	0.71	1.08	2.38	14.50	
Total pressure drop:	Kpa 400.00										
Total temperature drop:	°C 19.80										

Figure F 11-4: Vent pipe model predictions for air gas at 400 KPa gauge

Gas Property Calculation for Air @ 500 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>	Argon:0.0092;Oxygen:0.2096;Nitrogen:0.7812;										
Specific heat at constant pressure, cp:	J/kg.K 1014.92	1014.43	1013.92	1013.38	1012.79	1012.16	1011.47	1010.68	1009.74	1008.53	
Specific heat at constant volume, cv:	J/kg.K 719.11	719.03	718.95	718.86	718.76	718.65	718.53	718.38	718.20	717.92	
Ratio of specific heats, γ:	1.4113	1.4108	1.4103	1.4097	1.4091	1.4084	1.4077	1.4069	1.4059	1.4048	
Molecular weight, M.W:	kg/mole 28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	
Gas constant, R:	J/kg.K 287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	
Normal or standard flow:	m <sup>3</sup> /hr 43.0370	43.0370	43.0370	43.0370	43.0370	43.0370	43.0370	43.0370	43.0370	43.0370	
Phase flow:	lines/min 717.2829	717.2829	717.2829	717.2829	717.2829	717.2829	717.2829	717.2829	717.2829	717.2829	
<b>Actual inlet flow condition:</b>	Single										
kg/hr 52.73											
m <sup>3</sup> /hr 7.34	7.71	8.13	8.63	9.25	10.02	11.02	12.43	14.60	18.74		
Standard flow condition:	m <sup>3</sup> /hr 43.04	43.04	43.04	43.04	43.04	43.04	43.04	43.04	43.04	43.04	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C 293.11	293.11	293.05	292.98	292.91	292.83	292.82	292.66	292.55	292.43	
Inlet Stagnation Pressure:	Kpa abs 608.39	579.65	550.28	519.08	485.32	448.93	409.66	365.11	313.63	249.71	
Outlet Stagnation Pressure:	Kpa abs 579.65	550.28	519.08	485.32	448.93	409.66	365.11	313.63	249.71	144.34	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 7.24	6.90	6.55	6.18	5.78	5.35	4.88	4.35	3.74	2.98	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 292.18	292.24	292.24	292.25	292.26	292.26	292.25	292.29	292.31	292.34	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g 500.00	471.28	441.18	409.23	374.89	337.77	297.46	251.34	197.73	129.61	
Kpa abs 601.33	572.60	542.51	510.55	476.22	439.09	398.79	352.66	299.06	230.93		
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.8961	18.7115	18.4934	18.2228	17.8769	17.4898	16.7294	15.5669	12.9574	
Compressibility, Z <sub>1</sub> :	0.9979	0.9980	0.9981	0.9982	0.9983	0.9984	0.9986	0.9987	0.9988	0.9990	
Viscosity, μ <sub>1</sub> :	Pa.sec 1.83E-05	1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 7.1837	6.8424	6.4863	6.1082	5.7021	5.2632	4.7858	4.2428	3.6118	2.8139	
Velocity, V <sub>1</sub> :	m/sec 44.2447	46.4516	49.0018	52.0350	55.7406	60.3887	66.4121	74.9120	87.9992	112.9518	
Mach number at the inlet, M <sub>1</sub> :	0.1287	0.1352	0.1426	0.1514	0.1623	0.1760	0.1936	0.2185	0.2572	0.3315	
4fL <sub>1-2</sub> /D:	38.7991	34.9243	31.0518	27.1816	23.3139	19.4486	15.5857	11.7254	7.8677	4.0129	
Reynolds number, Re:	1.332E+05	1.333E+05	1.334E+05	1.335E+05	1.336E+05	1.338E+05	1.340E+05	1.343E+05	1.348E+05	1.358E+05	
Friction factor, 4f:	0.02460583	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	
Recovery factor, r:	0.72446114	0.7243	0.7241	0.7239	0.7237	0.7234	0.7232	0.7230	0.7227	0.7226	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.70	19.67	19.57	19.46	19.33	19.18	19.07	18.74	18.34	17.53	
Enthalpy, h:	KJ/kg 291.22	291.18	291.06	290.92	290.73	290.46	290.17	289.51	288.47	286.00	
Entropy, s:	kJ/kg.K 6.32500191	6.3389	6.3540	6.3709	6.3902	6.4125	6.4391	6.4721	6.5158	6.5813	
<b>Downstream Condition</b>											
4fL <sub>1-2</sub> /D:	3.8547	3.8546	3.8543	3.8543	3.8541	3.8539	3.8536	3.8531	3.8525	3.8510	
Mach number at the outlet, M <sub>2</sub> :	0.1352	0.1426	0.1514	0.1623	0.1760	0.1936	0.2185	0.2572	0.3315	0.7259	
Absolute outlet pressure, P <sub>2</sub> :	Kpa a 572.60	542.51	510.55	476.22	439.09	398.79	352.66	299.06	230.93	101.33	
Outlet pressure (gauge):	Kpa g 471.278	441.184	409.228	374.895	337.769	297.463	251.338	197.734	129.607	0.000	
Outlet temperature, T <sub>2</sub> :	°C 18.90	18.71	18.49	18.22	17.88	17.49	16.73	15.57	12.96	-8.98	
Compressibility, Z <sub>2</sub> :	0.9980	0.9981	0.9982	0.9983	0.9984	0.9986	0.9987	0.9988	0.9990	0.9993	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 6.8424	6.4863	6.1082	5.7021	5.2632	4.7858	4.2428	3.6118	2.8139	1.3368	
Viscosity of gas, μ <sub>2</sub> :	Pa.sec 1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05	1.68E-05	
Actual outlet flow:	m <sup>3</sup> /hr 7.7064	8.1295	8.6327	9.2474	10.0186	11.0179	12.4280	14.5992	18.7389	39.4439	
Velocity, V <sub>2</sub> :	m/sec 46.4516	49.0018	52.0350	55.7406	60.3887	66.4121	74.9120	87.9992	112.9518	237.7549	
Reynolds number, Re:	1.333E+05	1.334E+05	1.335E+05	1.336E+05	1.338E+05	1.340E+05	1.343E+05	1.348E+05	1.358E+05	1.449E+05	
Friction factor, 4f:	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0245	
Recovery factor, r:	0.7243	0.7241	0.7239	0.7237	0.7234	0.7232	0.7230	0.7227	0.7226	0.7250	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.6698	19.6153	19.5084	19.3854	19.2368	19.0726	18.8554	18.4135	17.6138	11.5097	
Enthalpy, h:	KJ/kg 291.1782	291.0627	290.9179	290.7258	290.4647	290.1700	289.5127	288.4689	286.0039	264.2607	
Entropy, s:	kJ/kg.K 6.3389	6.3540	6.3709	6.3902	6.4125	6.4391	6.4721	6.5158	6.5813	6.7386	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa G -30.76										
Kpa abs 70.56											
Critical Temperature:	°C 30.01										
243.14											
Max length of duct at which no shock occurs:	m 12.08										
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa 28.72	30.09	31.96	34.33	37.13	40.31	46.12	53.60	68.13	129.61	
Temperature drop / Segment Length:	°C 0.10	0.18	0.22	0.27	0.35	0.39	0.76	1.16	2.61	21.94	
Total pressure drop:	Kpa 500.00										
Total temperature drop:	°C 27.73										

Figure F 11-5: Vent pipe model predictions for air gas at 500 KPa gauge

Gas Property Calculation for Air @ 600 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>	Argon:0.0092;Oxygen:0.2096;Nitrogen:0.7812;										
Specific heat at constant pressure, cp:	J/kg K 1016.63	1016.06	1015.46	1014.83	1014.15	1013.41	1012.61	1011.68	1010.59	1009.18	
Specific heat at constant volume, cv:	J/kg K 719.37	719.28	719.19	719.08	718.97	718.84	718.70	718.53	718.32	718.01	
Ratio of specific heats, γ:	1.4132	1.4126	1.4120	1.4113	1.4106	1.4098	1.4089	1.4080	1.4069	1.4053	
Molecular weight, M.W:	kg/mole 28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	
Gas constant, R:	J/kg K 287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	
Normal or standard flow:	m <sup>3</sup> /hr 50.4426	50.4426	50.4426	50.4426	50.4426	50.4426	50.4426	50.4426	50.4426	50.4426	
litres/min:	840.7099	840.7099	840.7099	840.7099	840.7099	840.7099	840.7099	840.7099	840.7099	840.7099	
<b>Phase flow</b>	Single										
Actual inlet flow condition:	kg/hr 61.80										
m <sup>3</sup> /hr:	7.37	7.74	8.17	8.68	9.30	10.08	11.09	12.51	14.72	18.98	
Standard flow condition:	m <sup>3</sup> /hr 50.44	50.44	50.44	50.44	50.44	50.44	50.44	50.44	50.44	50.44	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C 293.12	293.12	293.04	292.96	292.88	292.79	292.77	292.58	292.46	292.31	
°F:	19.97	19.97	19.89	19.81	19.73	19.64	19.62	19.43	19.31	19.16	
Inlet Stagnation Pressure:	Kpa abs 709.64	675.83	641.35	604.82	565.41	523.03	477.03	424.98	364.55	289.16	
Outlet Stagnation Pressure:	Kpa abs 675.83	641.35	604.82	565.41	523.03	477.03	424.98	364.55	289.16	160.89	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 8.45	8.05	7.64	7.21	6.74	6.23	5.68	5.07	4.35	3.45	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 291.95	292.02	292.02	292.03	292.04	292.05	292.14	292.07	292.09	292.13	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g 600.00	566.36	531.11	493.71	453.56	410.17	362.99	308.93	245.97	163.60	
Kpa abs:	701.33	667.68	632.43	595.03	554.88	511.49	464.32	410.26	347.30	266.92	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.8956	18.6954	18.4634	18.1779	17.8163	17.4200	16.6222	15.4145	12.6793	
°F:	292.15	292.04	291.85	291.61	291.33	290.97	290.57	289.77	288.56	285.83	
Compressibility, Z <sub>1</sub> :	0.9976	0.9977	0.9978	0.9979	0.9980	0.9982	0.9983	0.9985	0.9987	0.9989	
Viscosity, μ <sub>1</sub> :	Pa.s 1.83E-05	1.83E-05	1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 8.3811	7.9811	7.5641	7.1217	6.6468	6.1339	5.5749	4.9386	4.1974	3.2561	
Velocity, V <sub>1</sub> :	m/sec 44.4491	46.6767	49.2499	52.3095	56.0464	60.7333	66.8224	75.4523	88.7518	114.4092	
Mach number at the inlet, M <sub>1</sub> :	0.1293	0.1359	0.1433	0.1522	0.1632	0.1769	0.1947	0.2200	0.2593	0.3358	
4fL <sub>1</sub> /D:	38.3674	34.5274	30.6890	26.8522	23.0170	19.1835	15.3517	11.5216	7.6934	3.8673	
Reynolds number, Re:	1.560E+05	1.561E+05	1.562E+05	1.564E+05	1.565E+05	1.567E+05	1.570E+05	1.574E+05	1.580E+05	1.593E+05	
Friction factor, 4f:	0.02442714	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	
Recovery factor, r:	0.72519404	0.7250	0.7247	0.7245	0.7243	0.7240	0.7237	0.7234	0.7231	0.7229	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.70	19.67	19.56	19.44	19.30	19.13	19.02	18.66	18.23	17.37	
Enthalpy, h:	kJ/kg 290.58	290.95	290.83	290.49	290.23	289.94	289.26	288.20	285.63	266.92	
Entropy, s:	kJ/kg K 6.28011837	6.2941	6.3092	6.3262	6.3456	6.3680	6.3947	6.4279	6.4720	6.5385	
<b>Downstream Condition</b>											
4fL <sub>2</sub> /D:	3.8267	3.8266	3.8265	3.8263	3.8261	3.8259	3.8257	3.8252	3.8246	3.8233	
Mach number at the outlet, M <sub>2</sub> :	0.1359	0.1433	0.1522	0.1632	0.1769	0.1947	0.2200	0.2593	0.3358	0.8369	
Absolute outlet pressure, P <sub>2</sub> :	Kpa a 667.68	632.43	595.03	554.88	511.49	464.32	410.26	347.30	266.92	101.32	
Outlet pressure (gauge):	Kpa g 566.357	531.108	493.710	453.559	410.169	362.994	308.932	245.974	163.596	0.000	
Outlet temperature, T <sub>2</sub> :	°C 18.89	18.70	18.46	18.18	17.82	17.42	16.62	15.41	12.68	-17.27	
Compressibility, Z <sub>2</sub> :	0.9977	0.9978	0.9979	0.9980	0.9982	0.9983	0.9985	0.9987	0.9989	0.9992	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 7.9811	7.5641	7.1217	6.6468	6.1339	5.5749	4.9386	4.1974	3.2561	1.3803	
Viscosity of gas, μ <sub>2</sub> :	Pa.s 1.83E-05	1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05	1.64E-05	
Actual outlet flow:	m <sup>3</sup> /hr 7.7457	8.1706	8.6782	9.2982	10.0757	11.0859	12.5143	14.7240	18.9806	44.7746	
Velocity, V <sub>2</sub> :	m/sec 46.6767	49.2499	52.3095	56.0464	60.7333	66.8224	75.4523	88.7518	114.4092	269.8866	
Reynolds number, Re:	1.561E+05	1.562E+05	1.564E+05	1.565E+05	1.567E+05	1.570E+05	1.574E+05	1.580E+05	1.593E+05	1.742E+05	
Friction factor, 4f:	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0243	
Recovery factor, r:	0.7250	0.7247	0.7245	0.7243	0.7240	0.7237	0.7234	0.7231	0.7229	0.7264	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.6752	19.6161	19.4968	19.3611	19.1993	19.0238	18.7944	18.3214	17.4739	9.1972	
Enthalpy, h:	kJ/kg 290.9494	290.8320	290.6856	290.4920	290.2294	289.9414	289.2647	288.1969	285.6335	255.9225	
Entropy, s:	kJ/kg K 6.2941	6.3092	6.3262	6.3456	6.3680	6.3947	6.4279	6.4720	6.5385	6.7065	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa G -18.69										
Kpa abs:	82.63										
Critical Temperature:	°C 30.19										
°F:	242.96										
Max length of duct at which no shock occurs:	m 12.03										
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa 33.64	35.25	37.40	40.15	43.39	47.17	54.06	62.96	80.38	165.60	
Temperature drop / Segment Length:	°C 0.11	0.20	0.23	0.29	0.36	0.40	0.80	1.21	2.74	29.95	
Total pressure drop:	Kpa 600.00										
Total temperature drop:	°C 36.10										

Figure F 11-6: Vent pipe model predictions for air gas at 600 KPa gauge



Gas Property Calculation for Air @ 700 Kpa gauge & 19 °C Inlet Conditions										by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10
Schedule number:	80	80	80	80	80	80	80	80	80	80
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
<b>Gas properties</b>	Argon:0.0092;Oxygen:0.2096;Nitrogen:0.7812;									
Specific heat at constant pressure, cp:	J/kg K 1018.35	1017.69	1017.01	1016.29	1015.51	1014.67	1013.75	1012.70	1011.46	1009.85
Specific heat at constant volume, cv:	J/kg K 719.64	719.53	719.42	719.30	719.17	719.03	718.88	718.68	718.45	718.11
Ratio of specific heats, γ:	1.4151	1.4144	1.4137	1.4129	1.4121	1.4112	1.4102	1.4091	1.4078	1.4063
Molecular weight, M.W:	kg/mole 28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96
Gas constant, R:	J/kg K 287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12
<b>Standard condition</b>										
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15
Compressibility at std cond, Z <sub>std</sub> :	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252
Normal or standard flow:	m <sup>3</sup> /hr 57.8210	57.8210	57.8210	57.8210	57.8210	57.8210	57.8210	57.8210	57.8210	57.8210
lines/min:	963.6828	963.6828	963.6828	963.6828	963.6828	963.6828	963.6828	963.6828	963.6828	963.6828
<b>Phase flow</b>	Single									
Actual inlet flow condition:	kg/hr 70.84									
m <sup>3</sup> /hr:	7.40	7.77	8.20	8.71	9.33	10.11	11.12	12.56	14.78	19.08
Standard flow condition:	m <sup>3</sup> /hr 57.82	57.82	57.82	57.82	57.82	57.82	57.82	57.82	57.82	57.82
<b>Stagnation Properties</b>										
Stagnation Temperature, T <sub>0</sub> :	°C 293.13	293.12	293.05	292.94	292.84	292.74	292.73	292.51	292.37	292.20
°C:	19.98	19.97	19.88	19.79	19.69	19.59	19.58	19.36	19.22	19.05
Inlet Stagnation Pressure:	Kpa abs 810.88	772.09	732.57	690.77	645.76	597.42	544.81	485.12	416.09	329.71
Outlet Stagnation Pressure:	Kpa abs 772.09	732.57	690.77	645.76	597.42	544.81	485.12	416.09	329.71	180.37
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 9.66	9.20	8.73	8.23	7.70	7.12	6.49	5.79	4.96	3.93
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 291.71	291.80	291.80	291.81	291.81	291.82	291.94	291.85	291.88	291.91
<b>Upstream Condition</b>										
Inlet pressure, P <sub>1</sub> :	Kpa g 700.00	661.49	621.14	578.35	532.44	482.84	428.93	366.94	294.90	202.74
Kpa abs:	801.33	762.82	722.47	679.68	633.77	584.17	530.25	468.26	396.22	304.06
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.8920	18.6815	18.4367	18.1379	17.7622	17.3610	16.5277	15.2926	12.4973
°C:	292.15	292.04	291.83	291.59	291.29	290.91	290.51	290.11	288.44	285.65
Compressibility, Z <sub>1</sub> :	0.9973	0.9974	0.9975	0.9976	0.9978	0.9979	0.9981	0.9983	0.9985	0.9987
Viscosity, μ <sub>1</sub> :	Pa.s 1.83E-05	1.83E-05	1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 9.5792	9.1212	8.6439	8.1378	7.5948	7.0085	6.3694	5.6399	4.7917	3.7122
Velocity, V <sub>1</sub> :	m/sec 44.5780	46.8163	49.4014	52.4739	56.2254	60.9292	67.0432	75.7140	89.1178	113.0334
Mach number at the inlet, M <sub>1</sub> :	0.1296	0.1362	0.1438	0.1527	0.1637	0.1774	0.1953	0.2208	0.2603	0.3376
4fL <sub>1</sub> /D:	38.0938	34.2796	30.4663	26.6542	22.8432	19.0334	15.2247	11.4173	7.6112	3.8067
Reynolds number, Re:	1.788E+05	1.788E+05	1.789E+05	1.791E+05	1.793E+05	1.796E+05	1.799E+05	1.804E+05	1.811E+05	1.826E+05
Friction factor, 4f:	0.02429196	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243
Recovery factor, r:	0.72591869	0.7257	0.7254	0.7251	0.7249	0.7246	0.7242	0.7239	0.7235	0.7233
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.71	19.67	19.55	19.42	19.27	19.09	18.97	18.58	18.13	17.24
Enthalpy, h:	kJ/kg 290.74	290.72	290.60	290.46	290.26	290.00	289.72	289.03	287.95	285.56
Entropy, s:	6.24113293	6.2552	6.2703	6.2873	6.3067	6.3291	6.3559	6.3892	6.4333	6.5002
<b>Downstream Condition</b>										
4fL <sub>2</sub> /D:	3.8055	3.8054	3.8053	3.8052	3.8050	3.8048	3.8045	3.8041	3.8036	3.8023
Mach number at the outlet, M <sub>2</sub> :	0.1362	0.1438	0.1527	0.1637	0.1774	0.1953	0.2208	0.2603	0.3376	0.9427
Absolute outlet pressure, P <sub>2</sub> :	Kpa a 762.82	722.47	679.68	633.77	584.17	530.25	468.26	396.22	304.06	101.33
Outlet pressure (gauge):	Kpa g 661.495	621.141	578.354	532.440	482.844	428.926	366.939	294.897	202.737	0.000
Outlet temperature, T <sub>2</sub> :	°C 18.89	18.68	18.44	18.14	17.76	17.36	16.53	15.29	12.57	-25.72
Compressibility, Z <sub>2</sub> :	0.9974	0.9975	0.9976	0.9978	0.9979	0.9981	0.9983	0.9985	0.9987	0.9990
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 9.1212	8.6439	8.1378	7.5948	7.0085	6.3694	5.6399	4.7917	3.7122	1.4277
Viscosity of gas, μ <sub>2</sub> :	Pa.s 1.83E-05	1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05	1.59E-05
Actual outlet flow:	m <sup>3</sup> /hr 7.7669	8.1958	8.7055	9.3279	10.1082	11.1226	12.5610	14.7848	19.0842	49.6203
Velocity, V <sub>2</sub> :	m/sec 46.8163	49.4014	52.4739	56.2254	60.9292	67.0432	75.7140	89.1178	113.0334	299.0954
Reynolds number, Re:	1.788E+05	1.789E+05	1.791E+05	1.793E+05	1.796E+05	1.799E+05	1.804E+05	1.811E+05	1.826E+05	2.052E+05
Friction factor, 4f:	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0242
Recovery factor, r:	0.7257	0.7254	0.7251	0.7249	0.7246	0.7242	0.7239	0.7235	0.7233	0.7280
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.6784	19.6153	19.4842	19.3365	19.1622	18.9764	18.7357	18.2341	17.3585	6.8708
Enthalpy, h:	kJ/kg 290.7218	290.6035	290.4566	290.2627	290.0002	289.7229	289.0283	287.9339	285.5669	247.4180
Entropy, s:	6.2552	6.2703	6.2873	6.3067	6.3291	6.3559	6.3892	6.4333	6.5002	6.6727
<b>Critical Properties at Outlet Mach 1</b>										
Critical Pressure:	Kpa G -6.70									
Kpa abs:	94.62									
Critical Temperature:	°C 30.37									
°C:	242.78									
Max length of duct at which no shock occurs:	m 12.01									
<b>Drop</b>										
Pressure drop / Segment Length:	Kpa 38.51	40.35	42.79	45.91	49.60	53.92	61.99	72.04	92.16	202.74
Temperature drop / Segment Length:	°C 0.11	0.21	0.24	0.30	0.38	0.40	0.83	1.24	2.80	38.22
Total pressure drop:	Kpa 700.00									
Total temperature drop:	°C 44.67									

Figure F 11-7: Vent pipe model predictions for air gas at 700 KPa gauge

Gas Property Calculation for Air @ 755.979489349149 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Gas properties											
Argon:0.0092;Oxygen:0.2096;Nitrogen:0.7812;											
Specific heat at constant pressure, cp	J/kg K	1019.31	1018.60	1017.86	1017.07	1016.23	1015.32	1014.32	1013.18	1011.83	1010.06
Specific heat at constant volume, cv	J/kg K	719.78	719.67	719.55	719.42	719.28	719.13	718.96	718.75	718.50	718.12
Ratio of specific heats, γ		1.4161	1.4154	1.4146	1.4137	1.4128	1.4119	1.4108	1.4096	1.4082	1.4063
Molecular weight, M.W	kg/mole	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96	28.96
Gas constant, R	J/kg K	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12	287.12
Standard condition											
Inlet pressure, P <sub>gpg</sub> (gauge)	K Pa g	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Atmospheric pressure	K Pa	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Inlet pressure, P <sub>gpa</sub> (absolute)	K Pa abs	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Temperature, T <sub>std</sub>	°C	15	15	15	15	15	15	15	15	15	15
Compressibility at std cond, Z <sub>std</sub>		0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996
Density at standard condition, ρ <sub>std</sub>	kg/m <sup>3</sup>	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252	1.2252
Normal or standard flow	m <sup>3</sup> /hr	61.9433	61.9433	61.9433	61.9433	61.9433	61.9433	61.9433	61.9433	61.9433	61.9433
	litres/min	1032.3884	1032.3884	1032.3884	1032.3884	1032.3884	1032.3884	1032.3884	1032.3884	1032.3884	1032.3884
Phase flow											
Single											
Actual inlet flow condition:	kg/hr	75.89									
	m <sup>3</sup> /hr	7.40	7.78	8.22	8.74	9.38	10.18	11.22	12.71	15.04	19.67
Standard flow condition:	m <sup>3</sup> /hr	61.94	61.94	61.94	61.94	61.94	61.94	61.94	61.94	61.94	61.94
Stagnation Properties											
Stagnation Temperature, T <sub>0</sub>	°C	293.13	293.12	293.02	292.93	292.82	292.71	292.69	292.45	292.30	292.12
	°C	19.98	19.97	19.87	19.78	19.67	19.56	19.54	19.30	19.15	18.97
Inlet Stagnation Pressure	Kpa abs	867.56	825.35	782.30	736.85	688.06	635.89	578.73	513.57	438.46	343.87
Outlet Stagnation Pressure	Kpa abs	825.35	782.30	736.85	688.06	635.89	578.73	513.57	438.46	343.87	192.61
Stagnation Density, ρ <sub>0</sub>	kg/m <sup>3</sup>	10.34	9.83	9.32	8.78	8.20	7.58	6.90	6.13	5.23	4.10
Stagnation Enthalpy, h <sub>0</sub>	KJ/kg	291.58	291.67	291.68	291.68	291.69	291.70	291.82	291.73	291.75	291.80
Upstream Condition											
Inlet pressure, P <sub>1</sub>	Kpa g	755.98	714.09	670.19	623.70	573.87	520.15	461.62	394.12	315.60	214.19
	Kpa abs	857.30	815.42	771.52	725.02	675.20	621.47	562.94	495.44	416.93	315.52
Inlet temperature, T <sub>1</sub>	°C	19.00	18.8896	18.6682	18.4114	18.0990	17.7080	17.2889	16.4056	15.0882	12.0110
	°C	292.15	292.04	291.82	291.56	291.25	290.86	290.44	289.56	288.24	285.16
Compressibility, Z <sub>1</sub>		0.9971	0.9972	0.9973	0.9975	0.9976	0.9978	0.9980	0.9982	0.9984	0.9987
Viscosity, μ <sub>1</sub>	Pa.s	1.83E-05	1.83E-05	1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.79E-05
Density, ρ <sub>1</sub>	kg/m <sup>3</sup>	10.2502	9.7519	9.2527	8.6827	8.0936	7.4584	6.7645	5.9704	5.0461	3.8588
Velocity, V <sub>1</sub>	m/sec	44.6298	46.9104	49.5483	52.6868	56.5221	61.3355	67.6275	76.6220	90.6581	118.5513
Mach number at the inlet, M <sub>1</sub>		0.1297	0.1365	0.1442	0.1533	0.1645	0.1785	0.1970	0.2235	0.2649	0.3481
4fL <sub>1-2</sub> /D		37.9833	34.1184	30.2615	26.4125	22.5714	18.7382	14.9130	11.0958	7.2866	3.4838
Reynolds number, Re <sub>1</sub>		1.913E+05	1.914E+05	1.916E+05	1.918E+05	1.921E+05	1.924E+05	1.927E+05	1.932E+05	1.941E+05	1.959E+05
Friction factor, 4f		0.02422969	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242
Recovery factor, r		0.72632083	0.7260	0.7258	0.7255	0.7252	0.7248	0.7245	0.7241	0.7237	0.7234
Adiabatic Wall Temperature, T <sub>w</sub>	°C	19.71	19.67	19.54	19.40	19.24	19.05	18.82	18.50	18.03	17.04
Enthalpy, h	KJ/kg	290.61	290.59	290.47	290.32	290.12	289.86	289.57	288.84	287.70	284.84
Entropy, s	KJ/kg K	6.22134538	6.2356	6.2511	6.2684	6.2881	6.3109	6.3383	6.3723	6.4178	6.4878
Downstream Condition											
4fL <sub>1-2</sub> /D		3.7958	3.7957	3.7955	3.7954	3.7952	3.7950	3.7948	3.7944	3.7938	3.7925
Mach number at the outlet, M <sub>2</sub>		0.1365	0.1442	0.1533	0.1645	0.1785	0.1970	0.2235	0.2649	0.3481	0.0000
Absolute outlet pressure, P <sub>2</sub>	Kpa a	815.42	771.52	725.02	675.20	621.47	562.94	495.44	416.93	315.52	101.3
Outlet pressure (gauge)	Kpa g	714.095	670.194	623.696	573.873	520.149	461.616	394.118	315.602	214.191	0.000
Outlet temperature, T <sub>2</sub>	°C	18.89	18.67	18.41	18.10	17.71	17.29	16.41	15.09	12.01	-30.47
Compressibility, Z <sub>2</sub>		0.9972	0.9973	0.9975	0.9976	0.9978	0.9980	0.9982	0.9984	0.9987	0.9989
Density, ρ <sub>2</sub>	kg/m <sup>3</sup>	9.7519	9.2527	8.6827	8.0936	7.4584	6.7645	5.9704	5.0461	3.8588	1.4555
Viscosity of gas, μ <sub>2</sub>	Pa.s	1.83E-05	1.83E-05	1.83E-05	1.82E-05	1.82E-05	1.81E-05	1.81E-05	1.81E-05	1.79E-05	1.75E-05
Actual outlet flow	m <sup>3</sup> /hr	7.825	8.2201	8.7408	9.3771	10.1756	11.2195	12.7117	15.0403	19.6678	52.1432
Velocity, V <sub>2</sub>	m/sec	46.9104	49.5483	52.6868	56.5221	61.3355	67.6275	76.6220	90.6581	118.5513	314.3027
Reynolds number, Re <sub>2</sub>		1.914E+05	1.916E+05	1.918E+05	1.921E+05	1.924E+05	1.927E+05	1.932E+05	1.941E+05	1.959E+05	2.233E+05
Friction factor, 4f		0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0241
Recovery factor, r		0.7260	0.7258	0.7255	0.7252	0.7248	0.7245	0.7241	0.7237	0.7234	0.7289
Adiabatic Wall Temperature, T <sub>w</sub>	°C	19.6791	19.6129	19.4726	19.3152	19.1308	18.9347	18.6777	18.1385	17.1752	5.5665
Enthalpy, h	KJ/kg	290.5945	290.4734	290.2228	290.1242	289.8556	289.5710	288.8387	287.6963	284.8371	242.6422
Entropy, s	KJ/kg K	6.2356	6.2511	6.2684	6.2881	6.3109	6.3383	6.3723	6.4178	6.4878	6.6533
Critical Properties at Outlet Mach 1											
Critical Pressure	Kpa G	-0.02									
	Kpa abs	101.31									
Critical Temperature	°C	30.47									
	°C	242.68									
Max length of duct at which no shock occurs	m	12.01									
Drop											
Pressure drop / Segment Length	Kpa	41.88	43.90	46.50	49.82	53.72	58.53	67.50	78.52	101.41	214.21
Temperature drop / Segment Length	°C	0.11	0.22	0.26	0.31	0.39	0.42	0.88	1.32	3.08	42.48
Total pressure drop:	Kpa	755.98									
Total temperature drop:	°C	49.47									

Figure F 11-8: Vent pipe model predictions for air gas at sonic conditions



Gas Property Calculation for Methane @ 100 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Methane:1:											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2224.57	2224.02	2223.35	2222.66	2221.89	2221.06	2220.41	2219.08	2217.87	2216.33	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1696.15	1695.98	1695.71	1695.43	1695.10	1694.73	1694.56	1693.76	1693.10	1692.19	
Ratio of specific heats, $\gamma$	1.3115	1.3113	1.3112	1.3110	1.3108	1.3106	1.3103	1.3102	1.3099	1.3097	
Molecular weight, M.W.	$kg/mole$ 16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	
Gas constant, R	$J/kg \cdot K$ 518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	
Normal or standard flow	$m^3/hr$ 16.7051	16.7051	16.7051	16.7051	16.7051	16.7051	16.7051	16.7051	16.7051	16.7051	
lines/min	278.4185	278.4185	278.4185	278.4185	278.4185	278.4185	278.4185	278.4185	278.4185	278.4185	
<b>Phase flow</b>											
Single											
Actual inlet flow condition	$kg/hr$ 11.36										
$m^3/hr$	8.51	8.84	9.22	9.64	10.14	10.72	11.40	12.26	13.34	14.77	
Standard flow condition	$m^3/hr$ 16.71	16.71	16.71	16.71	16.71	16.71	16.71	16.71	16.71	16.71	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.74	292.74	292.72	292.70	292.67	292.64	292.73	292.59	292.57	292.54	
$^{\circ}F$	19.59	19.59	19.57	19.55	19.52	19.49	19.58	19.44	19.42	19.39	
Inlet Stagnation Pressure	$KPa abs$ 203.09	196.01	187.80	179.97	171.13	162.05	152.69	142.19	131.19	118.92	
Outlet Stagnation Pressure	$KPa abs$ 196.01	187.80	179.97	171.13	162.05	152.69	142.19	131.19	118.92	105.03	
Stagnation Density, $\rho_0$	$kg/m^3$ 1.34	1.30	1.24	1.19	1.13	1.07	1.01	0.94	0.87	0.79	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 896.89	896.96	896.99	897.02	897.05	897.08	897.37	897.16	897.23	897.29	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 100.00	92.56	84.50	76.34	67.56	58.36	48.88	38.15	26.83	14.28	
$KPa abs$ 201.33	193.88	185.83	177.67	168.88	159.69	150.20	139.47	128.16	115.60		
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9558	18.8724	18.7860	18.6784	18.5529	18.5188	18.2041	17.9598	17.6023	
$^{\circ}F$	292.15	292.11	292.02	291.94	291.83	291.70	291.67	291.35	291.11	290.75	
Compressibility, $Z_1$	0.9965	0.9964	0.9965	0.9967	0.9968	0.9970	0.9972	0.9974	0.9976	0.9978	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	
Density, $\rho_1$	$kg/m^3$ 1.3346	1.2833	1.2321	1.1782	1.1201	1.0594	0.9964	0.9261	0.8515	0.7688	
Velocity, $V_1$	$m/sec$ 51.2905	33.2384	35.5597	38.1024	61.1130	64.6136	68.6993	73.9180	80.3930	89.0365	
Mach number at the inlet, $M_1$	0.1153	0.1195	0.1249	0.1304	0.1373	0.1452	0.1543	0.1661	0.1805	0.2000	
$d_{L1}/D$	53.2201	49.0270	44.8374	40.6513	36.4689	32.2901	28.1149	23.9432	19.7755	15.6115	
Reynolds number, $Re_1$	4.817E+04	4.818E+04	4.820E+04	4.822E+04	4.824E+04	4.826E+04	4.827E+04	4.832E+04	4.837E+04	4.843E+04	
Friction factor, $f_1$	0.02650902	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	
Recovery factor, $r_1$	0.72992420	0.7298	0.7297	0.7296	0.7295	0.7294	0.7293	0.7291	0.7290	0.7289	
Adiabatic Wall Temperature, $T_{w1}$	$^{\circ}C$ 19.43	19.42	19.38	19.34	19.29	19.24	19.20	19.10	19.02	18.91	
Enthalpy, $h_1$	$KJ/kg$ 895.59	895.57	895.46	895.35	895.20	895.02	895.04	894.45	894.02	893.36	
Entropy, $s_1$	6.27089020	6.2903	6.3118	6.3346	6.3603	6.3886	6.4203	6.4566	6.4989	6.5499	
<b>Downstream Condition</b>											
$d_{L1-2}/D$	4.1528	4.1528	4.1526	4.1525	4.1523	4.1521	4.1520	4.1515	4.1512	4.1507	
Mach number at the outlet, $M_2$	0.1195	0.1249	0.1304	0.1373	0.1452	0.1543	0.1661	0.1805	0.2000	0.2280	
Absolute outlet pressure, $P_2$	$KPa abs$ 193.88	185.83	177.67	168.88	159.69	150.20	139.47	128.16	115.60	101.33	
Outlet pressure (gauge)	$KPa g$ 92.558	84.302	76.343	67.556	58.364	48.876	38.148	26.833	14.276	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.96	18.87	18.79	18.68	18.55	18.52	18.20	17.96	17.60	17.04	
Compressibility, $Z_2$	0.9964	0.9965	0.9967	0.9968	0.9970	0.9972	0.9974	0.9976	0.9978	0.9981	
Density, $\rho_2$	$kg/m^3$ 1.2833	1.2321	1.1782	1.1201	1.0594	0.9964	0.9261	0.8515	0.7688	0.6750	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.08E-05	
Actual outlet flow	$m^3/hr$ 8.8556	9.2174	9.6393	10.1387	10.7195	11.3973	12.2631	13.3373	14.7713	16.8243	
Velocity, $V_2$	$m/sec$ 33.2384	35.5597	38.1024	61.1130	64.6136	68.6993	73.9180	80.3930	89.0365	101.4115	
Reynolds number, $Re_2$	4.818E+04	4.820E+04	4.822E+04	4.824E+04	4.826E+04	4.827E+04	4.832E+04	4.837E+04	4.843E+04	4.852E+04	
Friction factor, $f_2$	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	
Recovery factor, $r_2$	0.7298	0.7297	0.7296	0.7295	0.7294	0.7293	0.7291	0.7290	0.7289	0.7288	
Adiabatic Wall Temperature, $T_{w2}$	$^{\circ}C$ 19.4196	19.3986	19.3535	19.3109	19.2574	19.2291	19.2085	19.0354	18.9249	18.7536	
Enthalpy, $h_2$	$KJ/kg$ 895.5664	895.4626	895.3533	895.2033	895.0181	895.0387	894.4494	894.0226	893.3580	892.2625	
Entropy, $s_2$	6.2903	6.3118	6.3346	6.3603	6.3886	6.4203	6.4566	6.4989	6.5499	6.6143	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -79.75										
$KPa abs$ 21.58											
Critical Temperature	$^{\circ}C$ 19.85										
$^{\circ}F$ 253.30											
Max length of duct at which no shock occurs	$m$ 15.38										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 7.44	8.06	8.16	8.79	9.19	9.49	10.73	11.31	12.56	14.28	
Temperature drop / Segment Length	$^{\circ}C$ 0.04	0.08	0.09	0.11	0.13	0.03	0.31	0.24	0.36	0.56	
Total pressure drop	$KPa$ 100.00										
Total temperature drop	$^{\circ}C$ 1.76										

Figure F 11-9: Vent pipe model predictions for methane gas at 100 KPa gauge

Gas Property Calculation for Methane @ 200 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Methane:1:											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2230.75	2229.78	2228.66	2227.43	2226.09	2224.59	2223.24	2222.77	2218.12	2214.17	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1697.22	1696.93	1696.51	1696.03	1695.48	1694.83	1694.38	1693.93	1691.42	1688.81	
Ratio of specific heats, $\gamma$	1.3144	1.3140	1.3137	1.3133	1.3130	1.3126	1.3121	1.3118	1.3111	1.3111	
Molecular weight, M.W.	$kg/mole$ 16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	
Gas constant, R	$J/kg \cdot K$ 518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	
Normal or standard flow	$m^3/hr$ 27.6194	27.6194	27.6194	27.6194	27.6194	27.6194	27.6194	27.6194	27.6194	27.6194	
Actual inlet flow condition	$kg/hr$ 18.78										
Standard flow condition	$m^3/hr$ 27.62	27.62	27.62	27.62	27.62	27.62	27.62	27.62	27.62	27.62	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.87	292.87	292.82	292.78	292.73	292.69	292.80	292.58	292.54	292.48	
Inlet Stagnation Pressure	$KPa abs$ 304.54	291.41	277.90	262.99	247.46	230.99	213.37	193.17	170.97	144.78	
Outlet Stagnation Pressure	$KPa abs$ 291.41	277.90	262.99	247.46	230.99	213.37	193.17	170.97	144.78	111.14	
Stagnation Density, $\rho_0$	$kg/m^3$ 2.02	1.93	1.84	1.74	1.64	1.53	1.41	1.28	1.13	0.96	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 896.14	896.27	896.31	896.36	896.42	896.48	896.91	896.62	896.75	896.90	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 200.00	186.68	172.72	157.77	141.99	125.12	107.24	86.45	63.49	36.17	
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9304	18.8063	18.6580	18.4820	18.2664	18.1504	17.5837	16.9967	15.9182	
Compressibility, $Z_1$	0.9944	0.9946	0.9949	0.9952	0.9954	0.9957	0.9961	0.9964	0.9969	0.9973	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.08E-05	
Density, $\rho_1$	$kg/m^3$ 2.0013	1.9128	1.8204	1.7215	1.6172	1.5057	1.3869	1.2506	1.0995	0.9202	
Velocity, $V_1$	$m/sec$ 56.5528	39.1691	62.1713	65.7429	69.9838	75.1673	81.6045	90.4984	102.9363	122.9942	
Mach number at the inlet, $M_1$	0.1271	0.1330	0.1396	0.1477	0.1572	0.1688	0.1833	0.2034	0.2314	0.2768	
Reynolds number, $Re_1$	7.955E+04	7.958E+04	7.962E+04	7.967E+04	7.973E+04	7.980E+04	7.984E+04	8.000E+04	8.016E+04	8.045E+04	
Friction factor, $f_1$	0.02538367	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	
Recovery factor, $r_1$	0.73136208	0.7312	0.7310	0.7308	0.7306	0.7304	0.7301	0.7299	0.7297	0.7294	
Adiabatic Wall Temperature, $T_{w1}$	$^{\circ}C$ 19.52	19.50	19.44	19.37	19.29	19.19	19.24	18.93	18.74	18.41	
Enthalpy, $h_1$	$KJ/kg$ 894.57	894.55	894.42	894.24	894.01	893.70	893.63	893.58	891.51	889.40	
Entropy, $s_1$	6.05937785	6.0826	6.1078	6.1361	6.1677	6.2037	6.2459	6.2965	6.3602	6.4466	
<b>Downstream Condition</b>											
Mach number at the outlet, $M_2$	0.1330	0.1396	0.1477	0.1572	0.1688	0.1833	0.2034	0.2314	0.2768	0.3738	
Absolute outlet pressure, $P_2$	$KPa a$ 288.00	274.05	259.10	243.31	226.44	208.57	187.77	164.82	137.49	101.33	
Outlet pressure (gauge)	$KPa g$ 186.678	172.723	157.774	141.989	125.118	107.242	86.447	63.493	36.169	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.93	18.81	18.66	18.48	18.27	18.15	17.58	16.99	15.92	13.11	
Compressibility, $Z_2$	0.9946	0.9949	0.9952	0.9954	0.9957	0.9961	0.9964	0.9969	0.9973	0.9980	
Density, $\rho_2$	$kg/m^3$ 1.9128	1.8204	1.7215	1.6172	1.5057	1.3869	1.2506	1.0995	0.9202	0.6844	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.08E-05	1.07E-05	
Actual outlet flow	$m^3/hr$ 9.8162	10.3143	10.9068	11.6107	12.4704	13.5383	15.0138	17.0773	20.4049	27.4567	
Velocity, $V_2$	$m/sec$ 39.1691	62.1713	65.7429	69.9838	75.1673	81.6045	90.4984	102.9363	122.9942	165.3796	
Reynolds number, $Re_2$	7.958E+04	7.962E+04	7.967E+04	7.973E+04	7.980E+04	7.984E+04	8.000E+04	8.016E+04	8.045E+04	8.118E+04	
Friction factor, $f_2$	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0253	
Recovery factor, $r_2$	0.7312	0.7310	0.7308	0.7306	0.7304	0.7301	0.7299	0.7297	0.7294	0.7292	
Adiabatic Wall Temperature, $T_{w2}$	$^{\circ}C$ 19.5054	19.4709	19.4001	19.3194	19.2274	19.1623	19.0905	18.7704	18.4470	17.6480	
Enthalpy, $h_2$	$KJ/kg$ 894.5542	894.4194	894.2409	894.0099	893.7018	893.6260	892.5791	891.5116	889.4026	883.5656	
Entropy, $s_2$	6.0826	6.1078	6.1361	6.1677	6.2037	6.2459	6.2965	6.3602	6.4466	6.5842	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -65.72										
Critical Temperature	$^{\circ}C$ 20.04										
Max length of duct at which no shock occurs	$m$ 12.98										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 13.32	13.95	14.95	15.79	16.87	17.88	20.79	22.95	27.32	36.17	
Temperature drop / Segment Length	$^{\circ}C$ 0.07	0.12	0.15	0.18	0.22	0.12	0.57	0.59	1.08	2.81	
Total pressure drop	$KPa$ 200.00										
Total temperature drop	$^{\circ}C$ 5.57										

Figure F 11-10: Vent pipe model predictions for methane gas at 200 KPa gauge

Gas Property Calculation for Methane @ 300 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	m 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Methane:1:											
Specific heat at constant pressure, Cp	J/kg.K	2236.99	2233.66	2234.11	2232.46	2230.64	2228.60	2226.75	2223.37	2219.60	
Specific heat at constant volume, Cv	J/kg.K	1698.29	1697.92	1697.37	1696.76	1696.05	1695.22	1694.66	1692.75	1690.66	
Ratio of specific heats, γ		1.3172	1.3167	1.3162	1.3157	1.3152	1.3146	1.3140	1.3135	1.3129	
Molecular weight, M.W	kg/mole	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	
Gas constant, R	J/kg.K	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge)	K Pa g	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	K Pa	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute)	K Pa abs	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub>	°C	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub>		0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	
Density at standard condition, ρ <sub>std</sub>	kg/m <sup>3</sup>	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	
Normal or standard flow	m <sup>3</sup> /hr	37.9827	37.9827	37.9827	37.9827	37.9827	37.9827	37.9827	37.9827	37.9827	
litres/min		633.0444	633.0444	633.0444	633.0444	633.0444	633.0444	633.0444	633.0444	633.0444	
<b>Phase flow</b>											
Actual inlet flow condition:	kg/hr	25.82									
	m <sup>3</sup> /hr	9.67	10.14	10.69	11.33	12.11	13.09	14.30	16.06	18.63	
Standard flow condition:	m <sup>3</sup> /hr	37.98	37.98	37.98	37.98	37.98	37.98	37.98	37.98	37.98	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub>	°C	292.91	292.91	292.84	292.78	292.71	292.64	292.79	292.49	292.42	
	°C	19.76	19.76	19.69	19.63	19.56	19.49	19.64	19.34	19.27	
Inlet Stagnation Pressure	Kpa abs	405.88	387.22	367.82	347.52	325.78	302.47	277.73	248.66	216.18	
Outlet Stagnation Pressure	Kpa abs	387.22	367.82	347.52	325.78	302.47	277.73	248.66	216.18	176.68	
Stagnation Density, ρ <sub>0</sub>	kg/m <sup>3</sup>	2.69	2.57	2.44	2.31	2.16	2.01	1.84	1.63	1.43	
Stagnation Enthalpy, h <sub>0</sub>	KJ/kg	895.21	895.39	895.44	895.51	895.58	895.67	896.23	895.86	896.26	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub>	Kpa g	300.00	281.32	261.67	240.93	218.77	194.89	169.63	139.55	105.81	
	Kpa abs	401.33	382.65	362.99	342.26	320.09	296.21	270.96	240.88	207.13	
Inlet temperature, T <sub>1</sub>	°C	19.00	18.9196	18.7619	18.5835	18.3678	18.0992	17.7659	17.2302	16.4257	
	°C	292.15	292.07	291.91	291.73	291.52	291.25	290.91	290.38	289.71	
Compressibility, Z <sub>1</sub>		0.9925	0.9920	0.9915	0.9910	0.9904	0.9898	0.9894	0.9894	0.9896	
Viscosity, μ <sub>1</sub>	Pa.s	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	
Density, ρ <sub>1</sub>	kg/m <sup>3</sup>	2.6705	2.5460	2.4157	2.2782	2.1314	1.9734	1.8051	1.6079	1.3857	
Velocity, V <sub>1</sub>	m/sec	58.2844	61.1333	64.4314	68.3187	73.0253	78.8730	86.2253	96.7996	112.3244	
Mach number at the inlet, M <sub>1</sub>		0.1310	0.1375	0.1449	0.1536	0.1641	0.1772	0.1937	0.2176	0.2526	
4f <sub>1</sub> /D		40.0952	36.1871	32.2804	28.3752	24.4716	20.5695	16.6691	12.7701	8.8731	
Reynolds number, Re		1.093E+05	1.093E+05	1.094E+05	1.095E+05	1.096E+05	1.097E+05	1.098E+05	1.101E+05	1.104E+05	
Friction factor, 4f		0.02486675	0.0249	0.0249	0.0249	0.0249	0.0249	0.0249	0.0249	0.0248	
Recovery factor, r		0.73283029	0.7326	0.7323	0.7320	0.7317	0.7314	0.7311	0.7307	0.7303	
Adiabatic Wall Temperature, T <sub>w</sub>	°C	19.56	19.53	19.44	19.35	19.24	19.12	19.19	18.77	18.50	
Enthalpy, h	KJ/kg	895.56	895.57	895.42	895.23	892.97	892.62	892.58	891.25	889.81	
Entropy, s	KJ/kg.K	5.90833475	5.9329	5.9595	5.9891	6.0228	6.0615	6.1073	6.1634	6.2363	
<b>Downstream Condition</b>											
4f <sub>2</sub> /D		3.8956	3.8955	3.8953	3.8951	3.8949	3.8947	3.8945	3.8939	3.8933	
Mach number at the outlet, M <sub>2</sub>		0.1375	0.1449	0.1536	0.1641	0.1772	0.1937	0.2176	0.2526	0.3155	
Absolute outlet pressure, P <sub>2</sub>	Kpa a	382.65	362.99	342.26	320.09	296.21	270.96	240.88	207.13	165.38	
Outlet pressure (gauge)	Kpa g	281.323	261.669	240.933	218.766	194.889	169.634	139.551	105.809	64.058	
Outlet temperature, T <sub>2</sub>	°C	18.92	18.76	18.58	18.37	18.10	17.97	17.23	16.43	14.76	
Compressibility, Z <sub>2</sub>		0.9929	0.9932	0.9936	0.9940	0.9944	0.9949	0.9954	0.9960	0.9968	
Density, ρ <sub>2</sub>	kg/m <sup>3</sup>	2.5460	2.4157	2.2782	2.1314	1.9734	1.8051	1.6079	1.3857	1.1119	
Viscosity of gas, μ <sub>2</sub>	Pa.s	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.07E-05	
Actual outlet flow	m <sup>3</sup> /hr	10.1421	10.6893	11.3342	12.1150	13.0851	14.3049	16.0392	18.6348	23.2223	
Velocity, V <sub>2</sub>	m/sec	61.1333	64.4314	68.3187	73.0253	78.8730	86.2253	96.7996	112.3244	139.9764	
Reynolds number, Re		1.093E+05	1.094E+05	1.095E+05	1.096E+05	1.097E+05	1.098E+05	1.101E+05	1.104E+05	1.115E+05	
Friction factor, 4f		0.0249	0.0249	0.0249	0.0249	0.0249	0.0249	0.0249	0.0249	0.0248	
Recovery factor, r		0.7326	0.7323	0.7320	0.7317	0.7314	0.7311	0.7307	0.7303	0.7299	
Adiabatic Wall Temperature, T <sub>w</sub>	°C	19.5347	19.4894	19.3942	19.2905	19.1699	19.0837	18.9876	18.5522	18.0513	
Enthalpy, h	KJ/kg	895.5676	895.4155	895.2281	892.9729	892.6177	892.5787	891.2497	889.8096	886.5564	
Entropy, s	KJ/kg.K	5.9329	5.9595	5.9891	6.0228	6.0615	6.1073	6.1634	6.2363	6.3413	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	Kpa G	52.44									
	Kpa abs	48.89									
Critical Temperature	°C	20.31									
	°C	252.84									
Max length of duct at which no shock occurs	m	12.35									
<b>Drop</b>											
Pressure drop / Segment Length	Kpa	18.68	19.65	20.74	22.17	23.88	25.25	30.08	33.74	41.75	
Temperature drop / Segment Length	°C	0.08	0.16	0.18	0.22	0.27	0.13	0.74	0.80	1.66	
Total pressure drop	Kpa	300.00									
Total temperature drop	°C	10.78									

Figure F 11-11: Vent pipe model predictions for methane gas at 300 KPa gauge



Gas Property Calculation for Methane @ 400 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Methane:1:											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2243.28	2241.64	2239.70	2237.63	2235.37	2232.85	2230.57	2226.39	2221.76	2214.18	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1699.94	1698.94	1698.28	1697.55	1696.72	1695.75	1695.13	1692.86	1690.42	1685.55	
Ratio of specific heats, $\gamma$	1.3201	1.3194	1.3188	1.3181	1.3175	1.3167	1.3159	1.3152	1.3143	1.3136	
Molecular weight, M.W.	$kg/mole$ 16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	
Gas constant, R	$J/kg \cdot K$ 518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	
Normal or standard flow	$m^3/hr$ 48.1434	48.1434	48.1434	48.1434	48.1434	48.1434	48.1434	48.1434	48.1434	48.1434	
Phase flow	lines/min 802.3892	802.3892	802.3892	802.3892	802.3892	802.3892	802.3892	802.3892	802.3892	802.3892	
<b>Actual inlet flow condition:</b>											
Actual inlet flow condition	$kg/hr$ 32.73										
Standard flow condition	$m^3/hr$ 9.79	10.28	10.85	11.52	12.33	13.35	14.63	16.52	19.34	24.61	
Stagnation Properties											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.93	292.93	292.84	292.76	292.67	292.59	292.76	292.38	292.29	292.18	
Inlet Stagnation Pressure	$KPa abs$ 507.17	484.28	459.24	433.20	405.54	375.96	344.25	306.54	264.52	212.53	
Outlet Stagnation Pressure	$KPa abs$ 484.28	459.24	433.20	405.54	375.96	344.25	306.54	264.52	212.53	131.40	
Stagnation Density, $\rho_0$	$kg/m^3$ 3.37	3.22	3.05	2.88	2.69	2.50	2.28	2.03	1.75	1.41	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 894.22	894.45	894.52	894.60	894.69	894.79	895.49	895.03	895.25	895.54	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 400.00	376.53	351.36	324.85	296.57	266.12	233.88	194.88	151.10	95.88	
Inlet temperature, $T_1$	$^{\circ}C$ 501.33	477.86	452.68	426.18	397.90	367.44	335.20	296.20	252.43	197.21	
Compressibility, $Z_1$	0.9907	0.9911	0.9916	0.9920	0.9925	0.9931	0.9937	0.9944	0.9951	0.9961	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.07E-05	
Density, $\rho_1$	$kg/m^3$ 3.3421	3.1852	3.0179	2.8418	2.6541	2.4522	2.2366	1.9809	1.6922	1.3300	
Velocity, $V_1$	$m/sec$ 59.0293	61.9377	65.3710	69.4212	74.3307	80.4526	88.2052	99.5921	116.5818	148.3293	
Mach number at the inlet, $M_1$	0.1327	0.1391	0.1468	0.1559	0.1669	0.1805	0.1979	0.2236	0.2619	0.3341	
Reynolds number, $Re_1$	39.0050	35.1296	31.2574	27.3883	23.5225	19.6600	15.8007	11.9446	8.0921	4.2432	
Friction factor, $f_1$	0.02456108	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0245	0.0245	
Recovery factor, $r_1$	0.73432430	0.7340	0.7336	0.7333	0.7329	0.7325	0.7320	0.7316	0.7310	0.7305	
Adiabatic Wall Temperature, $T_{w1}$	$^{\circ}C$ 19.57	19.55	19.44	19.32	19.19	19.05	18.91	18.63	18.31	17.69	
Enthalpy, $h_1$	$KJ/kg$ 892.54	892.60	892.45	892.26	892.00	891.64	891.69	890.17	888.57	886.67	
Entropy, $s_1$	5.79050630	5.8153	5.8426	5.8730	5.9074	5.9472	5.9946	6.0531	6.1300	6.2439	
<b>Downstream Condition</b>											
Mach number at the outlet, $M_2$	0.1391	0.1468	0.1559	0.1669	0.1805	0.1979	0.2236	0.2619	0.3341	0.6358	
Absolute outlet pressure, $P_2$	$KPa a$ 477.86	452.68	426.18	397.90	367.44	335.20	296.20	252.43	197.21	101.33	
Outlet pressure (gauge)	$KPa g$ 376.533	351.359	324.852	296.574	266.118	233.880	194.875	151.101	95.882	0.001	
Outlet temperature, $T_2$	$^{\circ}C$ 18.92	18.74	18.53	18.29	17.99	17.66	17.00	16.08	14.06	1.59	
Compressibility, $Z_2$	0.9911	0.9916	0.9920	0.9925	0.9931	0.9937	0.9944	0.9951	0.9961	0.9977	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.07E-05	1.03E-05	
Density, $\rho_2$	$kg/m^3$ 3.1852	3.0179	2.8418	2.6541	2.4522	2.2366	1.9809	1.6922	1.3300	0.7133	
Actual outlet flow	$m^3/hr$ 10.2756	10.8451	11.5171	12.3316	13.3472	14.6334	16.5225	19.5411	24.6080	45.8863	
Velocity, $V_2$	$m/sec$ 61.9377	65.3710	69.4212	74.3307	80.4526	88.2052	99.5921	116.5818	148.3293	276.5881	
Reynolds number, $Re_2$	1.384E+05	1.383E+05	1.380E+05	1.388E+05	1.390E+05	1.391E+05	1.395E+05	1.400E+05	1.409E+05	1.467E+05	
Friction factor, $f_2$	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0245	0.0245	0.0245	
Recovery factor, $r_2$	0.7340	0.7336	0.7333	0.7329	0.7325	0.7320	0.7316	0.7310	0.7305	0.7307	
Adiabatic Wall Temperature, $T_{w2}$	$^{\circ}C$ 19.5486	19.4987	19.3825	19.2571	19.1139	19.0159	18.9078	18.3101	17.7678	14.3330	
Enthalpy, $h_2$	$KJ/kg$ 892.5974	892.4468	892.2593	892.0029	891.6423	891.6933	890.1718	888.5678	884.6882	858.2929	
Entropy, $s_2$	5.8153	5.8426	5.8730	5.9074	5.9472	5.9946	6.0531	6.1300	6.2439	6.4940	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ 39.56										
Critical Temperature	$^{\circ}C$ 20.59										
Max length of duct at which no shock occurs	$m$ 12.16										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 23.47	25.17	26.51	28.28	30.46	32.24	39.00	43.77	55.22	95.88	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.18	0.20	0.24	0.30	0.12	0.86	0.92	2.02	12.47	
Total pressure drop	$KPa$ 400.00										
Total temperature drop	$^{\circ}C$ 17.04										

Figure F 11-12: Vent pipe model predictions for methane gas at 400 KPa gauge

Gas Property Calculation for Methane @ 500 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2249.62	2247.67	2245.35	2242.88	2240.20	2237.20	2234.57	2229.64	2224.27	2215.54	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1700.44	1699.96	1699.20	1698.37	1697.43	1696.32	1695.70	1693.11	1690.41	1685.02	
Ratio of specific heats, $\gamma$	1.3230	1.3222	1.3214	1.3206	1.3198	1.3189	1.3178	1.3169	1.3158	1.3148	
Molecular weight, $M.W.$	$kg/mole$ 16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	
Gas constant, $R$	$J/kg \cdot K$ 518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	
Normal or standard flow	$m^3/hr$ 58.2093	58.2093	58.2093	58.2093	58.2093	58.2093	58.2093	58.2093	58.2093	58.2093	
litres/min	970.1542	970.1542	970.1542	970.1542	970.1542	970.1542	970.1542	970.1542	970.1542	970.1542	
<b>Phase flow</b>											
Actual inlet flow condition	$kg/hr$ 39.57										
$m^3/hr$	9.85	10.34	10.92	11.60	12.43	13.48	14.78	16.74	19.67	25.26	
Standard flow condition	$m^3/hr$ 58.21	58.21	58.21	58.21	58.21	58.21	58.21	58.21	58.21	58.21	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.93	292.93	292.83	292.73	292.63	292.52	292.72	292.26	292.14	292.00	
$^{\circ}F$	19.78	19.78	19.68	19.58	19.48	19.37	19.57	18.99	18.89	18.85	
Inlet Stagnation Pressure	$KPa abs$ 608.44	581.26	550.82	519.25	485.85	449.63	411.91	365.67	314.48	250.83	
Outlet Stagnation Pressure	$KPa abs$ 581.26	550.82	519.25	485.85	449.63	411.91	365.67	314.48	250.83	145.82	
Stagnation Density, $\rho_0$	$kg/m^3$ 4.05	3.87	3.67	3.46	3.23	2.99	2.74	2.09	1.67	1.67	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 893.21	893.49	893.57	893.66	893.77	893.89	894.73	894.16	894.42	894.76	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 500.00	471.82	441.30	409.20	374.99	337.95	299.32	251.57	198.22	130.40	
$KPa abs$ 601.33	573.15	542.63	510.52	476.31	439.27	400.65	352.90	299.54	231.72		
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9190	18.7164	18.4899	18.2230	17.8915	17.7947	16.8266	15.8294	13.6198	
$^{\circ}F$	292.15	292.07	291.87	291.64	291.37	291.04	290.94	289.98	288.98	286.77	
Compressibility, $Z_1$	0.9888	0.9893	0.9899	0.9905	0.9911	0.9917	0.9924	0.9933	0.9942	0.9954	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.07E-05	
Density, $\rho_1$	$kg/m^3$ 4.0163	3.8272	3.6239	3.4102	3.1826	2.9365	2.6773	2.3641	2.0117	1.5663	
Velocity, $V_1$	$m/sec$ 59.3910	62.3257	65.8218	69.9469	74.9483	81.2289	89.0945	100.8973	118.5736	152.2865	
Mach number at the inlet, $M_1$	0.1334	0.1398	0.1477	0.1570	0.1681	0.1822	0.1996	0.2264	0.2662	0.3427	
$4fL_1/D$	38.4391	34.5908	30.7463	26.9056	23.0686	19.2354	15.4060	11.5804	7.7589	3.9415	
Reynolds number, $Re_1$	1.670E+05	1.671E+05	1.673E+05	1.675E+05	1.677E+05	1.679E+05	1.680E+05	1.686E+05	1.693E+05	1.703E+05	
Friction factor, $4f$	0.02435710	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0243	0.0243	0.0243	
Recovery factor, $r$	0.73584190	0.7354	0.7350	0.7345	0.7341	0.7336	0.7330	0.7324	0.7318	0.7311	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.58	19.55	19.45	19.29	19.14	18.97	19.10	18.50	18.14	17.45	
Enthalpy, $h$	$KJ/kg$ 891.52	891.62	891.48	891.50	891.05	890.69	890.87	889.20	887.53	885.33	
Entropy, $s$	5.69371464	5.7187	5.7463	5.7769	5.8117	5.8520	5.9000	5.9595	6.0382	6.1560	
<b>Downstream Condition</b>											
$4fL_2/D$	3.8157	3.8156	3.8155	3.8153	3.8151	3.8149	3.8148	3.8142	3.8137	3.8125	
Mach number at the outlet, $M_2$	0.1398	0.1477	0.1570	0.1681	0.1822	0.1996	0.2264	0.2662	0.3427	0.5733	
Absolute outlet pressure, $P_2$	$KPa a$ 573.15	542.63	510.52	476.31	439.27	400.65	352.90	299.54	231.72	101.33	
Outlet pressure (gauge)	$KPa g$ 471.823	441.300	409.197	374.986	337.949	299.325	251.572	198.216	130.397	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.92	18.72	18.49	18.22	17.89	17.79	16.83	15.83	13.62	-5.36	
Compressibility, $Z_2$	0.9893	0.9899	0.9905	0.9911	0.9917	0.9924	0.9933	0.9942	0.9954	0.9974	
Density, $\rho_2$	$kg/m^3$ 3.8272	3.6239	3.4102	3.1826	2.9365	2.6773	2.3641	2.0117	1.5663	0.7319	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.07E-05	1.01E-05	
Actual outlet flow	$m^3/hr$ 10.3399	10.9199	11.6043	12.4340	13.4760	14.7809	16.7390	19.6715	25.2645	54.0633	
Velocity, $V_2$	$m/sec$ 62.3257	65.8218	69.9469	74.9483	81.2289	89.0945	100.8973	118.5736	152.2865	325.8881	
Reynolds number, $Re_2$	1.671E+05	1.673E+05	1.675E+05	1.677E+05	1.679E+05	1.680E+05	1.686E+05	1.693E+05	1.703E+05	1.815E+05	
Friction factor, $4f$	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0243	0.0243	0.0243	0.0243	
Recovery factor, $r$	0.7354	0.7350	0.7345	0.7341	0.7336	0.7330	0.7324	0.7318	0.7311	0.7317	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.5551	19.5004	19.3650	19.2196	19.0543	18.9466	18.8365	18.2297	17.5457	12.3582	
Enthalpy, $h$	$KJ/kg$ 891.6248	891.4813	891.3012	891.0528	890.6901	890.8695	889.1994	887.5300	883.3317	843.1538	
Entropy, $s$	5.7187	5.7463	5.7769	5.8117	5.8520	5.9000	5.9595	6.0382	6.1560	6.4382	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -26.85										
$KPa abs$ 74.47											
Critical Temperature	$^{\circ}C$ -20.89										
$^{\circ}F$ 252.26											
Max length of duct at which no shock occurs	$m$ 12.09										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 28.18	30.52	32.10	34.21	37.04	38.62	47.75	53.36	67.82	130.40	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.20	0.23	0.27	0.33	0.10	0.97	1.00	2.21	18.98	
Total pressure drop	$KPa$ 500.00										
Total temperature drop	$^{\circ}C$ 24.07										

Figure F 11-13: Vent pipe model predictions for methane gas at 500 KPa gauge

Gas Property Calculation for Methane @ 600 Kpa gauge & 19 °C Inlet Conditions										by Farhan Rajivate	
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	m 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Methane:1:											
Specific heat at constant pressure, Cp	J/kg K	2256.01	2253.75	2251.06	2248.19	2245.09	2241.64	2238.66	2233.02	2226.98	2217.30
Specific heat at constant volume, Cv	J/kg K	1701.51	1700.98	1700.13	1699.20	1698.15	1696.92	1696.30	1693.43	1690.54	1684.81
Ratio of specific heats, Y		1.3259	1.3250	1.3241	1.3231	1.3221	1.3210	1.3197	1.3186	1.3173	1.3161
Molecular weight, M.W	kg/mole	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04
Gas constant, R	J/kg K	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge)	K Pa g	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Atmospheric pressure	K Pa	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Inlet pressure, P <sub>std</sub> (absolute)	K Pa abs	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Temperature, T <sub>std</sub>	°C	15	15	15	15	15	15	15	15	15	15
Compressibility at std cond, Z <sub>std</sub>		0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980
Density at standard condition, ρ <sub>std</sub>	kg/m <sup>3</sup>	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798
Normal or standard flow	m <sup>3</sup> /hr	68.2271	68.2271	68.2271	68.2271	68.2271	68.2271	68.2271	68.2271	68.2271	68.2271
	litres/min	1137.1188	1137.1188	1137.1188	1137.1188	1137.1188	1137.1188	1137.1188	1137.1188	1137.1188	1137.1188
<b>Phase flow</b>											
Single											
Actual inlet flow condition	kg/hr	46.38									
	m <sup>3</sup> /hr	9.88	10.37	10.96	11.65	12.49	13.54	14.85	16.84	19.82	25.56
Standard flow condition	m <sup>3</sup> /hr	68.23	68.23	68.23	68.23	68.23	68.23	68.23	68.23	68.23	68.23
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub>	°C	292.94	292.94	292.82	292.70	292.57	292.44	292.68	292.14	291.99	291.82
	°F	19.79	19.79	19.67	19.55	19.42	19.29	19.53	18.99	18.84	18.67
Inlet Stagnation Pressure	Kpa abs	709.69	677.96	642.46	605.48	566.42	523.81	480.04	425.62	365.58	290.69
Outlet Stagnation Pressure	Kpa abs	677.96	642.46	605.48	566.42	523.81	480.04	425.62	365.58	290.69	163.33
Stagnation Density, ρ <sub>0</sub>	kg/m <sup>3</sup>	4.74	4.52	4.28	4.04	3.78	3.49	3.19	2.83	2.43	1.93
Stagnation Enthalpy, h <sub>0</sub>	KJ/kg	892.19	892.51	892.60	892.71	892.83	892.96	893.94	893.28	893.57	893.95
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub>	Kpa g	600.00	567.07	531.37	493.76	453.72	410.26	365.42	309.10	246.50	166.65
	Kpa abs	701.33	668.40	632.69	595.09	555.04	511.59	466.74	410.43	347.83	267.97
Inlet temperature, T <sub>1</sub>	°C	19.00	18.9177	18.6963	18.4459	18.1618	17.8050	17.3992	16.6785	15.6355	13.3184
	°F	292.15	292.07	291.85	291.60	291.31	290.96	290.89	289.83	288.79	286.47
Compressibility, Z <sub>1</sub>		0.9870	0.9876	0.9882	0.9889	0.9896	0.9904	0.9912	0.9921	0.9933	0.9947
Viscosity, μ <sub>1</sub>	Pa sec	1.10E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.07E-05
Density, ρ <sub>1</sub>	kg/m <sup>3</sup>	4.6930	4.4712	4.2329	3.9820	3.7150	3.4257	3.1235	2.7540	2.3398	1.8146
Velocity, V <sub>1</sub>	m/sec	59.5748	62.5298	66.0503	70.2121	75.2577	81.6131	89.5100	101.5190	119.4915	154.0708
Mach number at the inlet, M <sub>1</sub>		0.1338	0.1402	0.1482	0.1575	0.1687	0.1830	0.2004	0.2276	0.2680	0.3465
4fL <sub>1</sub> /D		38.1161	34.2891	30.4661	26.6470	22.8318	19.0207	15.2136	11.4103	7.6114	3.8168
Reynolds number, Re		1.955E+05	1.958E+05	1.958E+05	1.961E+05	1.964E+05	1.967E+05	1.968E+05	1.976E+05	1.984E+05	2.000E+05
Friction factor, 4f		0.02421064	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242
Recovery factor, r		0.73738185	0.7369	0.7364	0.7358	0.7353	0.7347	0.7340	0.7333	0.7325	0.7317
Adiabatic Wall Temperature, T <sub>w</sub>	°C	19.58	19.56	19.41	19.26	19.09	18.90	19.05	18.37	17.98	17.23
Enthalpy, h	KJ/kg	890.50	890.65	890.52	890.35	890.11	889.75	890.07	888.28	886.60	882.28
Entropy, s	J/kg K	5.61145191	5.6366	5.6642	5.6950	5.7299	5.7705	5.8187	5.8786	5.9580	6.0774
<b>Downstream Condition</b>											
4fL <sub>2</sub> /D		3.7928	3.7927	3.7925	3.7924	3.7922	3.7920	3.7919	3.7913	3.7908	3.7897
Mach number at the outlet, M <sub>2</sub>		0.1402	0.1482	0.1575	0.1687	0.1830	0.2004	0.2276	0.2680	0.3465	0.8734
Absolute outlet pressure, P <sub>2</sub>	Kpa g	668.40	632.69	595.09	555.04	511.59	466.74	410.43	347.83	267.97	101.32
	Kpa abs	567.072	531.369	493.764	453.716	410.265	365.419	309.103	246.505	166.650	0.000
Outlet temperature, T <sub>2</sub>	°C	18.92	18.70	18.45	18.16	17.81	17.34	16.68	15.64	13.32	-12.77
Compressibility, Z <sub>2</sub>		0.9876	0.9882	0.9889	0.9896	0.9904	0.9912	0.9921	0.9933	0.9947	0.9972
Density, ρ <sub>2</sub>	kg/m <sup>3</sup>	4.4712	4.2329	3.9820	3.7150	3.4257	3.1235	2.7540	2.3398	1.8146	0.7530
Viscosity of gas, μ <sub>2</sub>	Pa sec	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.07E-05	9.82E-06
Actual outlet flow	m <sup>3</sup> /hr	10.3738	10.9578	11.6483	12.4854	13.5397	14.8498	16.8421	19.8238	25.5606	61.6001
Velocity, V <sub>2</sub>	m/sec	62.5298	66.0503	70.2121	75.2577	81.6131	89.5100	101.5190	119.4915	154.0708	371.3055
Reynolds number, Re		1.956E+05	1.958E+05	1.961E+05	1.964E+05	1.967E+05	1.968E+05	1.976E+05	1.984E+05	2.000E+05	2.182E+05
Friction factor, 4f		0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0241
Recovery factor, r		0.7369	0.7364	0.7358	0.7353	0.7347	0.7340	0.7333	0.7325	0.7317	0.7330
Adiabatic Wall Temperature, T <sub>w</sub>	°C	19.5580	19.4981	19.3442	19.1798	18.9938	18.7880	18.7686	18.0900	17.3592	10.2741
Enthalpy, h	KJ/kg	890.6488	890.5153	890.3459	890.1090	889.7545	890.0676	888.2758	886.5976	882.2830	821.0969
Entropy, s	J/kg K	5.6366	5.6642	5.6950	5.7299	5.7705	5.8187	5.8786	5.9580	6.0774	6.3774
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	Kpa G	14.27									
	Kpa abs	87.05									
Critical Temperature	°C	21.20									
	°F	251.95									
Max length of duct at which no shock occurs	m	12.06									
<b>Drop</b>											
Pressure drop / Segment Length	Kpa	32.93	35.70	37.61	40.05	43.45	44.85	56.32	62.60	79.85	166.65
Temperature drop / Segment Length	°C	0.08	0.22	0.25	0.29	0.36	0.07	1.06	1.04	2.32	26.09
Total pressure drop	Kpa	600.00									
Total temperature drop	°C	31.63									

Figure F 11-14: Vent pipe model predictions for methane gas at 600 KPa gauge



Gas Property Calculation for Methane @ 700 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Methane:1:											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2262.46	2259.88	2256.81	2253.56	2250.05	2246.15	2242.82	2239.49	2236.81	2234.31	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1702.59	1702.01	1701.06	1700.03	1698.88	1697.54	1696.92	1696.78	1696.73	1696.74	
Ratio of specific heats, $\gamma$	1.3288	1.3278	1.3267	1.3256	1.3244	1.3232	1.3221	1.3210	1.3198	1.3187	
Molecular weight, M.W.	$kg/mole$ 16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	
Gas constant, R	$J/kg \cdot K$ 518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	
Normal or standard flow	$m^3/hr$ 1303.6887	1303.6887	1303.6887	1303.6887	1303.6887	1303.6887	1303.6887	1303.6887	1303.6887	1303.6887	
<b>Phase flow</b>											
Single											
Actual inlet flow condition	$kg/hr$ 53.18										
	$m^3/hr$ 9.90	10.39	10.98	11.67	12.51	13.57	14.88	16.89	19.89	25.67	
Standard flow condition	$m^3/hr$ 78.22	78.22	78.22	78.22	78.22	78.22	78.22	78.22	78.22	78.22	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.94	292.93	292.90	292.66	292.52	292.56	292.63	292.01	291.84	291.64	
	$^{\circ}F$ 19.79	19.78	19.65	19.51	19.37	19.21	19.48	18.86	18.69	18.49	
Inlet Stagnation Pressure	$KPa abs$ 810.93	774.58	734.13	691.80	647.13	598.28	548.58	486.03	417.35	331.61	
Outlet Stagnation Pressure	$KPa abs$ 774.58	734.13	691.80	647.13	598.28	548.58	486.03	417.35	331.61	184.20	
Stagnation Density, $\rho_0$	$kg/m^3$ 5.42	5.18	4.90	4.62	4.32	3.99	3.65	3.24	2.78	2.21	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 891.16	891.52	891.62	891.74	891.88	892.03	892.15	892.38	892.70	893.12	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 700.00	662.33	621.51	578.46	532.63	482.86	431.98	367.13	295.51	204.06	
	$KPa abs$ 801.33	763.65	722.83	679.78	633.95	584.19	533.30	468.46	396.83	305.39	
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9164	18.6765	18.4111	18.1027	17.7232	17.6916	16.5426	15.4661	13.0909	
	$^{\circ}F$ 292.15	292.07	291.83	291.56	291.25	290.87	290.84	289.69	288.62	286.24	
Compressibility, $Z_1$	0.9851	0.9858	0.9865	0.9873	0.9881	0.9890	0.9899	0.9910	0.9923	0.9939	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.10E-05	1.10E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	1.07E-05	
Density, $\rho_1$	$kg/m^3$ 5.3722	5.1176	4.8445	4.5566	4.2504	3.9184	3.5740	3.1484	2.6736	2.0712	
Velocity, $V_1$	$m/sec$ 59.6660	62.6347	66.1654	70.3459	75.4132	81.8032	89.6851	101.8090	119.8917	154.7571	
Mach number at the inlet, $M_1$	0.1340	0.1405	0.1484	0.1577	0.1690	0.1833	0.2007	0.2280	0.2687	0.3477	
$4fL_1/D$	37.9192	34.1090	30.3028	26.5006	22.7024	18.9083	15.1182	11.3321	7.5504	3.7729	
Reynolds number, $Re_1$	2.238E+05	2.240E+05	2.243E+05	2.246E+05	2.249E+05	2.253E+05	2.258E+05	2.265E+05	2.274E+05	2.293E+05	
Friction factor, $4f$	0.02410010	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	
Recovery factor, $r$	0.73894338	0.7384	0.7378	0.7372	0.7365	0.7358	0.7350	0.7342	0.7333	0.7323	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.58	19.56	19.39	19.22	19.03	18.82	19.01	18.24	17.83	17.04	
Enthalpy, $h$	$KJ/kg$ 889.47	889.67	889.55	889.39	889.17	888.82	889.28	887.37	885.71	883.38	
Entropy, $s$	5.53982874	5.5651	5.5927	5.6236	5.6586	5.6993	5.7476	5.8076	5.8871	6.0069	
<b>Downstream Condition</b>											
$4fL_2/D$	3.7755	3.7754	3.7752	3.7751	3.7749	3.7747	3.7746	3.7741	3.7736	3.7726	
Mach number at the outlet, $M_2$	0.1405	0.1484	0.1577	0.1690	0.1833	0.2007	0.2280	0.2687	0.3477	0.9845	
Absolute outlet pressure, $P_2$	$KPa a$ 763.65	722.83	679.78	633.95	584.19	533.30	468.46	396.83	305.39	101.33	
Outlet pressure (gauge)	$KPa g$ 662.329	621.510	578.456	532.627	482.864	431.979	367.133	295.506	204.064	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.92	18.68	18.41	18.10	17.72	17.69	16.54	15.47	13.09	-20.44	
Compressibility, $Z_2$	0.9858	0.9865	0.9873	0.9881	0.9890	0.9899	0.9910	0.9923	0.9939	0.9969	
Density, $\rho_2$	$kg/m^3$ 5.1176	4.8445	4.5566	4.2504	3.9184	3.5740	3.1484	2.6736	2.0712	0.7760	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.10E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.07E-05	1.06E-05	9.50E-06	
Actual outlet flow	$m^3/hr$ 10.3912	10.9769	11.6705	12.5112	13.5713	14.8789	16.8902	19.8902	25.6744	68.5234	
Velocity, $V_2$	$m/sec$ 62.6347	66.1654	70.3459	75.4132	81.8032	89.6851	101.8090	119.8917	154.7571	413.0371	
Reynolds number, $Re_2$	2.240E+05	2.243E+05	2.246E+05	2.249E+05	2.253E+05	2.258E+05	2.265E+05	2.274E+05	2.293E+05	2.370E+05	
Friction factor, $4f$	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0240	
Recovery factor, $r$	0.7384	0.7378	0.7372	0.7365	0.7358	0.7350	0.7342	0.7333	0.7323	0.7343	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.5590	19.4939	19.3217	19.1385	18.9323	18.8097	18.7028	17.9548	17.1903	8.1449	
Enthalpy, $h$	$KJ/kg$ 889.6714	889.5477	889.3907	889.1665	888.8248	889.2770	887.3724	885.7111	883.3845	810.5753	
Entropy, $s$	5.5651	5.5927	5.6236	5.6586	5.6993	5.7476	5.8076	5.8871	6.0069	6.3130	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -1.79										
	$KPa abs$ 99.54										
Critical Temperature	$^{\circ}C$ -21.51										
	$^{\circ}F$ -5.5164										
Max length of duct at which no shock occurs	$m$ 12.05										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 37.67	40.82	43.05	45.83	49.76	50.88	64.85	71.63	91.44	204.06	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.24	0.27	0.31	0.38	0.03	1.15	1.08	2.38	33.53	
Total pressure drop	$KPa$ 700.00										
Total temperature drop	$^{\circ}C$ 39.49										

Figure F 11-15: Vent pipe model predictions for methane gas at 700 KPa gauge

Gas Property Calculation for Methane @ 713.2 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, (e/D)	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	m 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Methane:1:											
Specific heat at constant pressure, Cp	J/kg.K	2263.32	2260.69	2257.58	2254.27	2250.71	2246.75	2243.37	2236.95	2230.19	
Specific heat at constant volume, Cv	J/kg.K	1702.73	1702.14	1701.18	1700.14	1698.98	1697.62	1697.00	1693.83	1690.76	
Ratio of specific heats, γ		1.3292	1.3281	1.3271	1.3259	1.3247	1.3235	1.3220	1.3206	1.3191	
Molecular weight, M.W	kg/mole	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	
Gas constant, R	J/kg.K	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	518.27	
<b>Standard condition</b>											
Inlet pressure, P <sub>gpg</sub> (gauge)	K Pa g	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	K Pa	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>gpa</sub> (absolute)	K Pa abs	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub>	°C	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub>		0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	
Density at standard condition, ρ <sub>std</sub>	kg/m <sup>3</sup>	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	0.6798	
Normal or standard flow	m <sup>3</sup> /hr	79.5396	79.5396	79.5396	79.5396	79.5396	79.5396	79.5396	79.5396	79.5396	
	litres/min	1325.6602	1325.6602	1325.6602	1325.6602	1325.6602	1325.6602	1325.6602	1325.6602	1325.6602	
<b>Phase flow</b>											
Single											
Actual inlet flow condition:	kg/hr	54.07									
	m <sup>3</sup> /hr	9.90	10.39	10.98	11.67	12.51	13.57	14.88	16.89	19.90	
Standard flow condition:	m <sup>3</sup> /hr	79.54	79.54	79.54	79.54	79.54	79.54	79.54	79.54	79.54	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub>	°C	292.34	292.93	292.79	292.65	292.51	292.35	292.63	291.99	291.82	
	°F	19.79	19.78	19.64	19.50	19.36	19.20	19.48	18.84	18.67	
Inlet Stagnation Pressure	Kpa abs	824.30	787.34	746.23	703.20	657.79	608.13	557.66	494.03	424.22	
Outlet Stagnation Pressure	Kpa abs	787.34	746.23	703.20	657.79	608.13	557.66	494.03	424.22	337.07	
Stagnation Density, ρ <sub>0</sub>	kg/m <sup>3</sup>	5.51	5.26	4.99	4.70	4.39	4.06	3.72	3.29	2.24	
Stagnation Enthalpy, h <sub>0</sub>	KJ/kg	891.02	891.39	891.49	891.62	891.75	891.91	893.04	892.26	892.58	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub>	Kpa g	713.20	674.91	633.41	589.64	543.05	492.46	440.79	374.82	302.01	
	Kpa abs	814.43	776.23	734.74	690.97	644.38	593.79	542.12	476.14	403.34	
Inlet temperature, T <sub>1</sub>	°C	19.00	18.9162	18.6739	18.4061	18.0950	17.7126	17.6857	16.5252	15.4448	
	°F	292.15	292.07	291.82	291.56	291.24	290.86	290.84	289.68	286.21	
Compressibility, Z <sub>1</sub>		0.9849	0.9856	0.9863	0.9871	0.9879	0.9888	0.9898	0.9909	0.9922	
Viscosity, μ <sub>1</sub>	Pa.s	1.10E-05	1.10E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.08E-05	
Density, ρ <sub>1</sub>	kg/m <sup>3</sup>	5.4620	5.2031	4.9254	4.6326	4.3213	3.9836	3.6338	3.2007	2.7179	
Velocity, V <sub>1</sub>	m/sec	59.6736	62.6435	66.1752	70.3574	75.4266	81.8193	89.6968	101.8323	119.9215	
Mach number at the inlet, M <sub>1</sub>		0.1340	0.1405	0.1484	0.1577	0.1690	0.1833	0.2007	0.2281	0.2687	
4fL <sub>1</sub> /D		37.8993	34.0910	30.2868	26.4865	22.6903	18.8981	15.1100	11.3259	7.5461	
Reynolds number, Re		2.27E+05	2.27E+05	2.280E+05	2.283E+05	2.287E+05	2.291E+05	2.293E+05	2.303E+05	2.312E+05	
Friction factor, 4f		0.02408750	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	
Recovery factor, r		0.73915108	0.7386	0.7380	0.7373	0.7367	0.7360	0.7352	0.7343	0.7334	
Adiabatic Wall Temperature, T <sub>w</sub>	°C	19.58	19.56	19.39	19.22	19.03	18.81	19.00	18.23	17.81	
Enthalpy, h	KJ/kg	889.34	889.54	889.42	889.26	889.04	888.70	889.17	887.25	885.60	
Entropy, s	J/kg.K	5.53102521	5.5363	5.5840	5.6148	5.6498	5.6905	5.7388	5.7988	5.8783	
<b>Downstream Condition</b>											
4fL <sub>2</sub> /D		3.7735	3.7734	3.7733	3.7731	3.7729	3.7727	3.7726	3.7721	3.7716	
Mach number at the outlet, M <sub>2</sub>		0.1405	0.1484	0.1577	0.1690	0.1833	0.2007	0.2281	0.2687	0.3477	
Absolute outlet pressure, P <sub>2</sub>	Kpa a	776.23	734.74	690.97	644.38	593.79	542.12	476.14	403.34	310.39	
Outlet pressure (gauge)	Kpa g	674.906	633.411	589.642	543.052	492.462	440.794	374.819	302.012	209.065	
Outlet temperature, T <sub>2</sub>	°C	18.92	18.67	18.41	18.09	17.71	17.69	16.53	15.44	13.06	
Compressibility, Z <sub>2</sub>		0.9856	0.9863	0.9871	0.9879	0.9888	0.9898	0.9909	0.9922	0.9938	
Density, ρ <sub>2</sub>	kg/m <sup>3</sup>	5.2031	4.9254	4.6326	4.3213	3.9836	3.6338	3.2007	2.7179	2.1056	
Viscosity of gas, μ <sub>2</sub>	Pa.s	1.10E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.09E-05	1.08E-05	1.07E-05	9.52E-06	
Actual outlet flow	m <sup>3</sup> /hr	10.3926	10.9786	11.6724	12.5134	13.5739	14.8808	16.8941	19.8951	25.6814	
Velocity, V <sub>2</sub>	m/sec	62.6435	66.1752	70.3574	75.4266	81.8193	89.6968	101.8323	119.9215	154.7993	
Reynolds number, Re		2.27E+05	2.280E+05	2.283E+05	2.287E+05	2.291E+05	2.293E+05	2.303E+05	2.312E+05	2.332E+05	
Friction factor, 4f		0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0240	
Recovery factor, r		0.7386	0.7380	0.7373	0.7367	0.7360	0.7352	0.7343	0.7334	0.7345	
Adiabatic Wall Temperature, T <sub>w</sub>	°C	19.5591	19.4932	19.3186	19.1330	18.9242	18.8007	18.6942	17.9371	17.1688	
Enthalpy, h	KJ/kg	889.5423	889.4198	889.2643	889.0421	888.7022	889.1732	887.2539	885.5960	881.2723	
Entropy, s	J/kg.K	5.5563	5.5840	5.6148	5.6498	5.6905	5.7388	5.7988	5.8783	5.9981	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	Kpa G	-0.15									
	Kpa abs	101.18									
Critical Temperature	°C	21.55									
	°F	251.60									
Max length of duct at which no shock occurs	m	12.05									
<b>Drop</b>											
Pressure drop / Segment Length	Kpa	38.29	41.49	43.77	46.59	50.59	51.67	65.98	72.81	92.95	
Temperature drop / Segment Length	°C	0.08	0.24	0.27	0.31	0.38	0.03	1.16	1.08	2.38	
Total pressure drop	Kpa	713.20									
Total temperature drop	°C	40.54									

Figure F 11-16: Vent pipe model predictions for methane gas at sonic conditions



Gas Property Calculation for Carbon-dioxide @ 100 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, (e/D):	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>	<b>Carbon dioxide,1:</b>										
Specific heat at constant pressure, cp:	J/kg K 852.66	852.05	851.33	850.60	849.81	848.97	848.41	847.03	845.91	844.58	
Specific heat at constant volume, cv:	J/kg K 654.16	653.91	653.58	653.23	652.86	652.45	652.35	651.47	650.88	650.14	
Ratio of specific heats, γ:	1.3034	1.3030	1.3026	1.3021	1.3017	1.3012	1.3005	1.3002	1.2996	1.2991	
Molecular weight, M.W:	kg/mole 44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	
Gas constant, R:	J/kg K 188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	
<b>Standard condition</b>	<b>Standard condition</b>										
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	
Normal or standard flow:	m <sup>3</sup> /hr 10.1870	10.1870	10.1870	10.1870	10.1870	10.1870	10.1870	10.1870	10.1870	10.1870	
litres/min:	169.7834	169.7834	169.7834	169.7834	169.7834	169.7834	169.7834	169.7834	169.7834	169.7834	
<b>Phase flow</b>	<b>Single</b>										
Actual inlet flow condition:	kg/hr 19.07										
m <sup>3</sup> /hr:	5.17	5.37	5.60	5.86	6.17	6.52	6.92	7.46	8.12	9.00	
Standard flow condition:	m <sup>3</sup> /hr 10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	10.19	
<b>Stagnation Properties</b>	<b>Stagnation Properties</b>										
Stagnation Temperature, T <sub>0</sub> :	°C 292.72	292.72	292.66	292.61	292.55	292.49	292.75	292.34	292.30	292.22	
°F:	19.57	19.57	19.51	19.46	19.40	19.34	19.60	19.19	19.15	19.07	
Inlet Stagnation Pressure:	Kpa abs 203.12	195.90	187.82	179.77	171.29	162.11	153.15	142.29	131.14	118.91	
Outlet Stagnation Pressure:	Kpa abs 195.90	187.82	179.77	171.29	162.11	153.15	142.29	131.14	118.91	105.14	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 3.71	3.58	3.43	3.28	3.13	2.96	2.79	2.60	2.39	2.17	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 500.24	500.31	500.34	500.38	500.41	500.45	500.76	500.52	500.59	500.64	
<b>Upstream Condition</b>	<b>Upstream Condition</b>										
Inlet pressure, P <sub>1</sub> :	Kpa g 100.00	92.33	84.50	76.26	67.58	58.35	49.33	38.13	26.77	14.23	
Kpa abs:	201.33	193.85	185.83	177.58	168.91	159.68	150.66	139.46	128.10	115.55	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9543	18.8410	18.7216	18.5872	18.4285	18.2526	17.9994	17.7279	17.3317	
°F:	292.15	292.10	291.99	291.87	291.74	291.58	291.72	291.15	290.88	290.48	
Compressibility, Z <sub>1</sub> :	0.9892	0.9896	0.9901	0.9905	0.9909	0.9914	0.9919	0.9925	0.9931	0.9937	
Viscosity, μ <sub>1</sub> :	Pa.sec 1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 3.6873	3.5495	3.4024	3.2514	3.0926	2.9237	2.7559	2.5546	2.3473	2.1188	
Velocity, V <sub>1</sub> :	m/sec 31.1719	32.3817	33.7814	35.3508	37.1653	39.3122	41.7067	44.9932	48.9671	54.2462	
Mach number at the inlet, M <sub>1</sub> :	0.1168	0.1212	0.1265	0.1323	0.1390	0.1471	0.1559	0.1682	0.1831	0.2028	
4fL <sub>1</sub> /D:	52.0304	47.9352	43.8424	39.7522	35.6646	31.5796	27.4972	23.4170	19.3400	15.2657	
Reynolds number, Re:	6.010E+04	6.012E+04	6.014E+04	6.017E+04	6.020E+04	6.023E+04	6.026E+04	6.038E+04	6.038E+04	6.047E+04	
Friction factor, 4f:	0.02596042	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0259	0.0259	
Recovery factor, r:	0.77059787	0.7702	0.7699	0.7695	0.7691	0.7687	0.7682	0.7678	0.7674	0.7669	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.44	19.43	19.36	19.29	19.21	19.13	19.36	18.92	18.82	18.67	
Enthalpy, h:	KJ/kg 499.78	499.81	499.79	499.77	499.74	499.70	499.91	499.53	499.42	499.20	
Entropy, s:	2.58751848	2.5947	2.6026	2.6110	2.6202	2.6306	2.6422	2.6554	2.6710	2.6896	
<b>Downstream Condition</b>	<b>Downstream Condition</b>										
4fL <sub>2</sub> /D:	4.0669	4.0668	4.0667	4.0665	4.0663	4.0661	4.0663	4.0656	4.0652	4.0647	
Mach number at the outlet, M <sub>2</sub> :	0.1212	0.1265	0.1323	0.1390	0.1471	0.1559	0.1682	0.1831	0.2028	0.2309	
Absolute outlet pressure, P <sub>2</sub> :	Kpa g 193.85	185.83	177.58	168.91	159.68	150.66	139.46	128.10	115.55	101.33	
Kpa abs:	92.526	84.500	76.255	67.585	58.353	49.334	38.133	26.773	14.225	0.000	
Outlet temperature, T <sub>2</sub> :	°C 18.95	18.84	18.72	18.59	18.43	18.27	18.00	17.73	17.33	16.74	
Compressibility, Z <sub>2</sub> :	0.9896	0.9901	0.9905	0.9909	0.9914	0.9919	0.9925	0.9931	0.9937	0.9943	
Viscosity of gas, μ <sub>2</sub> :	Pa.sec 1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	
Actual outlet flow:	m <sup>3</sup> /hr 5.3722	5.6044	5.8647	6.1658	6.5220	6.9192	7.4644	8.1237	8.9995	10.2496	
Velocity, V <sub>2</sub> :	m/sec 32.3817	33.7814	35.3508	37.1653	39.3122	41.7067	44.9932	48.9671	54.2462	61.7814	
Reynolds number, Re:	6.012E+04	6.014E+04	6.017E+04	6.020E+04	6.023E+04	6.026E+04	6.033E+04	6.038E+04	6.047E+04	6.059E+04	
Friction factor, 4f:	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0259	0.0259	0.0259	
Recovery factor, r:	0.7702	0.7699	0.7695	0.7691	0.7687	0.7682	0.7678	0.7674	0.7669	0.7663	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.4284	19.4020	19.3292	19.2555	19.1752	19.1611	19.2267	18.8533	18.7224	18.5283	
Enthalpy, h:	KJ/kg 499.8102	499.7926	499.7719	499.7429	499.6988	499.9096	499.5338	499.4159	499.2048	498.8455	
Entropy, s:	2.5947	2.6026	2.6110	2.6202	2.6306	2.6422	2.6554	2.6710	2.6896	2.7130	
<b>Critical Properties at Outlet Mach 1</b>	<b>Critical Properties at Outlet Mach 1</b>										
Critical Pressure:	Kpa G -79.42										
Kpa abs:	21.91										
Critical Temperature:	°C -18.96										
°F:	254.19										
Max length of duct at which no shock occurs:	m 15.35										
<b>Drop</b>	<b>Drop</b>										
Pressure drop / Segment Length:	Kpa 7.47	8.03	8.24	8.67	9.23	9.02	11.20	11.36	12.55	14.22	
Temperature drop / Segment Length:	°C 0.05	0.11	0.12	0.13	0.16	-0.14	0.57	0.27	0.40	0.59	
Total pressure drop:	Kpa 100.00										
Total temperature drop:	°C 1.76										

Figure F 11-17: Vent pipe model predictions for carbon-dioxide gas at 100 KPa gauge

Gas Property Calculation for Carbon-dioxide @ 200 Kpa gauge & 19 °C Inlet Conditions										by Farhan Rajivate	
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Carbon dioxide, 1:											
Specific heat at constant pressure, cp:	J/kg K	860.43	859.32	858.08	856.75	855.32	853.78	852.57	850.04	847.68	844.50
Specific heat at constant volume, cv:	J/kg K	656.92	656.48	655.92	655.32	654.65	653.92	653.57	652.03	650.75	648.84
Ratio of specific heats, γ:		1.3098	1.3090	1.3082	1.3074	1.3065	1.3056	1.3045	1.3037	1.3026	1.3015
Molecular weight, M.W:	kg/mole	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01
Gas constant, R:	J/kg K	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :		0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup>	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	
Normal or standard flow:	m <sup>3</sup> /hr	16.8211	16.8211	16.8211	16.8211	16.8211	16.8211	16.8211	16.8211	16.8211	
litres/min:		280.3522	280.3522	280.3522	280.3522	280.3522	280.3522	280.3522	280.3522	280.3522	
<b>Phase flow</b>											
Single											
Actual inlet flow condition:	kg/hr	31.49									
m <sup>3</sup> /hr:		5.67	5.94	6.24	6.60	7.03	7.56	8.18	9.11	10.37	12.40
Standard flow condition:	m <sup>3</sup> /hr	16.82	16.82	16.82	16.82	16.82	16.82	16.82	16.82	16.82	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C	292.83	292.82	292.72	292.62	292.51	292.40	292.74	292.13	292.02	291.88
°F:		19.68	19.67	19.57	19.47	19.36	19.25	19.59	18.98	18.87	18.73
Inlet Stagnation Pressure:	Kpa abs	304.38	291.24	277.75	263.07	247.51	231.04	214.16	193.12	170.94	144.90
Outlet Stagnation Pressure:	Kpa abs	291.24	277.75	263.07	247.51	231.04	214.16	193.12	170.94	144.90	111.32
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup>	5.60	5.35	5.10	4.83	4.54	4.23	3.92	3.54	3.13	2.65
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg	499.34	499.47	499.51	499.57	499.63	499.70	500.16	499.84	499.97	500.10
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g	200.00	186.62	172.64	157.75	141.92	125.03	108.08	86.29	63.35	36.10
Kpa abs:		301.33	287.95	273.97	259.07	243.25	226.36	209.41	187.61	164.68	137.43
Inlet temperature, T <sub>1</sub> :	°C	19.00	18.9285	18.7461	18.5458	18.3122	18.0365	18.1665	17.2061	16.5690	15.4288
°F:		292.15	292.08	291.90	291.70	291.46	291.19	291.32	290.36	288.58	288.58
Compressibility, Z <sub>1</sub> :		0.9838	0.9845	0.9853	0.9860	0.9869	0.9878	0.9887	0.9898	0.9910	0.9924
Viscosity, μ <sub>1</sub> :	Pa.s	1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.43E-05
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup>	5.5491	5.3003	5.0423	4.7677	4.4763	4.1657	3.8484	3.4555	3.0361	2.5401
Velocity, V <sub>1</sub> :	m/sec	34.2021	35.8080	37.6395	39.8081	42.3988	45.5606	49.3174	54.9242	62.5115	74.7186
Mach number at the inlet, M <sub>1</sub> :		0.1282	0.1342	0.1409	0.1490	0.1586	0.1703	0.1842	0.2053	0.2336	0.2792
4fL <sub>1-2</sub> /D:		42.2902	38.3543	34.4203	30.4883	26.5583	22.6303	18.7044	14.7802	10.8587	6.9395
Reynolds number, Re:		9.919E+04	9.922E+04	9.929E+04	9.936E+04	9.945E+04	9.955E+04	9.952E+04	9.985E+04	1.001E+05	1.005E+05
Friction factor, 4f:		0.02501052	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250
Recovery factor, r:		0.77579509	0.7751	0.7745	0.7738	0.7731	0.7723	0.7714	0.7707	0.7697	0.7687
Adiabatic Wall Temperature, T <sub>w</sub> :	°C	19.53	19.51	19.39	19.26	19.12	18.98	19.27	18.57	18.34	17.97
Enthalpy, h:	KJ/kg	498.79	498.86	498.84	498.82	498.77	498.71	498.99	498.38	498.07	497.38
Entropy, s:	J/kg K	2.50896426	2.5177	2.5268	2.5372	2.5488	2.5620	2.5775	2.5959	2.6192	2.6507
<b>Downstream Condition</b>											
4fL <sub>1-2</sub> /D:		3.9181	3.9180	3.9179	3.9177	3.9175	3.9172	3.9173	3.9165	3.9159	3.9150
Mach number at the outlet, M <sub>2</sub> :		0.1342	0.1409	0.1490	0.1586	0.1703	0.1842	0.2053	0.2336	0.2792	0.3769
Absolute outlet pressure, P <sub>2</sub> :	Kpa a	287.95	273.97	259.07	243.25	226.36	209.41	187.61	164.68	137.43	101.33
Outlet pressure (gauge):	Kpa g	186.624	172.644	157.746	141.925	125.032	108.081	86.288	63.353	36.101	0.000
Outlet temperature, T <sub>2</sub> :	°C	18.93	18.75	18.55	18.31	18.04	17.71	17.21	16.57	15.43	12.58
Compressibility, Z <sub>2</sub> :		0.9845	0.9853	0.9860	0.9869	0.9878	0.9887	0.9898	0.9910	0.9924	0.9942
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup>	5.3003	5.0423	4.7677	4.4763	4.1657	3.8484	3.4555	3.0361	2.5401	1.8880
Viscosity of gas, μ <sub>2</sub> :	Pa.s	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.43E-05	1.43E-05
Actual outlet flow:	m <sup>3</sup> /hr	5.9406	6.2444	6.6042	7.0340	7.5586	8.1818	9.1120	10.3707	12.3959	16.6771
Velocity, V <sub>2</sub> :	m/sec	35.8080	37.6395	39.8081	42.3988	45.5606	49.3174	54.9242	62.5115	74.7186	100.5242
Reynolds number, Re:		9.922E+04	9.929E+04	9.936E+04	9.945E+04	9.955E+04	9.952E+04	9.985E+04	1.001E+05	1.005E+05	1.015E+05
Friction factor, 4f:		0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250
Recovery factor, r:		0.7751	0.7745	0.7738	0.7731	0.7723	0.7714	0.7707	0.7697	0.7687	0.7679
Adiabatic Wall Temperature, T <sub>w</sub> :	°C	19.5108	19.4652	19.3396	19.2078	19.0611	19.0039	19.0455	18.4253	18.0773	17.3054
Enthalpy, h:	KJ/kg	498.8597	498.8416	498.8176	498.7745	498.7065	498.9853	498.3841	498.0718	497.3799	495.3470
Entropy, s:	J/kg K	2.5177	2.5268	2.5372	2.5488	2.5620	2.5775	2.5959	2.6192	2.6507	2.7009
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa G	-65.35									
Kpa abs:		35.97									
Critical Temperature:	°C	19.54									
°F:		253.61									
Max length of duct at which no shock occurs:	m	12.95									
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa	13.38	13.98	14.90	15.82	16.80	16.95	21.79	22.94	27.25	36.10
Temperature drop / Segment Length:	°C	0.07	0.18	0.20	0.23	0.28	-0.13	0.96	0.64	1.14	2.85
Total pressure drop:	Kpa	200.00									
Total temperature drop:	°C	5.59									

Figure F 11-18: Vent pipe model predictions for carbon-dioxide gas at 200 KPa gauge

Gas Property Calculation for Carbon-dioxide @ 300 Kpa gauge & 19 °C Inlet Conditions										by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10
Schedule number:	80	80	80	80	80	80	80	80	80	80
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
<b>Gas properties</b>										
Carbon dioxide, 1:										
Specific heat at constant pressure, cp:	J/kg K 868.41	866.86	865.09	863.23	861.23	859.05	857.32	853.77	850.33	845.44
Specific heat at constant volume, cv:	J/kg K 659.71	659.12	658.34	657.52	656.62	655.62	655.13	653.02	651.20	648.27
Ratio of specific heats, γ:	1.3163	1.3152	1.3140	1.3129	1.3116	1.3103	1.3086	1.3074	1.3058	1.3042
Molecular weight, M.W:	kg/mole 44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01
Gas constant, R:	J/kg K 188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92
<b>Standard condition</b>										
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15
Compressibility at std cond, Z <sub>std</sub> :	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718
Normal or standard flow:	m <sup>3</sup> /hr 23.1398	23.1398	23.1398	23.1398	23.1398	23.1398	23.1398	23.1398	23.1398	23.1398
lines/min:	385.6639	385.6639	385.6639	385.6639	385.6639	385.6639	385.6639	385.6639	385.6639	385.6639
<b>Phase flow</b>										
Single										
Actual inlet flow condition:	kg/hr 43.31									
m <sup>3</sup> /hr:	5.83	6.12	6.45	6.85	7.32	7.92	8.62	9.73	11.31	14.11
Standard flow condition:	m <sup>3</sup> /hr 23.14	23.14	23.14	23.14	23.14	23.14	23.14	23.14	23.14	23.14
<b>Stagnation Properties</b>										
Stagnation Temperature, T <sub>0</sub> :	°C 292.86	292.85	292.70	292.55	292.40	292.24	292.68	291.85	291.68	291.47
°F:	19.71	19.70	19.55	19.40	19.25	19.09	19.53	18.70	18.53	18.32
Inlet Stagnation Pressure:	Kpa abs 405.93	387.57	367.97	347.54	325.77	302.51	279.12	248.63	216.10	176.72
Outlet Stagnation Pressure:	Kpa abs 387.57	367.97	347.54	325.77	302.51	279.12	248.63	216.10	176.72	120.15
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 7.50	7.15	6.79	6.41	6.00	5.57	5.12	4.57	3.97	3.24
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 498.36	498.54	498.60	498.68	498.76	498.83	499.46	499.05	499.23	499.44
<b>Upstream Condition</b>										
Inlet pressure, P <sub>1</sub> :	Kpa g 300.00	281.43	261.59	240.72	218.47	194.53	170.90	139.10	105.37	63.73
Kpa abs:	401.33	382.75	362.92	342.05	319.79	295.87	272.22	240.42	206.69	165.06
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9206	18.6776	18.4184	18.1188	17.7654	17.3543	16.8829	15.7995	14.0420
°F:	292.15	292.07	291.83	291.57	291.27	290.91	291.10	289.83	288.95	287.19
Compressibility, Z <sub>1</sub> :	0.9784	0.9794	0.9804	0.9815	0.9826	0.9839	0.9852	0.9868	0.9885	0.9907
Viscosity, μ <sub>1</sub> :	Pa·sec 1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.45E-05	1.44E-05
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 7.4319	7.0826	6.7141	6.3267	5.9141	5.4714	5.0240	4.4496	3.8302	3.0708
Velocity, V <sub>1</sub> :	m/sec 35.1304	36.8627	38.8860	41.2673	44.1462	47.7177	51.9673	58.6760	68.1643	85.0225
Mach number at the inlet, M <sub>1</sub> :	0.1318	0.1381	0.1457	0.1545	0.1651	0.1783	0.1939	0.2189	0.2543	0.3175
4fL <sub>1</sub> /D:	39.6587	35.7909	31.9252	28.0614	24.1998	20.3402	16.4827	12.6271	8.7741	4.9236
Reynolds number, Re:	1.364E+05	1.364E+05	1.365E+05	1.367E+05	1.368E+05	1.370E+05	1.369E+05	1.376E+05	1.380E+05	1.388E+05
Friction factor, 4f:	0.02457785	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Recovery factor, r:	0.78112298	0.7802	0.7792	0.7783	0.7773	0.7762	0.7748	0.7730	0.7723	0.7708
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.56	19.53	19.56	19.19	19.00	18.79	19.17	18.24	17.91	17.34
Enthalpy, h:	KJ/kg 497.79	497.91	497.90	497.88	497.85	497.78	498.18	497.41	497.00	495.93
Entropy, s:	2.45242618	2.4616	2.4714	2.4823	2.4947	2.5089	2.5258	2.5463	2.5730	2.6114
<b>Downstream Condition</b>										
4fL <sub>2</sub> /D:	3.8503	3.8502	3.8501	3.8499	3.8497	3.8494	3.8495	3.8487	3.8481	3.8470
Mach number at the outlet, M <sub>2</sub> :	0.1381	0.1457	0.1545	0.1651	0.1783	0.1939	0.2189	0.2543	0.3175	0.5108
Absolute outlet pressure, P <sub>2</sub> :	Kpa g 382.75	362.92	342.05	319.79	295.87	272.22	240.42	206.69	165.06	101.33
Kpa abs:	281.426	261.590	240.724	218.466	194.546	170.898	139.098	105.368	63.733	0.000
Outlet temperature, T <sub>2</sub> :	°C 18.92	18.68	18.42	18.12	17.76	17.35	16.88	15.80	14.04	7.14
Compressibility, Z <sub>2</sub> :	0.9794	0.9804	0.9815	0.9826	0.9839	0.9852	0.9868	0.9885	0.9907	0.9938
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 7.0826	6.7141	6.3267	5.9141	5.4714	5.0240	4.4496	3.8302	3.0708	1.9254
Viscosity of gas, μ <sub>2</sub> :	Pa·sec 1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.45E-05	1.44E-05	1.41E-05
Actual outlet flow:	m <sup>3</sup> /hr 6.1156	6.4512	6.8463	7.3239	7.9164	8.6214	9.7344	11.3085	14.1054	22.4964
Velocity, V <sub>2</sub> :	m/sec 36.8627	38.8860	41.2673	44.1462	47.7177	51.9673	58.6760	68.1643	85.0225	135.6011
Reynolds number, Re:	1.364E+05	1.365E+05	1.367E+05	1.368E+05	1.370E+05	1.369E+05	1.376E+05	1.380E+05	1.388E+05	1.422E+05
Friction factor, 4f:	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0245
Recovery factor, r:	0.7802	0.7792	0.7783	0.7773	0.7762	0.7748	0.7730	0.7723	0.7708	0.7699
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.5369	19.4778	19.3003	19.1183	18.9174	18.8332	18.8853	18.0390	17.5027	15.7451
Enthalpy, h:	KJ/kg 497.9088	497.8968	497.8815	497.8460	497.7797	498.1799	497.4104	496.9971	495.9287	490.7986
Entropy, s:	2.4616	2.4714	2.4823	2.4947	2.5089	2.5258	2.5463	2.5730	2.6114	2.6848
<b>Critical Properties at Outlet Mach 1</b>										
Critical Pressure:	Kpa g 52.16									
Kpa abs:	49.17									
Critical Temperature:	°C 20.21									
°F:	252.94									
Max length of duct at which no shock occurs:	m 12.36									
<b>Drop</b>										
Pressure drop / Segment Length:	Kpa 18.57	19.84	20.87	22.26	23.92	23.65	31.80	33.73	41.63	63.73
Temperature drop / Segment Length:	°C 0.08	0.24	0.26	0.30	0.36	-0.19	1.27	0.88	1.76	6.90
Total pressure drop:	Kpa 300.00									
Total temperature drop:	°C 10.87									

Figure F 11-19: Vent pipe model predictions for carbon-dioxide gas at 300 KPa gauge



Gas Property Calculation for Carbon-dioxide @ 400 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, (e/D):	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Carbon dioxide, 1:											
Specific heat at constant pressure, cp:	J/kg.K 876.62	874.63	872.36	869.97	867.41	864.62	862.41	857.87	853.50	847.19	
Specific heat at constant volume, cv:	J/kg.K 662.55	661.81	660.84	659.80	658.68	657.43	656.84	654.21	651.97	648.27	
Ratio of specific heats, γ:	1.3231	1.3216	1.3201	1.3185	1.3169	1.3152	1.3130	1.3113	1.3091	1.3068	
Molecular weight, M.W:	kg/mole 44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	
Gas constant, R:	J/kg.K 188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	
Normal or standard flow:	m <sup>3</sup> /hr 29.3582	29.3582	29.3582	29.3582	29.3582	29.3582	29.3582	29.3582	29.3582	29.3582	
litres/min:	489.3033	489.3033	489.3033	489.3033	489.3033	489.3033	489.3033	489.3033	489.3033	489.3033	
<b>Phase flow</b>											
Single											
Actual inlet flow condition:	kg/hr 54.95										
m <sup>3</sup> /hr:	5.89	6.18	6.53	6.94	7.44	8.06	8.80	10.01	11.73	14.95	
Standard flow condition:	m <sup>3</sup> /hr 29.36	29.36	29.36	29.36	29.36	29.36	29.36	29.36	29.36	29.36	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C 292.87	292.86	292.66	292.47	292.27	292.05	292.60	291.54	291.32	291.03	
°F:	19.72	19.71	19.51	19.32	19.12	18.90	19.45	18.39	18.17	17.88	
Inlet Stagnation Pressure:	Kpa abs 507.23	484.56	459.31	433.13	405.41	375.58	346.18	306.16	264.19	212.36	
Outlet Stagnation Pressure:	Kpa abs 484.56	459.31	433.13	405.41	375.58	346.18	306.16	264.19	212.36	131.67	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 9.42	8.99	8.52	8.03	7.51	6.95	6.38	5.65	4.87	3.91	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 497.36	497.58	497.66	497.75	497.85	497.97	498.74	498.22	498.44	498.71	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g 400.00	376.62	351.19	324.49	296.06	265.42	235.74	194.02	150.31	95.25	
Kpa abs:	501.33	477.94	452.52	425.82	397.39	366.74	337.07	295.35	251.63	196.58	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9191	18.6248	18.3132	17.9580	17.5384	17.0238	16.2703	15.2380	13.0863	
°F:	292.15	292.07	291.77	291.46	291.11	290.69	290.07	289.42	288.39	286.24	
Compressibility, Z <sub>1</sub> :	0.9729	0.9741	0.9755	0.9768	0.9783	0.9799	0.9816	0.9836	0.9859	0.9888	
Viscosity, μ <sub>1</sub> :	Pa.sec 1.47E-05	1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.45E-05	1.44E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 9.3362	8.8916	8.4157	7.9164	7.3857	6.8148	6.2464	5.4914	4.6844	3.6765	
Velocity, V <sub>1</sub> :	m/sec 35.4799	37.2536	39.3603	41.8432	44.8498	48.6071	53.0300	60.3213	70.7121	90.0990	
Mach number at the inlet, M <sub>1</sub> :	0.1331	0.1395	0.1473	0.1565	0.1675	0.1813	0.1974	0.2247	0.2633	0.3357	
4fL <sub>1</sub> /D:	38.6375	34.7982	30.9622	27.1296	23.3003	19.4743	15.6318	11.8324	8.0169	4.2051	
Reynolds number, Re:	1.729E+05	1.730E+05	1.732E+05	1.734E+05	1.736E+05	1.739E+05	1.737E+05	1.747E+05	1.754E+05	1.767E+05	
Friction factor, 4f:	0.02432322	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	
Recovery factor, r:	0.78658774	0.7854	0.7842	0.7829	0.7816	0.7801	0.7783	0.7769	0.7750	0.7730	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.56	19.54	19.32	19.10	18.86	18.60	19.09	17.92	17.51	16.79	
Enthalpy, h:	KJ/kg 496.79	496.95	496.95	496.95	496.95	496.87	497.42	496.50	496.06	494.80	
Entropy, s:	2.40796830	2.4173	2.4274	2.4386	2.4513	2.4659	2.4835	2.5048	2.5331	2.5748	
<b>Downstream Condition</b>											
4fL <sub>2</sub> /D:	3.8104	3.8104	3.8102	3.8100	3.8098	3.8096	3.8097	3.8089	3.8083	3.8072	
Mach number at the outlet, M <sub>2</sub> :	0.1395	0.1473	0.1565	0.1675	0.1813	0.1974	0.2247	0.2633	0.3357	0.6370	
Absolute outlet pressure, P <sub>2</sub> :	Kpa g 477.94	452.52	425.82	397.39	366.74	337.07	295.35	251.63	196.58	101.33	
Kpa abs:	376.619	351.193	324.493	296.064	265.417	235.745	194.023	150.306	95.251	0.000	
Outlet temperature, T <sub>2</sub> :	°C 18.92	18.62	18.31	17.96	17.54	17.02	16.27	15.24	13.09	0.74	
Compressibility, Z <sub>2</sub> :	0.9741	0.9755	0.9768	0.9783	0.9799	0.9816	0.9836	0.9859	0.9888	0.9933	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 8.8916	8.4157	7.9164	7.3857	6.8148	6.2464	5.4914	4.6844	3.6765	1.9714	
Viscosity of gas, μ <sub>2</sub> :	Pa.sec 1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.45E-05	1.44E-05	1.37E-05	
Actual outlet flow:	m <sup>3</sup> /hr 6.1804	6.5209	6.9418	7.4406	8.0640	8.7978	10.0074	11.7312	14.9475	27.8761	
Velocity, V <sub>2</sub> :	m/sec 37.2536	39.3603	41.8432	44.8498	48.6071	53.0300	60.3213	70.7121	90.0990	168.0280	
Reynolds number, Re:	1.730E+05	1.732E+05	1.734E+05	1.736E+05	1.739E+05	1.737E+05	1.747E+05	1.754E+05	1.767E+05	1.846E+05	
Friction factor, 4f:	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	
Recovery factor, r:	0.7854	0.7842	0.7829	0.7816	0.7801	0.7783	0.7769	0.7750	0.7730	0.7723	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.5465	19.4777	19.2523	19.0221	18.7703	18.6651	18.7440	17.6817	17.0138	13.9744	
Enthalpy, h:	KJ/kg 496.9506	496.9503	496.9483	496.9269	496.8731	497.4185	496.5032	496.0637	494.7973	485.4811	
Entropy, s:	2.4173	2.4274	2.4386	2.4513	2.4659	2.4835	2.5048	2.5331	2.5748	2.6656	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa g -39.39										
Kpa abs:	61.93										
Critical Temperature:	°C 20.91										
°F:	252.24										
Max length of duct at which no shock occurs:	m 12.17										
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa 23.38	25.43	26.70	28.43	30.65	29.67	41.72	43.72	55.06	95.28	
Temperature drop / Segment Length:	°C 0.08	0.29	0.31	0.36	0.42	0.29	1.55	1.03	2.15	12.35	
Total pressure drop:	Kpa 400.00										
Total temperature drop:	°C 17.28										

Figure F 11-20: Vent pipe model predictions for carbon-dioxide gas at 400 KPa gauge

Gas Property Calculation for Carbon-dioxide @ 500 Kpa gauge & 19 °C Inlet Conditions										by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10
Schedule number:	80	80	80	80	80	80	80	80	80	80
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
<b>Gas properties</b>										
Carbon dioxide, 1:										
Specific heat at constant pressure, cp:	J/kg K 885.06	882.62	879.84	876.92	873.80	870.39	867.74	862.24	856.99	849.44
Specific heat at constant volume, cv:	J/kg K 665.42	664.54	663.37	662.14	660.80	659.30	658.64	655.52	652.91	648.62
Ratio of specific heats, γ:	1.3301	1.3282	1.3263	1.3244	1.3223	1.3202	1.3175	1.3154	1.3126	1.3096
Molecular weight, M.W:	kg/mole 44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01
Gas constant, R:	J/kg K 188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92
<b>Standard condition</b>										
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15
Compressibility at std cond, Z <sub>std</sub> :	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718
Normal or standard flow:	m <sup>3</sup> /hr 35.5435	35.5435	35.5435	35.5435	35.5435	35.5435	35.5435	35.5435	35.5435	35.5435
litres/min:	592.3917	592.3917	592.3917	592.3917	592.3917	592.3917	592.3917	592.3917	592.3917	592.3917
<b>Phase flow</b>										
Single										
Actual inlet flow condition:	kg/hr 66.53									
m <sup>3</sup> /hr:	5.91	6.21	6.56	6.98	7.49	8.13	8.87	10.13	11.93	15.35
Standard flow condition:	m <sup>3</sup> /hr 35.54	35.54	35.54	35.54	35.54	35.54	35.54	35.54	35.54	35.54
<b>Stagnation Properties</b>										
Stagnation Temperature, T <sub>0</sub> :	°C 292.87	292.86	292.61	292.57	292.12	291.86	292.52	291.22	290.94	290.57
°F:	19.72	19.71	19.46	19.22	18.97	18.71	19.37	18.07	17.79	17.42
Inlet Stagnation Pressure:	Kpa abs 608.30	581.43	550.76	519.01	485.49	449.04	414.45	365.00	313.87	250.35
Outlet Stagnation Pressure:	Kpa abs 581.43	550.76	519.01	485.49	449.04	414.45	365.00	313.87	250.35	146.00
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 11.37	10.85	10.27	9.67	9.03	8.35	7.67	6.77	5.81	4.62
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 496.33	496.60	496.69	496.80	496.92	497.06	497.99	497.35	497.62	497.94
<b>Upstream Condition</b>										
Inlet pressure, P <sub>1</sub> :	Kpa g 500.00	471.87	440.99	408.61	374.16	336.88	301.88	250.24	196.96	129.33
Kpa abs:	601.33	573.19	542.32	509.93	475.49	438.20	403.21	351.56	298.28	230.65
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9174	18.5730	18.2122	17.8050	17.3254	17.7274	15.9072	14.7696	12.5780
°F:	292.15	292.07	291.72	291.36	290.95	290.48	290.88	289.06	287.92	285.53
Compressibility, Z <sub>1</sub> :	0.9673	0.9680	0.9705	0.9721	0.9730	0.9759	0.9779	0.9804	0.9832	0.9867
Viscosity, μ <sub>1</sub> :	Pa.s 1.47E-05	1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.43E-05	1.43E-05
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 11.2626	10.7218	10.1395	9.5293	8.8816	8.1824	7.5027	6.5664	5.5774	4.3336
Velocity, V <sub>1</sub> :	m/sec 35.6075	37.4038	39.5515	42.0842	45.1532	49.0118	53.4520	61.0736	71.9035	92.5408
Mach number at the inlet, M <sub>1</sub> :	0.1336	0.1400	0.1480	0.1573	0.1685	0.1827	0.1986	0.2271	0.2672	0.3440
4fL <sub>1</sub> /D:	38.1217	34.3054	30.4929	26.6840	22.8790	19.0777	15.2803	11.4863	7.6967	3.9111
Reynolds number, Re:	2.091E+05	2.093E+05	2.095E+05	2.098E+05	2.102E+05	2.106E+05	2.103E+05	2.117E+05	2.126E+05	2.144E+05
Friction factor, 4f:	0.02415384	0.0242	0.0242	0.0242	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241
Recovery factor, r:	0.79219593	0.7907	0.7892	0.7876	0.7860	0.7842	0.7820	0.7803	0.7779	0.7753
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.57	19.54	19.27	19.01	18.72	18.41	19.01	17.59	17.12	16.29
Enthalpy, h:	KJ/kg 495.77	495.98	495.99	496.01	496.00	495.96	496.67	495.62	495.19	495.84
Entropy, s:	2.37115057	2.3806	2.3908	2.4022	2.4150	2.4299	2.4477	2.4694	2.4984	2.5416
<b>Downstream Condition</b>										
4fL <sub>2</sub> /D:	3.7839	3.7838	3.7837	3.7835	3.7833	3.7830	3.7832	3.7824	3.7818	3.7808
Mach number at the outlet, M <sub>2</sub> :	0.1400	0.1480	0.1573	0.1685	0.1827	0.1986	0.2271	0.2672	0.3440	0.7568
Absolute outlet pressure, P <sub>2</sub> :	Kpa g 573.19	542.32	509.93	475.49	438.20	403.21	351.56	298.28	230.65	101.33
Kpa abs:	471.868	440.995	408.609	374.162	336.880	301.884	250.239	196.957	129.327	0.000
Outlet temperature, T <sub>2</sub> :	°C 18.92	18.57	18.21	17.80	17.33	17.73	15.91	14.77	13.38	-6.37
Compressibility, Z <sub>2</sub> :	0.9689	0.9705	0.9721	0.9739	0.9759	0.9779	0.9804	0.9832	0.9867	0.9927
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 10.7218	10.1395	9.5293	8.8816	8.1824	7.5027	6.5664	5.5774	4.3336	2.0251
Viscosity of gas, μ <sub>2</sub> :	Pa.s 1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.43E-05	1.43E-05	1.43E-05
Actual outlet flow:	m <sup>3</sup> /hr 6.2053	6.5616	6.9818	7.4910	8.1311	8.8678	10.1322	11.9289	15.3527	32.8535
Velocity, V <sub>2</sub> :	m/sec 37.4038	39.5515	42.0842	45.1532	49.0118	53.4520	61.0736	71.9035	92.5408	198.0301
Reynolds number, Re:	2.093E+05	2.095E+05	2.098E+05	2.102E+05	2.106E+05	2.103E+05	2.117E+05	2.126E+05	2.144E+05	2.293E+05
Friction factor, 4f:	0.0242	0.0242	0.0242	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241
Recovery factor, r:	0.7907	0.7892	0.7876	0.7860	0.7842	0.7820	0.7803	0.7779	0.7753	0.7750
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.5491	19.4703	19.1965	18.9188	18.6164	18.4921	18.6119	17.3371	16.5708	12.0655
Enthalpy, h:	KJ/kg 495.9823	495.9938	496.0070	496.0015	495.9632	496.6680	495.6188	495.1866	493.8441	479.6239
Entropy, s:	2.3806	2.3908	2.4022	2.4150	2.4299	2.4477	2.4694	2.4984	2.5416	2.6439
<b>Critical Properties at Outlet Mach 1</b>										
Critical Pressure:	Kpa g -26.87									
Kpa abs:	74.45									
Critical Temperature:	°C -21.65									
°F:	251.50									
Max length of duct at which no shock occurs:	m 12.09									
<b>Drop</b>										
Pressure drop / Segment Length:	Kpa 28.13	30.87	32.39	34.45	37.28	35.00	51.65	53.28	67.63	129.33
Temperature drop / Segment Length:	°C 0.08	0.34	0.36	0.41	0.48	-0.40	1.82	1.14	2.39	18.75
Total pressure drop:	Kpa 500.00									
Total temperature drop:	°C 24.57									

Figure F 11-21: Vent pipe model predictions for carbon-dioxide gas at 500 KPa gauge

Gas Property Calculation for Carbon-dioxide @ 600 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, (e/D):	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Carbon dioxide, CO <sub>2</sub> :											
Specific heat at constant pressure, Cp:	J/kg K 893.76	890.84	887.54	884.08	880.39	876.36	873.26	866.81	860.69	852.02	
Specific heat at constant volume, Cv:	J/kg K 668.33	667.31	665.94	664.51	662.95	661.23	660.51	656.89	653.94	649.16	
Ratio of specific heats, γ:	1.3373	1.3350	1.3328	1.3304	1.3280	1.3254	1.3221	1.3196	1.3162	1.3125	
Molecular weight, M.W:	kg/mole 44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	
Gas constant, R:	J/kg K 188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	
Normal or standard flow:	m <sup>3</sup> /hr 41.7256	41.7256	41.7256	41.7256	41.7256	41.7256	41.7256	41.7256	41.7256	41.7256	
litres/min:	695.4270	695.4270	695.4270	695.4270	695.4270	695.4270	695.4270	695.4270	695.4270	695.4270	
<b>Phase flow</b>											
Actual inlet flow condition:	kg/hr 78.10										
m <sup>3</sup> /hr:	5.91	6.21	6.57	7.00	7.51	8.16	8.89	10.19	12.02	15.54	
Standard flow condition:	m <sup>3</sup> /hr 41.73	41.73	41.73	41.73	41.73	41.73	41.73	41.73	41.73	41.73	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C 292.86	292.85	292.55	292.27	291.97	291.65	292.44	290.89	290.54	290.10	
°F:	19.71	19.70	19.40	19.12	18.82	18.50	19.29	17.74	17.39	16.95	
Inlet Stagnation Pressure:	Kpa abs 709.75	678.07	642.21	605.00	565.75	522.92	483.44	424.53	364.57	289.84	
Outlet Stagnation Pressure:	Kpa abs 678.07	642.21	605.00	565.75	522.92	483.44	424.53	364.57	289.84	163.30	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 13.34	12.72	12.04	11.33	10.58	9.77	8.98	7.91	6.78	5.37	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 495.29	495.61	495.71	495.83	495.97	496.12	497.22	496.46	496.77	497.14	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g 600.00	567.09	530.88	492.88	452.48	408.72	368.84	307.14	244.63	165.01	
Kpa abs:	701.33	668.41	632.20	594.20	553.81	510.04	470.17	408.46	345.95	266.34	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9151	18.5195	18.1106	17.6519	17.1161	17.6459	15.5604	14.3425	11.7958	
°F:	292.15	292.07	291.67	291.26	290.80	290.27	290.80	288.71	287.49	284.95	
Compressibility, Z <sub>1</sub> :	0.9617	0.9636	0.9654	0.9674	0.9695	0.9718	0.9742	0.9771	0.9804	0.9845	
Viscosity, μ <sub>1</sub> :	Pa.s 1.47E-05	1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.44E-05	1.43E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 13.2119	12.5720	11.8839	11.1625	10.3974	9.5709	8.7848	7.6643	6.4970	5.0255	
Velocity, V <sub>1</sub> :	m/sec 35.6334	37.4474	39.6153	42.1757	45.2791	49.1893	53.5911	61.4260	72.4624	93.6797	
Mach number at the inlet, M <sub>1</sub> :	0.1337	0.1401	0.1482	0.1575	0.1688	0.1832	0.1988	0.2281	0.2687	0.3474	
4fL <sub>1</sub> /D:	37.8348	34.0365	30.2420	26.4514	22.6647	18.8819	15.1030	11.3277	7.5569	3.7903	
Reynolds number, Re:	2.453E+05	2.453E+05	2.459E+05	2.463E+05	2.467E+05	2.472E+05	2.469E+05	2.487E+05	2.498E+05	2.521E+05	
Friction factor, 4f:	0.02403248	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	
Recovery factor, r:	0.79795454	0.7961	0.7944	0.7925	0.7905	0.7884	0.7858	0.7837	0.7809	0.7777	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.57	19.54	19.22	18.91	18.57	18.20	18.94	17.27	16.72	15.80	
Enthalpy, h:	KJ/kg 494.74	495.00	495.03	495.05	495.07	495.04	495.92	494.73	494.53	492.98	
Entropy, s:	2.33959973	2.3492	2.3595	2.3709	2.3838	2.3988	2.4168	2.4386	2.4679	2.5118	
<b>Downstream Condition</b>											
4fL <sub>2</sub> /D:	3.7649	3.7648	3.7646	3.7645	3.7643	3.7640	3.7642	3.7634	3.7629	3.7619	
Mach number at the outlet, M <sub>2</sub> :	0.1401	0.1482	0.1575	0.1688	0.1832	0.1988	0.2281	0.2687	0.3474	0.8708	
Absolute outlet pressure, P <sub>2</sub> :	Kpa g 668.41	632.20	594.20	553.81	510.04	470.17	408.46	345.95	266.34	101.33	
Kpa abs:	567.089	530.875	492.877	452.481	408.717	368.841	307.139	244.625	165.014	0.000	
Outlet temperature, T <sub>2</sub> :	°C 18.92	18.32	18.11	17.65	17.12	17.65	15.56	14.34	11.80	-13.94	
Compressibility, Z <sub>2</sub> :	0.9636	0.9654	0.9674	0.9695	0.9718	0.9742	0.9771	0.9804	0.9845	0.9920	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 12.5720	11.8839	11.1625	10.3974	9.5709	8.7848	7.6643	6.4970	5.0255	2.0858	
Viscosity of gas, μ <sub>2</sub> :	Pa.s 1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.44E-05	1.43E-05	1.30E-05	
Actual outlet flow:	m <sup>3</sup> /hr 6.2126	6.5722	6.9970	7.5119	8.1606	8.8908	10.1907	12.0216	15.5416	37.4455	
Velocity, V <sub>2</sub> :	m/sec 37.4474	39.6153	42.1757	45.2791	49.1893	53.5911	61.4260	72.4624	93.6797	225.7093	
Reynolds number, Re:	2.455E+05	2.459E+05	2.463E+05	2.467E+05	2.472E+05	2.469E+05	2.487E+05	2.498E+05	2.521E+05	2.769E+05	
Friction factor, 4f:	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	0.0240	
Recovery factor, r:	0.7961	0.7944	0.7925	0.7905	0.7884	0.7858	0.7837	0.7809	0.7777	0.7778	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.5482	19.4590	19.1353	18.8098	18.4566	18.1343	18.4835	16.9930	16.1484	10.0827	
Enthalpy, h:	KJ/kg 495.0047	495.0258	495.0546	495.0655	495.0449	495.9168	494.7350	494.3286	492.9765	473.4357	
Entropy, s:	2.3492	2.3595	2.3709	2.3838	2.3988	2.4168	2.4386	2.4679	2.5118	2.6204	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa g -14.54										
Kpa abs:	86.78										
Critical Temperature:	°C 22.40										
°F:	250.75										
Max length of duct at which no shock occurs:	m 12.06										
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa 32.91	36.21	38.00	40.40	43.76	39.88	61.70	62.51	79.61	165.01	
Temperature drop / Segment Length:	°C 0.08	0.40	0.41	0.46	0.54	-0.53	2.09	1.22	2.55	25.74	
Total pressure drop:	Kpa 600.00										
Total temperature drop:	°C 32.47										

Figure F 11-22: Vent pipe model predictions for carbon-dioxide gas at 600 KPa gauge



Gas Property Calculation for Carbon-dioxide @ 700 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Carbon dioxide, 1:											
Specific heat at constant pressure, cp:	J/kg K 902.72	899.30	895.46	891.44	887.17	882.52	878.96	871.53	864.56	854.81	
Specific heat at constant volume, cv:	J/kg K 671.29	670.11	668.55	666.92	665.15	663.19	662.42	658.31	655.03	649.82	
Ratio of specific heats, γ:	1.3447	1.3420	1.3394	1.3367	1.3338	1.3307	1.3269	1.3239	1.3199	1.3155	
Molecular weight, M.W:	kg/mole 44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	
Gas constant, R:	J/kg K 188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	
<b>Standard condition</b>											
Inlet pressure, P <sub>gpp</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>gpp</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	
Normal or standard flow:	m <sup>3</sup> /hr 47.9207	47.9207	47.9207	47.9207	47.9207	47.9207	47.9207	47.9207	47.9207	47.9207	
lines/min:	798.6776	798.6776	798.6776	798.6776	798.6776	798.6776	798.6776	798.6776	798.6776	798.6776	
<b>Phase flow</b>											
Single											
Actual inlet flow condition:	kg/hr 89.70										
m <sup>3</sup> /hr:	5.91	6.21	6.57	7.00	7.52	8.17	8.89	10.22	12.06	15.62	
Standard flow condition:	m <sup>3</sup> /hr 47.92	47.92	47.92	47.92	47.92	47.92	47.92	47.92	47.92	47.92	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C 292.85	292.84	292.49	292.15	291.80	291.43	292.36	290.54	290.14	289.61	
°F:	19.70	19.69	19.34	19.00	18.65	18.28	19.21	17.39	16.99	16.46	
Inlet Stagnation Pressure:	Kpa abs 811.00	774.80	733.64	691.02	646.06	597.01	552.94	484.41	415.81	330.26	
Outlet Stagnation Pressure:	Kpa abs 774.80	733.64	691.02	646.06	597.01	552.94	484.41	415.81	330.26	183.76	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 15.33	14.62	13.83	13.01	12.15	11.21	10.32	9.07	7.76	6.15	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 494.24	494.60	494.71	494.83	495.00	495.17	496.44	495.55	495.90	496.31	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g 700.00	662.38	620.78	577.20	530.89	480.73	436.39	364.39	292.86	201.71	
Kpa abs:	801.33	763.70	722.11	678.52	632.21	582.06	537.71	465.72	394.18	303.03	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9133	18.4643	18.0063	17.4956	16.9044	17.5714	15.2151	13.9277	11.2715	
°F:	292.15	292.06	291.61	291.16	290.65	290.05	290.72	288.37	287.08	284.42	
Compressibility, Z <sub>1</sub> :	0.9561	0.9582	0.9603	0.9626	0.9650	0.9676	0.9704	0.9737	0.9775	0.9822	
Viscosity, μ <sub>1</sub> :	Pa·sec 1.47E-05	1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.44E-05	1.43E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 15.1848	14.4447	13.6485	12.8148	11.9312	10.9772	10.0890	8.7794	7.4354	5.7417	
Velocity, V <sub>1</sub> :	m/sec 35.6070	37.4314	39.6149	42.1923	45.3169	49.2551	53.5916	61.5856	72.7179	94.1679	
Mach number at the inlet, M <sub>1</sub> :	0.1337	0.1401	0.1481	0.1575	0.1688	0.1832	0.1985	0.2283	0.2690	0.3483	
4f <sub>1</sub> /D:	37.6633	33.8794	30.0994	26.3232	22.5509	18.7825	15.0180	11.2570	7.5006	3.7483	
Reynolds number, Re:	2.815E+05	2.817E+05	2.822E+05	2.827E+05	2.833E+05	2.840E+05	2.835E+05	2.838E+05	2.872E+05	2.900E+05	
Friction factor, 4f:	0.02394104	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	
Recovery factor, r:	0.80387101	0.8017	0.7997	0.7975	0.7952	0.7928	0.7897	0.7872	0.7839	0.7801	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.56	19.54	19.17	18.80	18.42	17.99	18.86	16.93	16.33	15.32	
Enthalpy, h:	KJ/kg 493.70	494.02	494.05	494.09	494.12	494.11	495.16	493.84	493.47	492.14	
Entropy, s:	2.31189701	2.3217	2.3319	2.3434	2.3563	2.3714	2.3895	2.4114	2.4408	2.4849	
<b>Downstream Condition</b>											
4f <sub>2</sub> /D:	3.7506	3.7505	3.7503	3.7501	3.7499	3.7497	3.7499	3.7491	3.7486	3.7477	
Mach number at the outlet, M <sub>2</sub> :	0.1401	0.1481	0.1575	0.1688	0.1832	0.1985	0.2283	0.2690	0.3483	0.4795	
Absolute outlet pressure, P <sub>2</sub> :	Kpa a 763.70	722.11	678.52	632.21	582.06	537.71	465.72	394.18	303.03	101.33	
Outlet pressure (gauge):	Kpa g 662.378	620.781	577.200	530.886	480.731	436.389	364.392	292.855	201.710	0.001	
Outlet temperature, T <sub>2</sub> :	°C 18.91	18.46	18.01	17.50	16.90	17.57	15.22	13.93	11.27	-21.78	
Compressibility, Z <sub>2</sub> :	0.9582	0.9603	0.9626	0.9650	0.9676	0.9704	0.9737	0.9775	0.9822	0.9911	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 14.4447	13.6485	12.8148	11.9312	10.9772	10.0890	8.7794	7.4354	5.7417	2.1527	
Viscosity of gas, μ <sub>2</sub> :	Pa·sec 1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.44E-05	1.43E-05	1.26E-05	
Actual outlet flow:	m <sup>3</sup> /hr 6.2059	6.5722	6.9998	7.5181	8.1715	8.9909	10.2171	12.0640	15.6226	41.6678	
Velocity, V <sub>2</sub> :	m/sec 37.4314	39.6149	42.1923	45.3169	49.2551	53.5916	61.5856	72.7179	94.1679	251.1604	
Reynolds number, Re:	2.817E+05	2.822E+05	2.827E+05	2.833E+05	2.840E+05	2.835E+05	2.838E+05	2.872E+05	2.900E+05	3.278E+05	
Friction factor, 4f:	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	
Recovery factor, r:	0.8017	0.7997	0.7975	0.7952	0.7928	0.7897	0.7872	0.7839	0.7801	0.7807	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.5458	19.4463	19.0704	18.6957	18.2906	18.1301	18.3563	16.6427	15.7294	8.0728	
Enthalpy, h:	KJ/kg 494.0171	494.0466	494.0903	494.1171	494.1147	495.1601	493.8420	493.4697	492.1431	467.0847	
Entropy, s:	2.3217	2.3319	2.3434	2.3563	2.3714	2.3895	2.4114	2.4408	2.4849	2.5955	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa G -2.38										
Kpa abs:	98.95										
Critical Temperature:	°C -23.19										
°F:	249.96										
Max length of duct at which no shock occurs:	m 12.05										
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa 37.62	41.60	43.58	46.31	50.16	44.34	72.00	71.54	91.15	201.71	
Temperature drop / Segment Length:	°C 0.09	0.45	0.46	0.51	0.59	-0.67	2.36	1.29	2.66	33.05	
Total pressure drop:	Kpa 700.00										
Total temperature drop:	°C 40.76										

Figure F 11-23: Vent pipe model predictions for carbon-dioxide gas at 700 KPa gauge

Gas Property Calculation for Carbon-dioxide @ 718.56680695343 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
Carbon dioxide, $CO_2$											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 904.41	900.89	896.96	892.83	888.45	883.68	880.04	872.42	865.29	855.35	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 671.85	670.64	669.04	667.37	665.56	663.56	662.78	658.58	655.24	649.95	
Ratio of specific heats, $\gamma$	1.3462	1.3433	1.3407	1.3378	1.3349	1.3317	1.3278	1.3247	1.3206	1.3160	
Molecular weight, $M.W.$	$kg/mole$ 44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	
Gas constant, $R$	$J/kg \cdot K$ 188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	188.92	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	0.9944	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	1.8718	
Normal or standard flow	$m^3/hr$ 49.0732	49.0732	49.0732	49.0732	49.0732	49.0732	49.0732	49.0732	49.0732	49.0732	
lines/min	817.8860	817.8860	817.8860	817.8860	817.8860	817.8860	817.8860	817.8860	817.8860	817.8860	
<b>Phase flow</b>											
Single											
Actual inlet flow condition	$kg/hr$ 91.86										
	$m^3/hr$ 5.91	6.21	6.57	7.00	7.52	8.17	8.89	10.22	12.07	15.63	
Standard flow condition	$m^3/hr$ 49.07	49.07	49.07	49.07	49.07	49.07	49.07	49.07	49.07	49.07	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.85	292.84	292.48	292.13	291.77	291.39	292.34	290.48	290.06	289.52	
	$^{\circ}F$ 19.70	19.69	19.33	18.98	18.62	18.24	19.19	17.33	16.91	16.37	
Inlet Stagnation Pressure	$KPa abs$ 829.79	792.77	750.61	706.99	660.98	610.79	565.89	495.56	425.37	337.84	
Outlet Stagnation Pressure	$KPa abs$ 792.77	750.61	706.99	660.98	610.79	565.89	495.56	425.37	337.84	187.92	
Stagnation Density, $\rho_0$	$kg/m^3$ 15.71	14.97	14.16	13.32	12.44	11.48	10.57	9.28	7.85	6.29	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 494.04	494.42	494.53	494.67	494.82	495.00	496.30	495.38	495.73	496.15	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 718.57	680.08	637.47	592.86	545.45	494.11	448.99	373.04	301.85	208.60	
	$KPa abs$ 819.89	781.40	738.80	694.18	646.77	595.44	550.31	476.37	403.17	309.92	
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9131	18.4539	17.9865	17.4660	16.8646	17.5580	15.1506	13.8509	11.1772	
	$^{\circ}F$ 292.15	292.06	291.60	291.14	290.62	290.01	290.71	288.30	287.00	284.33	
Compressibility, $Z_1$	0.9551	0.9572	0.9591	0.9617	0.9642	0.9668	0.9697	0.9731	0.9769	0.9818	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.47E-05	1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.44E-05	1.43E-05	
Density, $\rho_1$	$kg/m^3$ 15.5337	14.7949	13.9784	13.1236	12.2178	11.2401	10.3334	8.9881	7.6113	5.8767	
Velocity, $V_1$	$m/sec$ 35.5984	37.4243	39.6104	42.1902	45.3180	49.2599	53.5824	61.6025	72.7456	94.2167	
Mach number at the inlet, $M_1$	0.1336	0.1400	0.1481	0.1575	0.1688	0.1832	0.1984	0.2283	0.2690	0.3484	
$4fL_1/D$	37.6393	33.8579	30.8002	26.3064	22.5364	18.7704	15.0083	11.2496	7.4955	3.7455	
Reynolds number, $Re_1$	2.883E+05	2.884E+05	2.890E+05	2.895E+05	2.901E+05	2.908E+05	2.903E+05	2.928E+05	2.942E+05	2.971E+05	
Friction factor, $4f$	0.02392647	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	
Recovery factor, $r$	0.80498751	0.8028	0.8007	0.7985	0.7961	0.7936	0.7904	0.7879	0.7845	0.7806	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.56	19.54	19.15	18.78	18.39	17.95	18.85	16.86	16.25	15.23	
Enthalpy, $h$	$KJ/kg$ 493.51	493.83	493.86	493.91	493.94	493.94	495.02	493.67	493.58	491.99	
Entropy, $s$	2.30709800	2.3169	2.3271	2.3386	2.3516	2.3667	2.3848	2.4066	2.4361	2.4802	
<b>Downstream Condition</b>											
$4fL_2/D$	3.7483	3.7482	3.7480	3.7479	3.7477	3.7474	3.7476	3.7468	3.7463	3.7454	
Mach number at the outlet, $M_2$	0.1400	0.1481	0.1575	0.1688	0.1832	0.1984	0.2283	0.2690	0.3484	0.9988	
Absolute outlet pressure, $P_2$	$KPa a$ 781.40	738.80	694.18	646.77	595.44	550.31	476.37	403.17	309.92	101.33	
Outlet pressure (gauge)	$KPa g$ 680.076	637.474	592.857	545.446	494.111	448.985	375.044	301.849	208.599	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.91	18.45	17.99	17.47	16.86	15.15	13.85	11.18	8.25	-23.25	
Compressibility, $Z_2$	0.9572	0.9594	0.9617	0.9642	0.9668	0.9697	0.9731	0.9769	0.9818	0.9909	
Density, $\rho_2$	$kg/m^3$ 14.7949	13.9784	13.1236	12.2178	11.2401	10.3334	8.9881	7.6113	5.8767	2.1658	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.47E-05	1.47E-05	1.46E-05	1.46E-05	1.46E-05	1.46E-05	1.45E-05	1.44E-05	1.43E-05	1.20E-05	
Actual outlet flow	$m^3/hr$ 6.2087	6.5714	6.9994	7.5183	8.1723	8.8894	10.2199	12.0686	15.6307	42.4128	
Velocity, $V_2$	$m/sec$ 37.4243	39.6104	42.1902	45.3180	49.2599	53.5824	61.6025	72.7456	94.2167	255.6507	
Reynolds number, $Re_2$	2.884E+05	2.890E+05	2.895E+05	2.901E+05	2.908E+05	2.903E+05	2.928E+05	2.942E+05	2.971E+05	3.377E+05	
Friction factor, $4f$	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0239	0.0238	
Recovery factor, $r$	0.8028	0.8007	0.7985	0.7961	0.7936	0.7904	0.7879	0.7845	0.7806	0.7813	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.5453	19.4439	19.0580	18.6740	18.2591	18.0952	18.3327	16.5767	15.6513	7.6995	
Enthalpy, $h$	$KJ/kg$ 493.8326	493.8636	493.9099	493.9395	493.9406	493.9188	493.6749	493.3094	491.9896	465.8983	
Entropy, $s$	2.3169	2.3271	2.3386	2.3516	2.3667	2.3848	2.4066	2.4361	2.4802	2.5908	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -0.14										
	$KPa abs$ 101.19										
Critical Temperature	$^{\circ}C$ 23.33										
	$^{\circ}F$ 249.82										
Max length of duct at which no shock occurs	$m$ 12.05										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 38.49	42.60	44.62	47.41	51.34	45.13	73.94	73.20	93.25	208.60	
Temperature drop / Segment Length	$^{\circ}C$ 0.09	0.46	0.47	0.52	0.60	-0.69	2.41	1.30	2.67	34.43	
Total pressure drop	$KPa$ 718.57										
Total temperature drop	$^{\circ}C$ 42.33										

Figure F 11-24: Vent pipe model predictions for carbon-dioxide gas at sonic conditions



Gas Property Calculation for DBNGP Gas Mixture @ 100 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number:	80	80	80	80	80	80	80	80	80	80	
Outside diameter:	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness:	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness:	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter:	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, e:	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, e/D:	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, A:	m <sup>2</sup> 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments:	m 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
DBNGP Gas Mixture											
Specific heat at constant pressure, cp:	J/kg.K 2044.80	2044.25	2043.56	2042.87	2042.10	2041.26	2040.63	2039.26	2038.04	2036.50	
Specific heat at constant volume, cv:	J/kg.K 1570.97	1570.79	1570.51	1570.22	1569.89	1569.50	1569.35	1568.50	1567.84	1566.91	
Ratio of specific heats, γ:	1.3016	1.3014	1.3012	1.3010	1.3008	1.3006	1.3003	1.3001	1.2999	1.2997	
Molecular weight, M.W:	kg/mole 17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	
Gas constant, R:	J/kg.K 463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	
<b>Standard condition</b>											
Inlet pressure, P <sub>std</sub> (gauge):	K Pa g 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure:	K Pa 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, P <sub>std</sub> (absolute):	K Pa abs 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, T <sub>std</sub> :	°C 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, Z <sub>std</sub> :	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	
Density at standard condition, ρ <sub>std</sub> :	kg/m <sup>3</sup> 0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	
Normal or standard flow:	m <sup>3</sup> /hr 15.8109	15.8109	15.8109	15.8109	15.8109	15.8109	15.8109	15.8109	15.8109	15.8109	
lines/min	263.5150	263.5150	263.5150	263.5150	263.5150	263.5150	263.5150	263.5150	263.5150	263.5150	
<b>Phase flow</b>											
Actual inlet flow condition:	kg/hr 12.02										
m <sup>3</sup> /hr	8.05	8.36	8.72	9.12	9.59	10.14	10.78	11.61	12.62	13.98	
Standard flow condition:	m <sup>3</sup> /hr 15.81	15.81	15.81	15.81	15.81	15.81	15.81	15.81	15.81	15.81	
<b>Stagnation Properties</b>											
Stagnation Temperature, T <sub>0</sub> :	°C 292.73	292.73	292.70	292.68	292.65	292.62	292.72	292.56	292.54	292.51	
°C	19.58	19.58	19.55	19.53	19.50	19.47	19.57	19.41	19.39	19.36	
Inlet Stagnation Pressure:	Kpa abs 203.09	196.10	187.79	179.89	171.17	162.05	152.72	142.20	131.14	118.89	
Outlet Stagnation Pressure:	Kpa abs 196.10	187.79	179.89	171.17	162.05	152.72	142.20	131.14	118.89	105.04	
Stagnation Density, ρ <sub>0</sub> :	kg/m <sup>3</sup> 1.50	1.45	1.39	1.33	1.27	1.20	1.13	1.05	0.97	0.88	
Stagnation Enthalpy, h <sub>0</sub> :	KJ/kg 823.95	824.02	824.05	824.08	824.11	824.15	824.44	824.22	824.29	824.35	
<b>Upstream Condition</b>											
Inlet pressure, P <sub>1</sub> :	Kpa g 100.00	92.59	84.50	76.31	67.57	58.36	48.91	38.15	26.82	14.26	
Kpa abs	201.33	193.92	185.82	177.64	168.89	159.69	150.23	139.47	128.14	115.58	
Inlet temperature, T <sub>1</sub> :	°C 19.00	18.9576	18.8731	18.7854	18.6794	18.5542	18.5340	18.2078	17.9663	17.6143	
°C	292.15	292.11	292.02	291.94	291.83	291.70	291.68	291.36	291.12	290.76	
Compressibility, Z <sub>1</sub> :	0.9957	0.9959	0.9960	0.9962	0.9964	0.9966	0.9968	0.9970	0.9972	0.9975	
Viscosity, μ <sub>1</sub> :	Pa.sec 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.13E-05	
Density, ρ <sub>1</sub> :	kg/m <sup>3</sup> 1.4923	1.4373	1.3775	1.3170	1.2524	1.1844	1.1141	1.0353	0.9517	0.8593	
Velocity, V <sub>1</sub> :	m/sec 48.5325	50.3871	52.5750	54.9903	57.8280	61.1466	65.0041	69.9532	76.0972	84.2839	
Mach number at the inlet, M <sub>1</sub> :	0.1158	0.1200	0.1254	0.1310	0.1379	0.1458	0.1550	0.1668	0.1814	0.2009	
4fL <sub>1-2</sub> /D:	53.1369	48.9495	44.7656	40.5852	36.4083	32.2550	28.0651	23.8988	19.7362	15.5773	
Reynolds number, Re:	4.874E+04	4.875E+04	4.876E+04	4.878E+04	4.880E+04	4.882E+04	4.883E+04	4.889E+04	4.893E+04	4.899E+04	
Friction factor, 4f:	0.02647796	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	
Recovery factor, r:	0.74390939	0.7438	0.7437	0.7435	0.7434	0.7433	0.7431	0.7429	0.7428	0.7426	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.43	19.42	19.38	19.34	19.29	19.23	19.30	19.10	19.02	18.91	
Enthalpy, h:	KJ/kg 822.79	822.78	822.69	822.59	822.46	822.30	822.35	821.80	821.42	820.83	
Entropy, s:	KJ/kg.K 5.94853756	5.9658	5.9852	6.0057	6.0286	6.0539	6.0823	6.1148	6.1527	6.1983	
<b>Downstream Condition</b>											
4fL <sub>1-2</sub> /D:	4.1480	4.1479	4.1478	4.1476	4.1474	4.1472	4.1472	4.1467	4.1463	4.1458	
Mach number at the outlet, M <sub>2</sub> :	0.1200	0.1254	0.1310	0.1379	0.1458	0.1550	0.1668	0.1814	0.2009	0.2290	
Absolute outlet pressure, P <sub>2</sub> :	Kpa a 193.92	185.82	177.64	168.89	159.69	150.23	139.47	128.14	115.58	101.33	
Outlet pressure (gauge):	Kpa g 92.592	84.500	76.315	67.567	58.363	48.907	38.149	26.815	14.259	0.000	
Outlet temperature, T <sub>2</sub> :	°C 18.96	18.87	18.79	18.68	18.55	18.53	18.21	17.97	17.61	17.07	
Compressibility, Z <sub>2</sub> :	0.9959	0.9960	0.9962	0.9964	0.9966	0.9968	0.9970	0.9972	0.9975	0.9978	
Density, ρ <sub>2</sub> :	kg/m <sup>3</sup> 1.4373	1.3775	1.3170	1.2524	1.1844	1.1141	1.0353	0.9517	0.8593	0.7545	
Viscosity of gas, μ <sub>2</sub> :	Pa.sec 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.13E-05	1.13E-05	
Actual outlet flow:	m <sup>3</sup> /hr 8.3593	8.7223	9.1250	9.5938	10.1443	10.7843	11.6057	12.6246	13.9828	15.9252	
Velocity, V <sub>2</sub> :	m/sec 50.3871	52.5750	54.9903	57.8280	61.1466	65.0041	69.9532	76.0972	84.2839	95.9919	
Reynolds number, Re:	4.875E+04	4.876E+04	4.878E+04	4.880E+04	4.882E+04	4.883E+04	4.889E+04	4.893E+04	4.899E+04	4.908E+04	
Friction factor, 4f:	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	
Recovery factor, r:	0.7438	0.7437	0.7435	0.7434	0.7433	0.7431	0.7429	0.7428	0.7426	0.7424	
Adiabatic Wall Temperature, T <sub>w</sub> :	°C 19.4175	19.3977	19.3534	19.3084	19.2539	19.2286	19.2194	19.0369	18.9307	18.7681	
Enthalpy, h:	KJ/kg 822.7768	822.6861	822.5899	822.4622	822.3000	822.3548	821.7985	821.4215	820.8323	819.8635	
Entropy, s:	KJ/kg.K 5.9658	5.9852	6.0057	6.0286	6.0539	6.0823	6.1148	6.1527	6.1983	6.2559	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure:	Kpa G -79.61										
Kpa abs	21.72										
Critical Temperature:	°C 18.77										
°C	254.38										
Max length of duct at which no shock occurs:	m 15.37										
<b>Drop</b>											
Pressure drop / Segment Length:	Kpa 7.41	8.09	8.18	8.75	9.20	9.46	10.76	11.33	12.56	14.26	
Temperature drop / Segment Length:	°C 0.04	0.08	0.09	0.11	0.13	0.02	0.33	0.24	0.35	0.55	
Total pressure drop:	Kpa 100.00										
Total temperature drop:	°C 1.71										

Figure F 11-25: Vent pipe model predictions for DBNGP gas mixture at 100 KPa gauge

Gas Property Calculation for DBNGP Gas Mixture @ 200 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
DBNGP Gas Mixture											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2051.03	2050.05	2048.92	2047.67	2046.32	2044.81	2043.49	2040.95	2038.29	2034.32	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1572.12	1571.82	1571.38	1570.88	1570.31	1569.64	1569.22	1567.70	1566.16	1563.53	
Ratio of specific heats, $\gamma$	1.3046	1.3043	1.3039	1.3035	1.3031	1.3027	1.3022	1.3019	1.3015	1.3011	
Molecular weight, $M.W.$	$kg/mole$ 17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	
Gas constant, $R$	$J/kg \cdot K$ 463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	
Normal or standard flow	$m^3/hr$ 26.1394	26.1394	26.1394	26.1394	26.1394	26.1394	26.1394	26.1394	26.1394	26.1394	
Phase flow	lines/min 435.6568	435.6568	435.6568	435.6568	435.6568	435.6568	435.6568	435.6568	435.6568	435.6568	
<b>Actual inlet flow condition</b>											
Actual inlet flow condition	$kg/hr$ 19.86										
Standard flow condition	$m^3/hr$ 8.87	9.29	9.76	10.32	10.98	11.80	12.81	14.21	16.16	19.31	
Standard flow condition	$m^3/hr$ 26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.85	292.85	292.80	292.75	292.70	292.65	292.78	292.55	292.49	292.43	
Inlet Stagnation Pressure	$KPa abs$ 304.54	291.31	277.92	265.02	247.48	231.04	215.40	193.14	170.94	144.80	
Outlet Stagnation Pressure	$KPa abs$ 291.31	277.92	263.02	247.48	231.04	213.40	193.14	170.94	144.80	111.15	
Stagnation Density, $\rho_0$	$kg/m^3$ 2.26	2.16	2.06	1.95	1.83	1.71	1.58	1.43	1.26	1.07	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 823.17	823.30	823.35	823.40	823.45	823.52	823.95	823.66	823.79	823.94	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 200.00	186.65	172.74	157.79	142.01	125.13	107.32	86.45	65.50	36.19	
Inlet pressure, $P_1$	$KPa abs$ 301.33	287.97	274.06	259.12	243.33	226.47	208.64	187.78	164.82	137.51	
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9312	18.8065	18.6579	18.4818	18.2673	18.1709	17.9885	17.9114	15.9552	
Compressibility, $Z_1$	0.9936	0.9930	0.9924	0.9918	0.9913	0.9908	0.9903	0.9898	0.9894	0.9890	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.13E-05	
Density, $\rho_1$	$kg/m^3$ 2.2383	2.1390	2.0360	1.9253	1.8085	1.6839	1.5512	1.3983	1.2292	1.0287	
Velocity, $V_1$	$m/sec$ 53.4941	55.9773	58.8096	62.1894	66.2057	71.1064	77.1877	85.6281	97.4065	116.3902	
Mach number at the inlet, $M_1$	0.1276	0.1336	0.1401	0.1483	0.1579	0.1695	0.1840	0.2042	0.2324	0.2780	
Reynolds number, $Re_1$	42.9292	38.9285	34.9308	30.9361	26.9443	22.9556	18.9699	14.9871	11.0078	7.0318	
Friction factor, $f_1$	0.045E+04	0.051E+04	0.055E+04	0.060E+04	0.066E+04	0.073E+04	0.077E+04	0.083E+04	0.090E+04	0.100E+04	
Recovery factor, $r_1$	0.02536227	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0253	0.0253	
Adiabatic Wall Temperature, $T_{aw}$	19.52	19.50	19.44	19.36	19.28	19.19	19.26	18.92	18.74	18.43	
Enthalpy, $h_1$	$KJ/kg$ 821.77	821.77	821.65	821.50	821.30	821.03	821.02	820.04	819.10	817.23	
Entropy, $s_1$	5.75902489	5.7799	5.8023	5.8277	5.8560	5.8882	5.9260	5.9713	6.0283	6.1056	
<b>Downstream Condition</b>											
Mach number at the outlet, $M_2$	3.9732	3.9731	3.9729	3.9728	3.9726	3.9723	3.9722	3.9716	3.9710	3.9700	
Absolute outlet pressure, $P_2$	0.1336	0.1401	0.1483	0.1579	0.1695	0.1840	0.2042	0.2324	0.2780	0.3754	
Outlet pressure (gauge)	$KPa g$ 287.97	274.06	259.12	243.33	226.47	208.64	187.78	164.82	137.51	101.33	
Outlet temperature, $T_2$	186.646	172.739	157.793	142.007	125.149	107.316	86.453	63.498	36.189	0.000	
Compressibility, $Z_2$	18.93	18.81	18.66	18.48	18.27	17.99	17.61	15.96	13.20		
Density, $\rho_2$	0.9939	0.9942	0.9945	0.9948	0.9951	0.9955	0.9959	0.9964	0.9970	0.9977	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 2.1390	2.0360	1.9253	1.8085	1.6839	1.5512	1.3983	1.2292	1.0287	0.7647	
Actual outlet flow	$m^3/hr$ 9.2867	9.7566	10.3173	10.9836	11.7966	12.8055	14.2058	16.1599	19.3093	25.9750	
Velocity, $V_2$	$m/sec$ 55.9773	58.8096	62.1894	66.2057	71.1064	77.1877	85.6281	97.4065	116.3902	156.5687	
Reynolds number, $Re_2$	8.051E+04	8.053E+04	8.060E+04	8.066E+04	8.073E+04	8.077E+04	8.093E+04	8.109E+04	8.138E+04	8.210E+04	
Friction factor, $f_2$	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0253	0.0253	0.0253	
Recovery factor, $r_2$	0.7454	0.7452	0.7449	0.7447	0.7444	0.7441	0.7438	0.7435	0.7431	0.7428	
Adiabatic Wall Temperature, $T_{aw}$	$^{\circ}C$ 19.5025	19.4689	19.3973	19.3162	19.2243	19.1626	19.1061	18.7760	18.4697	17.7199	
Enthalpy, $h_2$	$KJ/kg$ 821.7683	821.6543	821.5018	821.3019	821.0347	821.0194	820.0427	819.1006	817.2306	812.0157	
Entropy, $s_2$	5.7799	5.8023	5.8277	5.8560	5.8882	5.9260	5.9713	6.0283	6.1056	6.2287	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -65.49										
Critical Temperature	$^{\circ}C$ 35.83										
Max length of duct at which no shock occurs	$m$ 18.99										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 13.35	13.91	14.95	15.79	16.86	17.83	20.86	22.96	27.31	36.19	
Temperature drop / Segment Length	$^{\circ}C$ 0.07	0.12	0.15	0.18	0.21	0.10	0.58	0.58	1.06	2.75	
Total pressure drop	$KPa$ 200.00										
Total temperature drop	$^{\circ}C$ 5.45										

Figure F 11-26: Vent pipe model predictions for DBNGP gas mixture at 200 KPa gauge

Gas Property Calculation for DBNGP Gas Mixture @ 300 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
DBNGP Gas Mixture											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2057.33	2055.99	2054.42	2052.74	2050.90	2048.84	2047.03	2045.55	2043.76	2043.69	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1573.28	1572.89	1572.31	1571.67	1570.94	1570.08	1569.55	1567.54	1565.41	1561.38	
Ratio of specific heats, $\gamma$	1.3077	1.3071	1.3066	1.3061	1.3055	1.3049	1.3042	1.3037	1.3030	1.3025	
Molecular weight, M.W.	$kg/mole$ 17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	
Gas constant, R	$J/kg \cdot K$ 463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	
Normal or standard flow	$m^3/hr$ 35.9483	35.9483	35.9483	35.9483	35.9483	35.9483	35.9483	35.9483	35.9483	35.9483	
Phase flow	Single										
Actual inlet flow condition	$kg/hr$ 27.32										
Standard flow condition	$m^3/hr$ 35.95	35.95	35.95	35.95	35.95	35.95	35.95	35.95	35.95	35.95	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.89	292.89	292.82	292.75	292.68	292.61	292.76	292.44	292.36	292.28	
Inlet Stagnation Pressure	$KPa abs$ 405.88	387.41	367.92	347.57	325.83	302.57	277.87	248.74	216.20	176.73	
Outlet Stagnation Pressure	$KPa abs$ 387.41	367.92	347.57	325.83	302.57	277.87	248.74	216.20	176.73	119.91	
Stagnation Density, $\rho_0$	$kg/m^3$ 3.01	2.88	2.73	2.58	2.42	2.26	2.06	1.84	1.60	1.31	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 822.23	822.41	822.47	822.53	822.61	822.70	823.27	822.89	823.07	823.30	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 300.00	281.38	261.68	240.92	218.75	194.89	169.73	139.54	105.78	64.05	
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9225	18.7620	18.5814	18.3648	18.0968	17.9894	17.2328	16.4407	14.8112	
Compressibility, $Z_1$	0.9915	0.9919	0.9922	0.9927	0.9931	0.9936	0.9942	0.9948	0.9955	0.9963	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	
Density, $\rho_1$	$kg/m^3$ 2.9875	2.8485	2.7023	2.5482	2.3838	2.2070	2.0192	1.7979	1.5491	1.2429	
Velocity, $V_1$	$m/sec$ 55.1185	57.8072	60.9355	64.6195	69.0765	74.6097	81.5484	91.5864	106.2969	132.4810	
Mach number at the inlet, $M_1$	0.1315	0.1379	0.1454	0.1541	0.1647	0.1779	0.1944	0.2184	0.2536	0.3167	
Reynolds number, $Re_1$	1.106E+05	1.106E+05	1.107E+05	1.108E+05	1.109E+05	1.110E+05	1.111E+05	1.111E+05	1.117E+05	1.123E+05	
Friction factor, $f_1$	0.02485001	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	
Recovery factor, $r_1$	0.74733469	0.7470	0.7467	0.7464	0.7460	0.7456	0.7452	0.7448	0.7443	0.7437	
Adiabatic Wall Temperature, $T_{w1}$	$^{\circ}C$ 19.55	19.53	19.44	19.34	19.23	19.11	19.20	18.76	18.50	18.02	
Enthalpy, $h_1$	$KJ/kg$ 820.76	820.79	820.66	820.50	820.28	819.97	820.01	818.77	817.50	814.62	
Entropy, $s_1$	$KJ/kg \cdot K$ 5.62362056	5.6456	5.6694	5.6960	5.7261	5.7607	5.8018	5.8520	5.9173	6.0112	
<b>Downstream Condition</b>											
Mach number at the outlet, $M_2$	3.8930	3.8929	3.8927	3.8925	3.8923	3.8921	3.8919	3.8914	3.8907	3.8896	
Absolute outlet pressure, $P_2$	$KPa g$ 0.1379	0.1454	0.1541	0.1647	0.1779	0.1944	0.2184	0.2536	0.3167	0.5107	
Outlet pressure (gauge)	$KPa g$ 281.382	261.683	240.923	218.749	194.886	169.727	139.538	105.783	64.054	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.92	18.76	18.58	18.36	18.10	17.99	17.23	16.44	14.81	8.03	
Compressibility, $Z_2$	0.9919	0.9923	0.9927	0.9931	0.9936	0.9942	0.9948	0.9955	0.9963	0.9973	
Density, $\rho_2$	$kg/m^3$ 2.8485	2.7023	2.5482	2.3838	2.2070	2.0192	1.7979	1.5491	1.2429	0.7789	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	1.10E-05	
Actual outlet flow	$m^3/hr$ 9.5903	10.1093	10.7205	11.4599	12.3778	13.5290	15.1943	17.6348	21.9788	35.0719	
Velocity, $V_2$	$m/sec$ 57.8072	60.9355	64.6195	69.0765	74.6097	81.5484	91.5864	106.2969	132.4810	211.4020	
Reynolds number, $Re_2$	1.106E+05	1.107E+05	1.108E+05	1.109E+05	1.110E+05	1.111E+05	1.111E+05	1.117E+05	1.123E+05	1.148E+05	
Friction factor, $f_2$	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	0.0248	
Recovery factor, $r_2$	0.7470	0.7467	0.7464	0.7460	0.7456	0.7452	0.7448	0.7443	0.7437	0.7433	
Adiabatic Wall Temperature, $T_{w2}$	$^{\circ}C$ 19.5319	19.4886	19.3907	19.2852	19.1640	19.0818	19.0060	18.5577	18.0830	16.2779	
Enthalpy, $h_2$	$KJ/kg$ 820.7872	820.6580	820.4987	820.2804	819.9745	820.0115	818.7729	817.5027	814.6133	801.5679	
Entropy, $s_2$	$KJ/kg \cdot K$ 5.6456	5.6694	5.6960	5.7261	5.7607	5.8018	5.8520	5.9173	6.0112	6.1919	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ 52.16										
Critical Temperature	$^{\circ}C$ 19.28										
Max length of duct at which no shock occurs	$m$ 12.36										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 18.62	19.70	20.76	22.17	23.86	25.16	30.19	33.76	41.73	64.05	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.16	0.18	0.22	0.27	0.11	0.76	0.79	1.63	6.78	
Total pressure drop	$KPa$ 300.00										
Total temperature drop	$^{\circ}C$ 10.55										

Figure F 11-27: Vent pipe model predictions for DBNGP gas mixture at 300 KPa gauge



Gas Property Calculation for DBNGP Gas Mixture @ 400 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
DBNGP Gas Mixture											
Specific heat at constant pressure, $C_p$	$J/kg \cdot K$ 2063.69	2062.04	2060.07	2057.96	2055.67	2053.11	2050.89	2046.57	2041.91	2034.29	
Specific heat at constant volume, $C_v$	$J/kg \cdot K$ 1574.44	1574.00	1573.30	1572.53	1571.67	1570.65	1570.07	1567.67	1565.17	1560.24	
Ratio of specific heats, $\gamma$	1.3107	1.3101	1.3094	1.3087	1.3080	1.3072	1.3062	1.3055	1.3046	1.3038	
Molecular weight, M.W.	$kg/mole$ 17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	
Gas constant, R	$J/kg \cdot K$ 463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	
Normal or standard flow	$m^3/hr$ 45.5677	45.5677	45.5677	45.5677	45.5677	45.5677	45.5677	45.5677	45.5677	45.5677	
Phase flow	lines/min 759.4610	759.4610	759.4610	759.4610	759.4610	759.4610	759.4610	759.4610	759.4610	759.4610	
<b>Actual inlet flow condition</b>											
Actual inlet flow condition	$kg/hr$ 34.63										
Standard flow condition	$m^3/hr$ 9.26	9.71	10.25	10.89	11.66	12.63	13.84	15.63	18.30	23.29	
Stagnation Properties											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.90	292.90	292.81	292.73	292.63	292.54	292.73	292.31	292.21	292.10	
Inlet Stagnation Pressure	$KPa abs$ 507.18	484.52	459.38	433.29	405.64	375.91	344.50	306.56	264.54	212.59	
Outlet Stagnation Pressure	$KPa abs$ 484.52	459.38	433.29	405.64	375.91	344.50	306.56	264.54	212.59	131.49	
Stagnation Density, $\rho_0$	$kg/m^3$ 3.77	3.60	3.42	3.22	3.01	2.79	2.56	2.24	1.96	1.58	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 821.24	821.46	821.53	821.62	821.71	821.82	822.53	822.06	822.28	822.57	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 400.00	376.61	351.39	324.86	296.58	266.06	234.07	194.83	151.08	95.90	
Inlet temperature, $T_1$	$^{\circ}C$ 501.33	477.94	452.72	426.18	397.90	367.39	335.39	296.17	252.41	197.22	
Compressibility, $Z_1$	1.9.00	18.9222	18.7364	18.5285	18.2826	17.9789	17.8878	16.9949	16.0845	14.1062	
Viscosity, $\mu_1$	$Pa \cdot sec$ 292.15	292.07	291.89	291.68	291.43	291.13	291.04	290.14	289.23	287.26	
Density, $\rho_1$	$kg/m^3$ 0.9893	0.9898	0.9903	0.9909	0.9915	0.9921	0.9928	0.9935	0.9944	0.9956	
Velocity, $V_1$	$m/sec$ 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	
Mach number at the inlet, $M_1$	3.7399	3.5646	3.3769	3.1795	2.9693	2.7427	2.5029	2.2153	1.8922	1.4870	
Reynolds number, $Re_1$	55.8112	38.5553	61.8105	65.6476	70.2952	76.1023	83.3941	94.2209	110.3101	140.3685	
Friction factor, $f_1$	0.1331	0.1395	0.1473	0.1565	0.1675	0.1812	0.1985	0.2244	0.2629	0.3353	
Recovery factor, $r_1$	38.9927	35.1167	31.2441	27.3751	23.5096	19.6476	15.7893	11.9343	8.0833	4.2363	
Adiabatic Wall Temperature, $T_{w1}$	1.400E+05	1.400E+05	1.402E+05	1.403E+05	1.404E+05	1.406E+05	1.407E+05	1.412E+05	1.416E+05	1.426E+05	
Entropy, $s_1$	0.02454717	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	
Entropy, $s$	0.74908514	0.7487	0.7483	0.7478	0.7474	0.7469	0.7463	0.7458	0.7451	0.7444	
Downstream Condition											
Mach number at the outlet, $M_2$	4f <sub>1-2</sub> /D 3.8455	3.8454	3.8453	3.8451	3.8449	3.8447	3.8445	3.8440	3.8434	3.8422	
Absolute outlet pressure, $P_2$	$KPa a$ 0.1395	0.1473	0.1565	0.1675	0.1812	0.1985	0.2244	0.2629	0.3353	0.6385	
Outlet pressure (gauge)	$KPa g$ 477.94	452.72	426.18	397.90	367.39	335.39	296.17	252.41	197.22	101.33	
Outlet temperature, $T_2$	$^{\circ}C$ 376.614	351.391	324.859	296.579	266.065	234.066	194.847	151.082	95.895	0.000	
Compressibility, $Z_2$	18.92	18.74	18.53	18.28	17.98	17.69	16.99	16.08	14.11	11.90	
Density, $\rho_2$	$kg/m^3$ 0.9898	0.9903	0.9909	0.9915	0.9921	0.9928	0.9935	0.9944	0.9956	0.9973	
Velocity, $V_2$	$m/hr$ 3.5646	3.3769	3.1795	2.9693	2.7427	2.5029	2.2153	1.8922	1.4870	0.7964	
Reynolds number, $Re_2$	$Pa \cdot sec$ 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	1.08E-05	
Friction factor, $f_2$	9.7144	10.2544	10.8910	11.6621	12.6255	13.8352	15.6314	18.5006	23.2873	43.4784	
Recovery factor, $r_2$	58.5553	61.8105	65.6476	70.2952	76.1023	83.3941	94.2209	110.3101	140.3685	262.0737	
Adiabatic Wall Temperature, $T_{w2}$	1.400E+05	1.402E+05	1.403E+05	1.404E+05	1.406E+05	1.407E+05	1.412E+05	1.416E+05	1.426E+05	1.483E+05	
Entropy, $s_2$	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	0.0245	
Entropy, $s$	19.5455	19.4975	19.3774	19.2489	19.1034	19.0084	18.9252	18.7389	17.7969	14.5823	
Critical Properties at Outlet Mach 1											
Critical Pressure	$KPa g$ 39.21										
Critical Temperature	$^{\circ}C$ 62.11										
Max length of duct at which no shock occurs	$m$ 19.59										
Drop											
Pressure drop / Segment Length	$KPa$ 23.39	28.22	26.53	28.28	30.51	32.00	39.22	43.77	55.19	95.90	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.19	0.21	0.25	0.30	0.09	0.89	0.91	1.98	12.21	
Total pressure drop	$KPa$ 400.00										
Total temperature drop	$^{\circ}C$ 16.71										

Figure F 11-28: Vent pipe model predictions for DBNGP gas mixture at 400 KPa gauge

Gas Property Calculation for DBNGP Gas Mixture @ 500 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
DBNGP Gas Mixture											
Specific heat at constant pressure, $C_p$	$J/kg \cdot K$ 2070.12	2068.15	2065.79	2063.27	2060.55	2057.50	2054.93	2049.83	2044.42	2035.62	
Specific heat at constant volume, $C_v$	$J/kg \cdot K$ 1575.60	1575.10	1574.30	1573.42	1572.43	1571.27	1570.69	1567.94	1565.18	1559.70	
Ratio of specific heats, $\gamma$	1.3139	1.3130	1.3122	1.3113	1.3104	1.3095	1.3083	1.3073	1.3062	1.3051	
Molecular weight, $M_w$	$kg/mole$ 17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	
Gas constant, $R$	$J/kg \cdot K$ 463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	
Normal or standard flow	$m^3/hr$ 55.0997	55.0997	55.0997	55.0997	55.0997	55.0997	55.0997	55.0997	55.0997	55.0997	
Phase flow	lines/min 918.3286	918.3286	918.3286	918.3286	918.3286	918.3286	918.3286	918.3286	918.3286	918.3286	
<b>Single</b>											
Actual inlet flow condition	$kg/hr$ 41.87										
Standard flow condition	$m^3/hr$ 9.31	9.77	10.32	10.97	11.76	12.75	13.97	15.83	18.61	23.91	
Stagnation Properties											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.91	292.91	292.90	292.69	292.38	292.46	292.69	292.18	292.06	291.91	
Inlet Stagnation Pressure	$KPa abs$ 608.44	581.29	550.98	519.37	485.98	449.59	412.21	365.74	314.55	250.91	
Outlet Stagnation Pressure	$KPa abs$ 581.29	550.98	519.37	485.98	449.59	412.21	365.74	314.55	250.91	145.96	
Stagnation Density, $\rho_0$	$kg/m^3$ 4.54	4.33	4.11	3.87	3.62	3.35	3.06	2.72	2.34	1.86	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 820.22	820.49	820.58	820.67	820.78	820.91	821.77	821.19	821.45	821.79	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 500.00	471.84	441.34	409.21	375.00	337.90	299.59	251.56	198.23	130.43	
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9208	18.7155	18.4827	18.2121	17.8766	17.4818	16.8120	15.8290	13.6578	
Compressibility, $Z_1$	0.9872	0.9878	0.9884	0.9891	0.9898	0.9905	0.9914	0.9923	0.9934	0.9947	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	
Density, $\rho_1$	$kg/m^3$ 4.4955	4.2836	4.0561	3.8164	3.5615	3.2853	2.9969	2.6445	2.2500	1.7515	
Velocity, $V_1$	$m/sec$ 56.1423	38.9201	62.2255	66.1331	70.8671	76.8236	84.2184	95.4396	112.1742	144.0954	
Mach number at the inlet, $M_1$	0.1339	0.1403	0.1482	0.1575	0.1687	0.1829	0.2002	0.2271	0.2671	0.3439	
Reynolds number, $Re_1$	1.690E+05	1.691E+05	1.693E+05	1.695E+05	1.697E+05	1.699E+05	1.701E+05	1.707E+05	1.713E+05	1.726E+05	
Friction factor, $f_1$	0.02434511	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	
Recovery factor, $r_1$	0.75086096	0.7504	0.7499	0.7493	0.7488	0.7482	0.7475	0.7468	0.7460	0.7450	
Adiabatic Wall Temperature, $T_{w1}$	$^{\circ}C$ 19.57	19.55	19.42	19.28	19.12	18.95	18.77	18.47	18.12	17.46	
Enthalpy, $h_1$	$KJ/kg$ 818.72	818.84	818.72	818.58	818.37	818.06	818.33	816.76	815.30	811.58	
Entropy, $s_1$	5.43107305	5.4355	5.4781	5.5056	5.5367	5.5729	5.6158	5.6691	5.7395	5.8448	
<b>Downstream Condition</b>											
Mach number at the outlet, $M_2$	0.1403	0.1482	0.1575	0.1687	0.1829	0.2002	0.2271	0.2671	0.3439	0.7605	
Absolute outlet pressure, $P_2$	$KPa a$ 573.16	542.67	510.54	476.33	439.23	400.91	352.89	299.55	231.76	101.33	
Outlet pressure (gauge)	$KPa g$ 471.835	441.344	409.214	375.003	337.901	299.585	251.561	198.226	130.432	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.92	18.71	18.48	18.21	17.88	17.48	16.81	15.83	13.66	-4.95	
Compressibility, $Z_2$	0.9878	0.9884	0.9891	0.9898	0.9905	0.9914	0.9923	0.9934	0.9947	0.9971	
Density, $\rho_2$	$kg/m^3$ 4.2836	4.0561	3.8164	3.5615	3.2853	2.9969	2.6445	2.2500	1.7515	0.8170	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	1.09E-05	
Actual outlet flow	$m^3/hr$ 9.749	10.3233	10.9716	11.7570	12.7451	13.9730	15.8336	18.6098	23.9056	51.2530	
Velocity, $V_2$	$m/sec$ 38.9201	62.2255	66.1331	70.8671	76.8236	84.2184	95.4396	112.1742	144.0954	308.9366	
Reynolds number, $Re_2$	1.691E+05	1.693E+05	1.695E+05	1.697E+05	1.699E+05	1.701E+05	1.707E+05	1.713E+05	1.726E+05	1.835E+05	
Friction factor, $f_2$	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	0.0243	
Recovery factor, $r_2$	0.7504	0.7499	0.7493	0.7488	0.7482	0.7475	0.7468	0.7460	0.7450	0.7447	
Adiabatic Wall Temperature, $T_{w2}$	$^{\circ}C$ 19.5515	19.4983	19.3579	19.2083	19.0393	18.9339	18.8521	18.2197	17.5682	12.7069	
Enthalpy, $h_2$	$KJ/kg$ 818.8404	818.7240	818.5763	818.3688	818.0584	818.3311	816.7601	815.2989	811.5760	775.5702	
Entropy, $s_2$	5.4535	5.4781	5.5056	5.5367	5.5729	5.6158	5.6691	5.7395	5.8448	6.0972	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa a$ 26.45										
Critical Temperature	$^{\circ}C$ 74.88										
Max length of duct at which no shock occurs	$m$ 12.09										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 28.16	30.49	32.13	34.21	37.10	38.32	48.02	53.34	67.79	130.43	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.21	0.23	0.27	0.34	0.06	1.01	0.98	2.17	18.61	
Total pressure drop	$KPa$ 500.00										
Total temperature drop	$^{\circ}C$ 23.64										

Figure F 11-29: Vent pipe model predictions for DBNGP gas mixture at 500 KPa gauge

Gas Property Calculation for DBNGP Gas Mixture @ 600 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajiwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
DBNGP Gas Mixture											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2076.62	2074.32	2071.58	2068.66	2065.50	2061.99	2059.07	2053.23	2047.14	2037.38	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1576.77	1576.21	1575.30	1574.32	1573.21	1571.92	1571.34	1568.28	1565.32	1559.49	
Ratio of specific heats, $\gamma$	1.3170	1.3160	1.3150	1.3140	1.3129	1.3118	1.3104	1.3092	1.3078	1.3064	
Molecular weight, $M.W.$	$kg/mole$ 17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	
Gas constant, $R$	$J/kg \cdot K$ 463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	
Normal or standard flow	$m^3/hr$ 64.5888	64.5888	64.5888	64.5888	64.5888	64.5888	64.5888	64.5888	64.5888	64.5888	
Phase flow	Single										
Actual inlet flow condition	$kg/hr$ 49.08										
Standard flow condition	$m^3/hr$ 64.59	64.59	64.59	64.59	64.59	64.59	64.59	64.59	64.59	64.59	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.91	292.91	292.78	292.65	292.52	292.38	292.65	292.05	291.89	291.71	
Inlet Stagnation Pressure	$KPa abs$ 709.69	677.80	642.65	605.62	566.58	523.78	480.52	425.71	365.69	290.81	
Outlet Stagnation Pressure	$KPa abs$ 677.80	642.65	605.62	566.58	523.78	480.52	425.71	365.69	290.81	163.57	
Stagnation Density, $\rho_0$	$kg/m^3$ 5.30	5.06	4.80	4.52	4.23	3.91	3.58	3.17	2.72	2.16	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 819.19	819.51	819.60	819.72	819.84	819.98	820.98	820.30	820.60	820.98	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 600.00	567.02	531.42	493.79	453.74	410.21	365.73	309.10	246.53	166.72	
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9187	18.6915	18.4396	18.1463	17.7840	17.7606	16.6542	15.6245	13.3466	
Compressibility, $Z_1$	0.9851	0.9858	0.9865	0.9873	0.9881	0.9890	0.9899	0.9910	0.9922	0.9939	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.15E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	
Density, $\rho_1$	$kg/m^3$ 5.2545	5.0053	4.7389	4.4574	4.1582	3.8335	3.4971	3.0813	2.6175	2.0297	
Velocity, $V_1$	$m/sec$ 56.3058	59.1088	62.4315	66.3738	71.1497	77.1766	84.6014	96.0164	113.0290	145.7604	
Mach number at the inlet, $M_1$	0.1343	0.1408	0.1487	0.1580	0.1693	0.1836	0.2010	0.2283	0.2689	0.3475	
Reynolds number, $Re_1$	1.979E+05	1.980E+05	1.983E+05	1.985E+05	1.988E+05	1.991E+05	1.992E+05	2.000E+05	2.008E+05	2.024E+05	
Friction factor, $f_1$	0.02420005	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	
Recovery factor, $r_1$	0.75266227	0.7521	0.7515	0.7508	0.7502	0.7495	0.7487	0.7478	0.7468	0.7457	
Adiabatic Wall Temperature, $T_{w1}$	$^{\circ}C$ 19.57	19.55	19.40	19.24	19.07	18.87	18.63	18.33	17.95	17.23	
Enthalpy, $h_1$	$KJ/kg$ 817.69	817.86	817.76	817.62	817.45	817.12	817.53	815.84	814.38	810.56	
Entropy, $s_1$	5.35720890	5.3798	5.4045	5.4321	5.4633	5.4997	5.5429	5.5964	5.6674	5.7742	
<b>Downstream Condition</b>											
Mach number at the outlet, $M_2$	3.7911	3.7910	3.7909	3.7907	3.7905	3.7903	3.7902	3.7897	3.7892	3.7882	
Absolute outlet pressure, $P_2$	$KPa g$ 668.35	632.75	595.11	555.06	511.34	467.06	410.42	347.86	268.05	101.33	
Outlet pressure (gauge)	$KPa g$ 567.02	531.42	493.785	453.737	410.213	365.733	309.098	246.530	166.721	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.92	18.69	18.44	18.15	17.78	17.36	16.65	13.35	10.26	-12.26	
Compressibility, $Z_2$	0.9858	0.9865	0.9873	0.9881	0.9890	0.9899	0.9910	0.9923	0.9939	0.9968	
Density, $\rho_2$	$kg/m^3$ 5.0053	4.7389	4.4574	4.1582	3.8335	3.4971	3.0813	2.6175	2.0297	0.8401	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	1.03E-05	
Actual outlet flow	$m^3/hr$ 9.8062	10.3575	11.0115	11.8038	12.8037	14.0555	15.9293	18.7517	24.1819	38.4255	
Velocity, $V_2$	$m/sec$ 59.1088	62.4315	66.3738	71.1497	77.1766	84.6014	96.0164	113.0290	145.7604	352.1703	
Reynolds number, $Re_2$	1.980E+05	1.983E+05	1.985E+05	1.988E+05	1.991E+05	1.992E+05	2.000E+05	2.008E+05	2.024E+05	2.202E+05	
Friction factor, $f_2$	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0241	
Recovery factor, $r_2$	0.7521	0.7515	0.7508	0.7502	0.7495	0.7487	0.7478	0.7468	0.7457	0.7457	
Adiabatic Wall Temperature, $T_{w2}$	$^{\circ}C$ 19.5539	19.4951	19.3351	19.1651	18.9739	18.8594	18.7813	18.7002	17.3721	10.7235	
Enthalpy, $h_2$	$KJ/kg$ 817.8618	817.7558	817.6205	817.4252	817.1249	817.5340	815.8425	814.3795	810.5613	761.0566	
Entropy, $s_2$	5.3798	5.4045	5.4321	5.4633	5.4997	5.5429	5.5964	5.6674	5.7742	6.0424	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -13.81										
Critical Temperature	$^{\circ}C$ 87.51										
Max length of duct at which no shock occurs	$m$ 23.90										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 32.98	35.60	37.64	40.05	43.52	44.48	56.64	62.57	79.81	166.72	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.23	0.25	0.29	0.36	0.02	1.11	1.03	2.28	25.61	
Total pressure drop	$KPa$ 600.00										
Total temperature drop	$^{\circ}C$ 31.11										

Figure F 11-30: Vent pipe model predictions for DBNGP gas mixture at 600 KPa gauge



Gas Property Calculation for DBNGP Gas Mixture @ 700 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajwate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
DBNGP Gas Mixture											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2083.18	2080.55	2077.43	2074.11	2070.52	2066.54	2063.29	2056.72	2049.98	2039.37	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1577.95	1577.33	1576.32	1575.22	1574.01	1572.59	1572.02	1568.66	1565.52	1559.44	
Ratio of specific heats, $\gamma$	1.3202	1.3190	1.3179	1.3167	1.3154	1.3141	1.3125	1.3111	1.3095	1.3078	
Molecular weight, M.W.	$kg/mole$ 17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	
Gas constant, R	$J/kg \cdot K$ 463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 7.0599	7.0599	7.0599	7.0599	7.0599	7.0599	7.0599	7.0599	7.0599	7.0599	
Normal or standard flow	$m^3/hr$ 74.0582	74.0582	74.0582	74.0582	74.0582	74.0582	74.0582	74.0582	74.0582	74.0582	
Phase flow	litres/min 1234.3026	1234.3026	1234.3026	1234.3026	1234.3026	1234.3026	1234.3026	1234.3026	1234.3026	1234.3026	
<b>Actual inlet flow condition</b>											
Actual inlet flow condition	$kg/hr$ 56.28										
Standard flow condition	$m^3/hr$ 74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.91	292.91	292.76	292.61	292.46	292.29	292.60	291.91	291.73	291.51	
Inlet Stagnation Pressure	$KPa abs$ 810.93	774.40	734.33	691.95	647.31	598.26	548.96	486.13	417.49	331.77	
Outlet Stagnation Pressure	$KPa abs$ 774.40	734.33	691.95	647.31	598.26	548.96	486.13	417.49	331.77	184.59	
Stagnation Density, $\rho_0$	$kg/m^3$ 6.07	5.80	5.49	5.17	4.84	4.47	4.09	3.63	3.11	2.47	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 818.16	818.52	818.62	818.75	818.89	819.04	820.19	819.40	819.73	820.15	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 700.00	662.28	621.56	578.48	532.64	482.80	432.40	367.12	295.54	204.16	
Inlet temperature, $T_1$	$^{\circ}C$ 801.33	763.60	722.89	679.80	633.97	584.13	533.72	468.45	396.86	305.49	
Compressibility, $Z_1$	1.15E-05	1.13E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	
Viscosity, $\mu_1$	$Pa \cdot sec$ 0.9830	0.9838	0.9846	0.9854	0.9864	0.9874	0.9885	0.9897	0.9912	0.9930	
Density, $\rho_1$	$kg/m^3$ 6.0166	5.7304	5.4250	5.1019	4.7586	4.3858	4.0027	3.5233	2.9915	2.3172	
Velocity, $V_1$	$m/sec$ 56.3823	59.1982	62.5310	66.4912	71.2881	77.3477	84.7503	96.2826	113.3987	146.3951	
Mach number at the inlet, $M_1$	0.1345	0.1410	0.1488	0.1582	0.1695	0.1839	0.2012	0.2288	0.2695	0.3487	
Reynolds number, $Re_1$	37.9091	34.0994	30.2939	26.4924	22.6951	18.9019	15.1129	11.3279	7.5474	3.7713	
Friction factor, $f_1$	0.02409058	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	
Recovery factor, $r_1$	0.75448918	0.7538	0.7531	0.7524	0.7516	0.7508	0.7499	0.7489	0.7477	0.7464	
Adiabatic Wall Temperature, $T_{w1}$	$^{\circ}C$ 19.58	19.55	19.58	19.20	19.00	18.78	19.02	18.20	17.79	17.03	
Enthalpy, $h_1$	$KJ/kg$ 816.67	816.88	816.79	816.66	816.48	816.20	816.75	814.94	813.50	809.68	
Entropy, $s_1$	5.29286293	5.3156	5.3403	5.3679	5.3992	5.4357	5.4790	5.5326	5.6038	5.7109	
<b>Downstream Condition</b>											
Mach number at the outlet, $M_2$	0.1410	0.1488	0.1582	0.1695	0.1839	0.2012	0.2288	0.2695	0.3487	0.9888	
Absolute outlet pressure, $P_2$	$KPa a$ 763.60	722.89	679.80	633.97	584.13	533.72	468.45	396.86	305.49	101.33	
Outlet pressure (gauge)	$KPa g$ 662.276	621.565	578.476	532.644	482.801	432.398	367.122	295.537	204.161	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.92	18.67	18.40	18.08	17.71	16.51	15.44	13.11	11.84	-19.84	
Compressibility, $Z_2$	0.9838	0.9846	0.9854	0.9864	0.9874	0.9885	0.9897	0.9912	0.9930	0.9965	
Density, $\rho_2$	$kg/m^3$ 5.7304	5.4250	5.1019	4.7586	4.3858	4.0027	3.5233	2.9915	2.3172	0.8655	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.15E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	1.00E-05	
Actual outlet flow	$m^3/hr$ 9.8211	10.3740	11.0510	11.8268	12.8321	14.0602	15.9734	18.8130	24.2871	65.0251	
Velocity, $V_2$	$m/sec$ 59.1982	62.5310	66.4912	71.2881	77.3477	84.7503	96.2826	113.3987	146.3951	391.9506	
Reynolds number, $Re_2$	2.268E+05	2.271E+05	2.274E+05	2.277E+05	2.281E+05	2.285E+05	2.293E+05	2.302E+05	2.321E+05	2.396E+05	
Friction factor, $f_2$	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0240	
Recovery factor, $r_2$	0.7538	0.7531	0.7524	0.7516	0.7508	0.7499	0.7489	0.7477	0.7464	0.7469	
Adiabatic Wall Temperature, $T_{w2}$	$^{\circ}C$ 19.5548	19.4906	19.3106	19.1203	18.9073	18.7852	18.7132	17.9243	17.1915	8.6915	
Enthalpy, $h_2$	$KJ/kg$ 816.8819	816.7857	816.6633	816.4815	816.1952	816.7484	814.9412	813.4984	809.6767	746.1151	
Entropy, $s_2$	5.3156	5.3403	5.3679	5.3992	5.4357	5.4790	5.5326	5.6038	5.7109	5.9842	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -1.28										
Critical Temperature	$^{\circ}C$ 100.05										
Max length of duct at which no shock occurs	$m$ 20.59										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 37.72	40.71	43.09	45.83	49.84	50.40	65.28	71.59	91.38	204.16	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.25	0.27	0.32	0.39	0.02	1.20	1.06	2.34	32.94	
Total pressure drop	$KPa$ 700.00										
Total temperature drop	$^{\circ}C$ 38.90										

Figure F 11-31: Vent pipe model predictions for DBNGP gas mixture at 700 KPa gauge

Gas Property Calculation for DBNGP Gas Mixture @ 709.142009419784 Kpa gauge & 19 °C Inlet Conditions											by Farhan Rajivate
Pipe segments	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5	Segment-6	Segment-7	Segment-8	Segment-9	Segment-10	
Schedule number	80	80	80	80	80	80	80	80	80	80	
Outside diameter	mm 13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	
Special wall thickness	mm 0	0	0	0	0	0	0	0	0	0	
Wall thickness	mm 3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
Internal diameter	mm 7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	
Roughness, $\epsilon$	mm 0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	
Relative roughness, $\epsilon/D$	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03	
Cross sectional area, $A_c$	$m^2$ 4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	4.61E-05	
Length of pipe	$m$ 12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Pipe segments	$m$ 1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	
<b>Gas properties</b>											
DBNGP Gas Mixture											
Specific heat at constant pressure, $c_p$	$J/kg \cdot K$ 2083.79	2081.12	2077.97	2074.61	2070.99	2066.96	2063.68	2057.05	2050.24	2039.56	
Specific heat at constant volume, $c_v$	$J/kg \cdot K$ 1578.05	1577.43	1576.41	1575.31	1574.08	1572.65	1572.09	1568.69	1565.54	1559.44	
Ratio of specific heats, $\gamma$	1.3205	1.3193	1.3182	1.3170	1.3157	1.3143	1.3127	1.3113	1.3096	1.3079	
Molecular weight, M.W.	$kg/mole$ 17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	17.93	
Gas constant, R	$J/kg \cdot K$ 463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	463.78	
<b>Standard condition</b>											
Inlet pressure, $P_{std}$ (gauge)	$KPa g$ 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Atmospheric pressure	$KPa$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Inlet pressure, $P_{std}$ (absolute)	$KPa abs$ 101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	101.325	
Temperature, $T_{std}$	$^{\circ}C$ 15	15	15	15	15	15	15	15	15	15	
Compressibility at std cond, $Z_{std}$	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	0.9977	
Density at standard condition, $\rho_{std}$	$kg/m^3$ 0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	0.7599	
Normal or standard flow	$m^3/hr$ 74.9234	74.9234	74.9234	74.9234	74.9234	74.9234	74.9234	74.9234	74.9234	74.9234	
Phase flow	lines/min 1248.7229	1248.7229	1248.7229	1248.7229	1248.7229	1248.7229	1248.7229	1248.7229	1248.7229	1248.7229	
<b>Actual inlet flow condition</b>											
Actual inlet flow condition	$kg/hr$ 56.94										
Standard flow condition	$m^3/hr$ 9.35	9.82	10.37	11.03	11.83	12.83	14.06	15.98	18.82	24.29	
Standard flow condition	$m^3/hr$ 74.92	74.92	74.92	74.92	74.92	74.92	74.92	74.92	74.92	74.92	
<b>Stagnation Properties</b>											
Stagnation Temperature, $T_0$	$^{\circ}C$ 292.91	292.91	292.76	292.61	292.45	292.29	292.60	291.90	291.71	291.49	
Inlet Stagnation Pressure	$KPa abs$ 820.19	783.24	742.72	699.85	654.69	605.07	555.26	491.68	422.24	335.56	
Outlet Stagnation Pressure	$KPa abs$ 783.24	742.72	699.85	654.69	605.07	555.26	491.68	422.24	335.56	186.69	
Stagnation Density, $\rho_0$	$kg/m^3$ 6.14	5.86	5.56	5.23	4.89	4.52	4.14	3.55	2.50	1.86	
Stagnation Enthalpy, $h_0$	$KJ/kg$ 818.06	818.43	818.53	818.66	818.80	818.96	820.11	819.32	819.65	820.08	
<b>Upstream Condition</b>											
Inlet pressure, $P_1$	$KPa g$ 709.14	670.99	629.81	586.22	539.86	489.45	438.51	372.44	300.04	207.63	
Inlet pressure, $P_1$	$KPa abs$ 810.47	772.31	731.13	687.55	641.19	590.77	539.84	473.77	401.37	308.95	
Inlet temperature, $T_1$	$^{\circ}C$ 19.00	18.9173	18.6680	18.3938	18.0765	17.6877	17.1080	16.4946	15.4271	13.0859	
Compressibility, $Z_1$	0.9828	0.9836	0.9844	0.9853	0.9862	0.9872	0.9883	0.9896	0.9911	0.9929	
Viscosity, $\mu_1$	$Pa \cdot sec$ 1.15E-05	1.15E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	
Density, $\rho_1$	$kg/m^3$ 6.0865	5.7969	5.4879	5.1610	4.8136	4.4365	4.0492	3.5639	3.0259	2.3439	
Velocity, $V_1$	$m/sec$ 56.3864	59.2032	62.5367	66.4981	71.2962	77.3576	84.7567	96.2974	113.4178	146.4223	
Mach number at the inlet, $M_1$	0.1345	0.1410	0.1488	0.1582	0.1695	0.1839	0.2012	0.2288	0.2695	0.3487	
Reynolds number, $Re_1$	4 $ft_1/D_1$ 37.8954	34.0871	30.2828	26.4827	22.6868	18.8950	15.1073	11.3237	7.5445	3.7698	
Reynolds number, $Re_1$	2.293E+05	2.294E+05	2.297E+05	2.300E+05	2.304E+05	2.308E+05	2.309E+05	2.320E+05	2.329E+05	2.349E+05	
Friction factor, $f_1$	0.02408189	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	
Recovery factor, $r_1$	0.75465747	0.7540	0.7533	0.7525	0.7517	0.7509	0.7500	0.7490	0.7478	0.7465	
Adiabatic Wall Temperature, $T_{w1}$	$^{\circ}C$ 19.58	19.55	19.38	19.20	19.00	18.77	19.01	18.18	17.77	17.01	
Enthalpy, $h_1$	$KJ/kg$ 816.57	816.79	816.70	816.58	816.40	816.11	816.68	814.86	813.42	809.60	
Entropy, $s_1$	5.28737045	5.3101	5.3348	5.3624	5.3937	5.4302	5.4735	5.5271	5.5983	5.7054	
<b>Downstream Condition</b>											
$4ft_{1-2}/D_2$	3.7726	3.7725	3.7724	3.7722	3.7720	3.7718	3.7718	3.7712	3.7708	3.7698	
Mach number at the outlet, $M_2$	0.1410	0.1488	0.1582	0.1695	0.1839	0.2012	0.2288	0.2695	0.3487	0.9988	
Absolute outlet pressure, $P_2$	$KPa a$ 772.31	731.13	687.55	641.19	590.77	539.84	473.77	401.37	308.95	101.32	
Outlet pressure (gauge)	$KPa g$ 670.986	629.808	586.222	539.864	489.446	438.513	372.444	300.042	207.626	0.000	
Outlet temperature, $T_2$	$^{\circ}C$ 18.92	18.67	18.39	18.08	17.69	17.17	16.49	15.43	13.09	-20.54	
Compressibility, $Z_2$	0.9836	0.9844	0.9853	0.9862	0.9872	0.9883	0.9896	0.9911	0.9929	0.9965	
Density, $\rho_2$	$kg/m^3$ 5.7969	5.4879	5.1610	4.8136	4.4365	4.0492	3.5639	3.0259	2.3439	0.8679	
Viscosity of gas, $\mu_2$	$Pa \cdot sec$ 1.15E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.14E-05	1.13E-05	1.13E-05	1.12E-05	9.98E-06	
Actual outlet flow	$m^3/hr$ 9.8219	10.3749	11.0321	11.8381	12.8337	14.0613	15.9759	18.8162	24.2917	65.6010	
Velocity, $V_2$	$m/sec$ 59.2032	62.5367	66.4981	71.2962	77.3576	84.7567	96.2974	113.4178	146.4223	395.4217	
Reynolds number, $Re_2$	2.294E+05	2.297E+05	2.300E+05	2.304E+05	2.308E+05	2.309E+05	2.320E+05	2.329E+05	2.349E+05	2.633E+05	
Friction factor, $f_2$	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0241	0.0240	
Recovery factor, $r_2$	0.7540	0.7533	0.7525	0.7517	0.7509	0.7500	0.7490	0.7478	0.7465	0.7470	
Adiabatic Wall Temperature, $T_{w2}$	$^{\circ}C$ 19.5549	19.4901	19.3083	19.1162	18.9012	18.7784	18.7070	17.9110	17.1753	8.3049	
Enthalpy, $h_2$	$KJ/kg$ 816.7923	816.6969	816.5758	816.3952	816.1102	816.6768	814.8592	813.4188	809.5994	744.7391	
Entropy, $s_2$	5.3101	5.3348	5.3624	5.3937	5.4302	5.4735	5.5271	5.5983	5.7054	5.9788	
<b>Critical Properties at Outlet Mach 1</b>											
Critical Pressure	$KPa g$ -0.14										
Critical Pressure	$KPa abs$ 101.19										
Critical Temperature	$^{\circ}C$ 20.62										
Max length of duct at which no shock occurs	$m$ 12.05										
<b>Drop</b>											
Pressure drop / Segment Length	$KPa$ 38.16	41.18	43.59	46.36	50.42	50.93	66.07	72.40	92.42	207.63	
Temperature drop / Segment Length	$^{\circ}C$ 0.08	0.25	0.27	0.32	0.39	0.42	1.21	1.07	2.34	33.62	
Total pressure drop	$KPa$ 709.14										
Total temperature drop	$^{\circ}C$ 39.62										

Figure F 11-32: Vent pipe model predictions for DBNGP gas mixture at sonic conditions



## **Appendix G**

### **12.1 Vent Pipe Model Comparison with Hysys Simulation**

Table G 12-1: Comparison of vent pipe model predictions with Hysys simulation in pressure range 100 - 500 KPa gauge for air

Length	m	ASHEN HYSYS Plant case 2A												Vent Pipe Model Predictions												Vent Pipe Model Comparison with HYSYS											
		0	0.6	1.6	3	4.4	5.4	6.6	7.6	8	10.2	11.4	12	INLET	0.6	1.6	3	4.4	5.4	6.6	7.6	8	10.2	11.4	12	INLET	0.6	1.6	3	4.4	5.4	6.6	7.6	8	10.2	11.4	12
Pressure	K Pa	201.3	197.4	189.7	181.7	173.3	164.3	154.9	144.8	133.9	121.1	108.7	201.3	197.4	189.7	181.7	173.3	164.3	154.9	144.8	133.9	121.1	108.7	201.3	197.4	189.7	181.7	173.3	164.3	154.9	144.8	133.9	121.1	108.7			
Temperature	°C	19.00	18.96	18.87	18.75	18.62	18.44	18.19	17.86	17.35	16.68	14.60	19.00	18.96	18.87	18.75	18.62	18.44	18.19	17.86	17.35	16.68	14.60	19.00	18.96	18.87	18.75	18.62	18.44	18.19	17.86	17.35	16.68	14.60			
Mass Flow	kg/hr	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23	34.23			
Sid Vol Gas Flo	dm <sup>3</sup> /hr	4.79	4.68	4.46	4.22	3.96	3.69	3.40	3.07	2.70	2.26	1.69	4.79	4.68	4.46	4.22	3.96	3.69	3.40	3.07	2.70	2.26	1.69	4.79	4.68	4.46	4.22	3.96	3.69	3.40	3.07	2.70	2.26	1.69			
Velocity	m/sec	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213			
Density	kg/m <sup>3</sup>	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216			
Match Number		0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669	0.669			
Pressure	K Pa	601.3	597.5	579.0	549.1	494.1	428.7	351.2	274.9	225.3	169.5	101.3	601.3	597.5	579.0	549.1	494.1	428.7	351.2	274.9	225.3	169.5	101.3	601.3	597.5	579.0	549.1	494.1	428.7	351.2	274.9	225.3	169.5	101.3			
Temperature	°C	19.00	18.96	18.84	18.70	18.52	18.29	17.96	17.47	16.65	14.88	9.55	19.00	18.96	18.84	18.70	18.52	18.29	17.96	17.47	16.65	14.88	9.55	19.00	18.96	18.84	18.70	18.52	18.29	17.96	17.47	16.65	14.88	9.55			
Mass Flow	kg/hr	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54	52.54			
Sid Vol Gas Flo	dm <sup>3</sup> /hr	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08			
Velocity	m/sec	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08			
Density	kg/m <sup>3</sup>	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216	1.216			
Match Number		0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741	0.741			

Table G 12-2: Comparison of vent pipe model predictions with Hysys simulation in pressure range 600 - 1000 KPa gauge for air

ASPEX HYSYS Plant ver 7.1	Vent Pipe Model Predictions												
	0	0.6E	1.8E	3	4.3	5.4	6.6	7.8	9	10.2	11.4	12	
	INLET	1E	2E	3E	4E	5E	6E	7E	8E	9E	10E	11E	12
Pressure	701.3	664.7	604.3	576.9	544.6	489.2	459.2	381.7	312.1	244.2	111.2	0.00%	0.00%
Temperature	19.00	18.95	18.84	18.70	18.52	17.95	17.43	16.66	15.06	9.38	-11.96	-0.24%	0.06%
Mass Flow	61.85	61.85	61.85	61.85	61.85	61.85	61.85	61.85	61.85	61.85	61.85	0.23%	0.23%
Sid. Vol Gas Flow	50.25	50.25	50.25	50.25	50.25	50.25	50.25	50.25	50.25	50.25	50.25	0.19%	0.19%
Velocity	44.23	45.29	47.54	50.41	53.74	57.86	63.12	70.23	80.64	94.44	122.30	0.30%	0.30%
Density	8.39	8.19	7.79	7.36	6.91	6.41	5.88	5.28	4.60	3.77	2.44	-0.88%	-0.88%
Mach Number	0.1387	0.1318	0.1237	0.1168	0.1095	0.1020	0.0945	0.0868	0.0786	0.0697	0.0599	-0.23%	-0.23%
Pressure	801.3	782.3	743.4	702.2	658.3	611.0	569.4	502.0	435.9	374.3	125.2	0.00%	0.00%
Temperature	19.00	18.95	18.84	18.70	18.51	18.28	17.94	17.44	16.59	14.78	9.37	-0.18%	0.18%
Mass Flow	70.54	70.54	70.54	70.54	70.54	70.54	70.54	70.54	70.54	70.54	70.54	0.14%	0.14%
Sid. Vol Gas Flow	57.60	57.60	57.60	57.60	57.60	57.60	57.60	57.60	57.60	57.60	57.60	0.20%	0.20%
Velocity	46.31	47.77	50.14	52.88	56.00	60.28	66.00	73.60	83.84	98.00	131.00	0.10%	0.10%
Density	9.28	9.28	9.28	9.28	9.28	9.28	9.28	9.28	9.28	9.28	9.28	-0.12%	-0.12%
Mach Number	0.1295	0.1271	0.1249	0.1229	0.1210	0.1192	0.1174	0.1156	0.1138	0.1120	0.1102	-0.19%	-0.19%
Pressure	901.2	879.9	836.3	789.6	740.2	687.2	638.7	564.4	496.5	409.9	274.2	0.14%	0.14%
Temperature	19.00	18.95	18.84	18.68	18.51	18.27	17.90	17.44	16.62	14.99	9.69	-0.03%	0.06%
Mass Flow	79.67	79.67	79.67	79.67	79.67	79.67	79.67	79.67	79.67	79.67	79.67	0.15%	0.15%
Sid. Vol Gas Flow	65.02	65.02	65.02	65.02	65.02	65.02	65.02	65.02	65.02	65.02	65.02	0.11%	0.11%
Velocity	44.45	45.64	48.00	50.82	54.19	58.33	63.69	70.84	81.30	95.59	141.88	0.25%	0.25%
Density	10.78	10.52	10.00	9.45	8.86	8.23	7.54	6.78	5.91	4.85	3.38	-0.11%	-0.11%
Mach Number	0.1294	0.1277	0.1261	0.1245	0.1229	0.1213	0.1197	0.1181	0.1165	0.1149	0.1133	-0.18%	-0.18%
Pressure	1001.3	977.4	929.1	877.1	821.3	761.6	698.4	627.0	544.9	445.2	301.7	0.03%	0.03%
Temperature	19.00	18.95	18.84	18.68	18.51	18.27	17.90	17.43	16.61	14.96	9.61	-0.02%	0.02%
Mass Flow	88.66	88.66	88.66	88.66	88.66	88.66	88.66	88.66	88.66	88.66	88.66	0.11%	0.11%
Sid. Vol Gas Flow	72.36	72.36	72.36	72.36	72.36	72.36	72.36	72.36	72.36	72.36	72.36	0.07%	0.07%
Velocity	44.62	45.70	48.07	50.90	54.27	58.41	63.79	70.95	81.43	95.71	142.19	0.24%	0.24%
Density	11.98	11.69	11.12	10.50	9.85	9.15	8.38	7.53	6.56	5.39	3.76	-0.10%	-0.10%
Mach Number	0.1294	0.1278	0.1262	0.1246	0.1230	0.1214	0.1198	0.1182	0.1166	0.1150	0.1134	-0.19%	-0.19%
Pressure	1101.3	1075.6	1021.9	964.7	904.4	839.7	768.0	685.6	599.1	499.4	334.6	0.04%	0.04%
Temperature	19.00	18.95	18.84	18.68	18.51	18.26	17.88	17.42	16.59	14.93	9.52	-0.04%	0.04%
Mass Flow	97.59	97.59	97.59	97.59	97.59	97.59	97.59	97.59	97.59	97.59	97.59	0.08%	0.08%
Sid. Vol Gas Flow	79.71	79.71	79.71	79.71	79.71	79.71	79.71	79.71	79.71	79.71	79.71	0.04%	0.04%
Velocity	44.67	45.76	48.13	50.96	54.34	58.49	63.88	71.05	81.56	95.90	142.62	0.27%	0.27%
Density	13.18	12.86	12.33	11.65	10.93	10.06	9.21	8.29	7.12	5.93	4.13	-0.17%	-0.17%
Mach Number	0.1295	0.1279	0.1263	0.1247	0.1231	0.1215	0.1199	0.1183	0.1167	0.1151	0.1135	-0.20%	-0.20%



Table G 12-3: Comparison of vent pipe model predictions with Hysys simulation in pressure range 100 - 500 KPa gauge for carbon-dioxide

Length	m	ASPEN HYSYS Plant no. 71												
		0	0.6	1.8	3	4.2	5.4	6.6	7.8	9	10.2	11.4	12	
Pressure	KPa	201.3	197.6	189.8	181.7	173.3	164.4	154.8	144.8	134.0	122.1	108.7	101.3	OUTLET
Temperature	°C	19.00	18.96	18.89	18.80	18.71	18.60	18.46	18.27	18.00	17.58	17.32	17.25	OUTLET
Mass Flow	kg/hr	18.99	18.99	18.99	18.99	18.99	18.99	18.99	18.99	18.99	18.99	18.99	18.99	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	10.20	10.20	10.20	10.20	10.20	10.20	10.20	10.20	10.20	10.20	10.20	10.20	OUTLET
Velocity	m/sec	31.10	31.69	32.98	34.43	36.10	38.05	40.36	43.15	46.64	51.18	57.40	61.64	OUTLET
Density	kg/m <sup>3</sup>	3.68	3.61	3.47	3.32	3.17	3.01	2.84	2.65	2.46	2.24	1.99	1.86	OUTLET
Mach Number		0.1171	0.1193	0.1242	0.1297	0.1360	0.1433	0.1521	0.1626	0.1758	0.1930	0.2168	0.2320	OUTLET
Pressure	KPa	301.3	294.7	281.0	266.7	251.4	235.2	217.6	198.3	176.7	151.6	119.6	101.3	OUTLET
Temperature	°C	19.00	18.97	18.89	18.80	18.69	18.54	18.35	18.07	17.64	16.88	15.02	13.66	OUTLET
Mass Flow	kg/hr	31.22	31.22	31.22	31.22	31.22	31.22	31.22	31.22	31.22	31.22	31.22	31.22	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	16.68	16.68	16.68	16.68	16.68	16.68	16.68	16.68	16.68	16.68	16.68	16.68	OUTLET
Velocity	m/sec	33.91	34.66	36.39	38.39	40.70	43.54	47.14	51.63	57.87	67.24	84.02	99.76	OUTLET
Density	kg/m <sup>3</sup>	5.65	5.43	5.17	4.90	4.62	4.32	3.99	3.65	3.25	2.80	2.24	1.89	OUTLET
Mach Number		0.1272	0.1298	0.1363	0.1437	0.1522	0.1627	0.1761	0.1926	0.2129	0.2372	0.2672	0.2921	OUTLET
Pressure	KPa	401.3	391.9	374.2	352.7	331.6	308.8	283.0	256.4	228.3	188.1	138.9	101.3	OUTLET
Temperature	°C	19.00	18.96	18.88	18.78	18.63	18.43	18.18	17.80	17.29	16.22	13.36	8.14	OUTLET
Mass Flow	kg/hr	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	22.88	22.88	22.88	22.88	22.88	22.88	22.88	22.88	22.88	22.88	22.88	22.88	OUTLET
Velocity	m/sec	34.73	35.88	37.39	39.59	42.14	45.28	49.39	54.57	62.11	74.24	99.81	134.86	OUTLET
Density	kg/m <sup>3</sup>	7.43	7.26	6.90	6.52	6.13	5.70	5.23	4.73	4.16	3.48	2.59	1.92	OUTLET
Mach Number		0.1303	0.1346	0.1400	0.1463	0.1536	0.1627	0.1741	0.1884	0.2056	0.2254	0.2476	0.2693	OUTLET
Pressure	KPa	601.3	589.5	565.5	539.5	512.8	483.6	450.4	409.6	361.4	297.7	217.7	161.0	OUTLET
Temperature	°C	19.00	18.96	18.87	18.67	18.01	17.61	17.08	16.43	15.68	14.18	12.11	9.78	OUTLET
Mass Flow	kg/hr	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	28.94	28.94	28.94	28.94	28.94	28.94	28.94	28.94	28.94	28.94	28.94	28.94	OUTLET
Velocity	m/sec	34.98	35.84	37.73	39.99	42.63	45.92	50.26	55.73	63.86	77.33	106.33	162.77	OUTLET
Density	kg/m <sup>3</sup>	9.34	9.11	8.65	8.17	7.66	7.11	6.50	5.86	5.11	4.22	3.01	1.96	OUTLET
Mach Number		0.1312	0.1348	0.1413	0.1495	0.1592	0.1713	0.1874	0.2074	0.2314	0.2597	0.2923	0.3294	OUTLET
Pressure	KPa	601.3	587.0	558.1	526.6	494.5	459.1	418.6	373.8	328.8	268.5	186.5	101.3	OUTLET
Temperature	°C	19.00	18.96	18.86	18.64	18.29	17.78	17.10	16.28	15.48	14.18	11.39	8.52	OUTLET
Mass Flow	kg/hr	65.40	65.40	65.40	65.40	65.40	65.40	65.40	65.40	65.40	65.40	65.40	65.40	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	34.94	34.94	34.94	34.94	34.94	34.94	34.94	34.94	34.94	34.94	34.94	34.94	OUTLET
Velocity	m/sec	35.00	35.88	37.79	40.08	42.76	46.11	50.58	56.15	64.83	78.61	112.38	182.28	OUTLET
Density	kg/m <sup>3</sup>	11.26	10.99	10.43	9.83	9.22	8.55	7.79	7.02	6.11	5.01	3.51	2.04	OUTLET
Mach Number		0.1313	0.1346	0.1416	0.1498	0.1595	0.1718	0.1882	0.2085	0.2322	0.2592	0.2912	0.3277	OUTLET

Length	m	Vent Pipe Model Comparison with HYSYS												
		0	0.6	1.8	3	4.2	5.4	6.6	7.8	9	10.2	11.4	12	
Pressure	KPa	0.01%	0.05%	0.07%	0.04%	-0.02%	0.01%	-0.05%	0.07%	0.05%	0.02%	0.15%	0.34%	OUTLET
Temperature	°C	0.00%	-0.01%	-0.02%	-0.15%	-0.05%	-0.04%	-0.46%	-0.08%	-0.12%	-0.13%	-0.1%	-0.38%	OUTLET
Mass Flow	kg/hr	0.14%	0.16%	0.15%	0.16%	0.16%	0.16%	0.16%	0.16%	0.16%	0.16%	0.16%	0.16%	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	-0.09%	-0.09%	-0.09%	-0.09%	-0.09%	-0.09%	-0.09%	-0.09%	-0.09%	-0.09%	-0.09%	-0.09%	OUTLET
Velocity	m/sec	-0.34%	-0.34%	-0.29%	-0.22%	-0.16%	-0.16%	-0.16%	-0.09%	-0.03%	0.06%	0.08%	0.15%	OUTLET
Density	kg/m <sup>3</sup>	0.17%	0.18%	0.13%	0.08%	0.03%	0.01%	-0.10%	-0.08%	-0.12%	-0.12%	-0.09%	-0.12%	OUTLET
Mach Number		-0.78%	-0.85%	-0.84%	-0.88%	-0.82%	-0.77%	-0.90%	-0.94%	-0.91%	-1.06%	-1.13%	-0.77%	OUTLET
Pressure	KPa	0.01%	0.05%	0.09%	0.08%	0.02%	0.01%	-0.21%	0.06%	0.12%	0.08%	1.36%	0.03%	OUTLET
Temperature	°C	0.00%	0.00%	0.00%	-0.26%	-0.06%	-0.06%	-0.90%	-0.15%	-0.17%	0.04%	1.69%	1.09%	OUTLET
Mass Flow	kg/hr	-0.34%	-0.34%	-0.34%	-0.34%	-0.34%	-0.34%	-0.34%	-0.34%	-0.34%	-0.34%	-0.34%	-0.34%	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	-0.90%	-0.90%	-0.90%	-0.90%	-0.90%	-0.90%	-0.90%	-0.90%	-0.90%	-0.90%	-0.90%	-0.90%	OUTLET
Velocity	m/sec	-0.75%	-0.76%	-0.63%	-0.50%	-0.48%	-0.48%	-0.48%	-0.15%	-0.25%	-0.24%	-1.08%	0.23%	OUTLET
Density	kg/m <sup>3</sup>	0.43%	0.44%	0.39%	0.17%	0.14%	0.06%	0.20%	0.09%	0.13%	0.1%	0.75%	0.56%	OUTLET
Mach Number		-1.20%	-1.30%	-1.14%	-1.10%	-1.23%	-1.21%	-1.06%	-1.31%	-1.37%	-1.67%	-2.57%	-1.52%	OUTLET
Pressure	KPa	0.01%	-0.04%	0.02%	-0.09%	-0.02%	0.04%	-0.77%	0.09%	0.20%	0.60%	3.88%	0.03%	OUTLET
Temperature	°C	0.00%	-0.01%	-0.02%	-0.41%	-0.11%	-0.10%	-1.31%	-0.22%	-0.20%	0.19%	11.09%	5.70%	OUTLET
Mass Flow	kg/hr	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	OUTLET
Velocity	m/sec	1.13%	1.06%	1.02%	0.80%	0.76%	0.68%	0.33%	0.47%	0.42%	0.59%	3.00%	0.77%	OUTLET
Density	kg/m <sup>3</sup>	0.62%	0.53%	0.50%	0.28%	0.23%	0.16%	-0.21%	0.06%	-0.09%	0.06%	2.59%	0.76%	OUTLET
Mach Number		-1.53%	-1.38%	-1.58%	-1.65%	-1.47%	-1.54%	-1.23%	-1.56%	-1.73%	-2.11%	-4.97%	-1.62%	OUTLET
Pressure	KPa	0.00%	0.03%	0.09%	0.11%	0.02%	0.00%	0.40%	0.02%	0.14%	0.57%	7.23%	0.03%	OUTLET
Temperature	°C	0.00%	-0.01%	-0.01%	-0.47%	-0.07%	-0.14%	-1.65%	-0.24%	-0.24%	0.28%	39.19%	-30.24%	OUTLET
Mass Flow	kg/hr	-0.72%	-0.72%	-0.72%	-0.72%	-0.72%	-0.72%	-0.72%	-0.72%	-0.72%	-0.72%	-0.72%	-0.72%	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	-1.29%	-1.29%	-1.29%	-1.29%	-1.29%	-1.29%	-1.29%	-1.29%	-1.29%	-1.29%	-1.29%	-1.29%	OUTLET
Velocity	m/sec	1.50%	1.42%	1.32%	1.10%	1.03%	0.77%	0.41%	0.55%	0.44%	0.58%	4.59%	0.23%	OUTLET
Density	kg/m <sup>3</sup>	0.80%	0.71%	0.69%	0.38%	0.31%	0.15%	-0.31%	0.18%	-0.28%	0.14%	4.89%	0.96%	OUTLET
Mach Number		-1.85%	-1.75%	-1.89%	-1.82%	-1.91%	-1.90%	-1.53%	-1.89%	-2.03%	-2.42%	-7.98%	-2.11%	OUTLET
Pressure	KPa	0.00%	-0.03%	0.00%	-0.15%	-0.02%	0.05%	-0.65%	-0.53%	0.01%	0.39%	10.95%	0.03%	OUTLET
Temperature	°C	0.00%	-0.02%	-0.04%	-0.57%	-0.09%	-0.16%	-2.05%	-0.27%	-0.31%	0.26%	12.17%	24.65%	OUTLET
Mass Flow	kg/hr	-0.92%	-0.92%	-0.92%	-0.92%	-0.92%	-0.92%	-0.92%	-0.92%	-0.92%	-0.92%	-0.92%	-0.92%	OUTLET
Std Vol Gas Flow	Nm <sup>3</sup> /hr	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	OUTLET
Velocity	m/sec	1.85%	1.75%	1.60%	1.35%	1.25%	1.02%	0.46%	0.60%	0.40%	0.51%	7.51%	0.58%	OUTLET
Density	kg/m <sup>3</sup>	0.92%	0.80%	0.70%	0.43%	0.33%	0.11%	-0.46%	0.33%	-0.51%	0.50%	7.14%	1.24%	OUTLET
Mach Number		-2.13%	-2.09%	-2.16%	-2.09%	-2.19%	-2.14%	-1.70%	-2.15%	-2.23%	-2.58%	-10.89%	-2.14%	OUTLET

Table G 12-4: Comparison of vent pipe model predictions with Hysys simulation in pressure range 600 - 1000 KPa gauge for carbon-dioxide

	ASPHEN HYSYS Plant ver 7.1											
	0	0.6	1.8	3	4.5	6.6	7.8	9	10.2	11.4	12	OUTLET
Pressure K Pa	701.3	684.6	650.9	614.0	576.7	538.5	497.8	446.7	383.5	314.2	198.8	117.7
Temperature °C	19.00	18.96	18.86	18.75	18.60	18.40	18.14	17.73	17.04	15.85	4.82	-4.93
Mass Flow kg/hr	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155
Velocity m/sec	35.68	35.63	35.42	34.64	33.31	31.41	29.02	26.19	23.00	19.50	12.60	7.95
Density kg/m <sup>3</sup>	13.07	12.76	12.13	11.47	10.76	10.00	9.17	8.25	7.19	5.90	3.83	2.39
Mach Number	0.1343	0.1376	0.1447	0.1531	0.1632	0.1757	0.1917	0.2132	0.2419	0.2991	0.4694	0.7667
Pressure K Pa	801.3	782.5	743.7	702.8	659.1	612.1	560.8	503.7	438.1	375.6	213.6	134.5
Temperature °C	19.00	18.96	18.86	18.75	18.60	18.40	18.14	17.73	17.04	15.85	4.82	-4.93
Mass Flow kg/hr	88.71	88.71	88.71	88.71	88.71	88.71	88.71	88.71	88.71	88.71	88.71	88.71
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176
Velocity m/sec	35.67	35.62	35.41	34.64	33.31	31.41	29.02	26.19	23.00	19.50	12.60	7.95
Density kg/m <sup>3</sup>	14.99	14.64	13.92	13.16	12.35	11.47	10.52	9.47	8.25	6.77	4.40	2.74
Mach Number	0.1343	0.1376	0.1447	0.1531	0.1632	0.1757	0.1917	0.2132	0.2419	0.2991	0.4694	0.7702
Pressure K Pa	901.3	880.1	836.6	790.5	741.3	688.4	630.7	566.5	492.7	421.4	251.0	160.2
Temperature °C	19.00	18.96	18.86	18.74	18.59	18.38	18.10	17.69	16.98	15.48	4.27	-5.89
Mass Flow kg/hr	100.15	100.15	100.15	100.15	100.15	100.15	100.15	100.15	100.15	100.15	100.15	100.15
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201
Velocity m/sec	36.65	36.40	35.99	35.01	33.51	31.41	28.79	25.66	22.00	17.90	11.60	7.30
Density kg/m <sup>3</sup>	16.93	16.54	15.72	14.86	13.95	12.93	11.89	10.69	9.33	7.65	4.97	3.08
Mach Number	0.1343	0.1376	0.1447	0.1531	0.1632	0.1757	0.1917	0.2132	0.2419	0.2991	0.4700	0.7702
Pressure K Pa	1001.0	977.8	929.4	876.2	813.7	752.0	690.9	629.6	547.7	447.5	281.8	172.4
Temperature °C	19.00	18.96	18.86	18.74	18.59	18.38	18.10	17.69	16.96	15.44	4.79	-4.81
Mass Flow kg/hr	110.60	110.60	110.60	110.60	110.60	110.60	110.60	110.60	110.60	110.60	110.60	110.60
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226
Velocity m/sec	36.61	36.46	36.35	35.87	34.33	32.23	29.61	26.48	22.80	18.70	12.40	8.00
Density kg/m <sup>3</sup>	18.89	18.45	17.54	16.58	15.56	14.46	13.26	11.93	10.41	8.55	5.59	3.54
Mach Number	0.1343	0.1374	0.1446	0.1529	0.1630	0.1756	0.1914	0.2132	0.2444	0.2984	0.4650	0.7702
Pressure K Pa	1101.0	1075.0	1022.0	965.8	905.8	841.1	776.6	692.1	601.9	491.4	306.1	182.7
Temperature °C	19.00	18.96	18.86	18.74	18.58	18.37	18.08	17.65	16.92	15.37	3.79	-6.70
Mass Flow kg/hr	123.20	123.20	123.20	123.20	123.20	123.20	123.20	123.20	123.20	123.20	123.20	123.20
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.251	0.251	0.251	0.251	0.251	0.251	0.251	0.251	0.251	0.251	0.251	0.251
Velocity m/sec	36.58	36.43	36.32	35.84	34.30	32.19	29.57	26.44	22.76	18.66	12.36	7.96
Density kg/m <sup>3</sup>	20.87	20.38	19.38	18.32	17.19	15.97	14.65	13.18	11.49	9.43	6.12	3.80
Mach Number	0.1341	0.1373	0.1444	0.1528	0.1629	0.1754	0.1913	0.2132	0.2444	0.2986	0.4696	0.7702

	Vent Pipe Model Predictions											
	0	0.6	1.8	3	4.5	6.6	7.8	9	10.2	11.4	12	OUTLET
Pressure K Pa	701.3	684.6	650.9	614.0	576.7	538.5	497.8	446.7	383.5	314.2	198.8	117.7
Temperature °C	19.00	18.96	18.86	18.75	18.60	18.40	18.14	17.73	17.04	15.85	4.82	-4.93
Mass Flow kg/hr	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33	77.33
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155
Velocity m/sec	34.88	35.76	37.67	39.99	42.66	46.01	50.32	56.07	64.47	78.56	112.39	195.84
Density kg/m <sup>3</sup>	13.21	12.82	12.23	11.53	10.80	10.02	9.12	8.22	7.15	5.87	4.10	2.35
Mach Number	0.1309	0.1342	0.1410	0.1494	0.1591	0.1713	0.1878	0.2079	0.2385	0.2902	0.4164	0.7454
Pressure K Pa	801.3	782.5	743.7	702.8	659.1	612.1	560.8	503.7	438.1	375.6	213.6	134.5
Temperature °C	19.00	18.96	18.86	18.75	18.60	18.40	18.14	17.73	17.04	15.85	4.82	-4.93
Mass Flow kg/hr	87.51	87.51	87.51	87.51	87.51	87.51	87.51	87.51	87.51	87.51	87.51	87.51
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176	0.176
Velocity m/sec	34.74	35.62	37.53	39.86	42.53	45.88	50.43	55.96	64.36	78.46	112.31	195.85
Density kg/m <sup>3</sup>	15.18	14.81	14.06	13.23	12.40	11.50	10.46	9.43	8.20	6.72	4.70	2.69
Mach Number	0.1304	0.1337	0.1405	0.1489	0.1588	0.1706	0.1873	0.2071	0.2376	0.2891	0.4147	0.7450
Pressure K Pa	901.3	879.8	836.7	788.5	741.1	688.4	630.7	566.5	492.7	421.4	251.0	160.2
Temperature °C	19.00	18.96	18.86	18.75	18.60	18.40	18.14	17.73	17.04	15.85	4.82	-4.93
Mass Flow kg/hr	98.58	98.58	98.58	98.58	98.58	98.58	98.58	98.58	98.58	98.58	98.58	98.58
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201	0.201
Velocity m/sec	34.65	35.46	37.38	39.73	42.40	45.75	50.35	55.86	64.28	78.43	112.49	199.08
Density kg/m <sup>3</sup>	17.18	16.75	15.90	14.96	14.01	12.99	11.80	10.64	9.24	7.58	5.28	2.98
Mach Number	0.1298	0.1331	0.1398	0.1484	0.1579	0.1698	0.1866	0.2062	0.2366	0.2879	0.4131	0.7431
Pressure K Pa	1001.0	977.8	929.4	876.2	813.7	752.0	690.9	629.6	547.7	447.5	281.8	172.4
Temperature °C	19.00	18.96	18.86	18.75	18.60	18.40	18.14	17.73	17.04	15.85	4.82	-4.93
Mass Flow kg/hr	109.60	109.60	109.60	109.60	109.60	109.60	109.60	109.60	109.60	109.60	109.60	109.60
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226	0.226
Velocity m/sec	34.40	35.23	37.20	39.56	42.21	45.57	50.18	55.65	64.04	78.11	111.66	191.02
Density kg/m <sup>3</sup>	19.20	18.73	17.76	16.70	15.65	14.50	13.16	11.87	10.32	8.46	5.92	3.46
Mach Number	0.1292	0.1325	0.1391	0.1476	0.1570	0.1689	0.1857	0.2050	0.2351	0.2859	0.4091	0.7172
Pressure K Pa	1101.0	1075.0	1022.0	965.8	905.8	841.1	776.6	692.1	601.9	491.4	306.1	182.7
Temperature °C	19.00	18.96	18.86	18.74	18.58	18.37	18.08	17.65	16.92	15.37	3.79	-6.70
Mass Flow kg/hr	120.71	120.71	120.71	120.71	120.71	120.71	120.71	120.71	120.71	120.71	120.71	120.71
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249
Velocity m/sec	34.24	35.11	37.05	39.42	42.08	45.44	50.04	55.56	64.00	78.15	112.11	196.57
Density kg/m <sup>3</sup>	21.25	20.73	19.64	18.46	17.19	15.87	14.52	13.10	11.37	9.31	6.49	3.70
Mach Number	0.1286	0.1316	0.1385	0.1470	0.1563	0.1682	0.1850	0.2041	0.2342	0.2851	0.4090	0.7373



Table G 12-5: Comparison of vent pipe model predictions with Hysys simulation in pressure range 100 - 500 KPa gauge for methane

Length	m	ASPEX HYSYS Plant ver 7.1													
		0	0.6	1.8	3	4.2	5.4	6.6	7.8	9	10.2	11.4	12		
Pressure	KPa	201.3	197.5	189.9	181.7	173.3	164.4	154.9	144.8	134.9	125.1	115.4	106.7	101.3	OUTLET
Temperature	°C	19.00	18.96	18.93	18.86	18.79	18.70	18.59	18.46	18.25	17.97	17.54	17.28	17.28	OUTLET
Mass Flow	kg/hr	11.30	11.30	11.30	11.30	11.30	11.30	11.30	11.30	11.30	11.30	11.30	11.30	11.30	OUTLET
Sid Vol Gas Flow	Nm <sup>3</sup> /hr	16.65	16.65	16.65	16.65	16.65	16.65	16.65	16.65	16.65	16.65	16.65	16.65	16.65	OUTLET
Velocity	m/sec	51.00	52.00	54.10	56.49	59.23	62.43	66.21	70.80	76.52	83.96	94.22	100.80	100.80	OUTLET
Density	kg/m <sup>3</sup>	1.33	1.31	1.26	1.20	1.15	1.10	1.05	1.00	0.96	0.91	0.87	0.83	0.81	OUTLET
Mach Number		0.1149	0.1170	0.1218	0.1272	0.1334	0.1406	0.1491	0.1595	0.1725	0.1893	0.2126	0.2376	0.2776	OUTLET
Pressure	KPa	301.3	294.7	281.0	266.7	251.4	235.1	217.5	198.2	176.6	151.4	119.5	101.3	101.3	OUTLET
Temperature	°C	19.00	18.97	18.89	18.80	18.68	18.53	18.33	18.04	17.60	16.92	14.91	13.52	13.52	OUTLET
Mass Flow	kg/hr	18.69	18.69	18.69	18.69	18.69	18.69	18.69	18.69	18.69	18.69	18.69	18.69	18.69	OUTLET
Sid Vol Gas Flow	Nm <sup>3</sup> /hr	27.54	27.54	27.54	27.54	27.54	27.54	27.54	27.54	27.54	27.54	27.54	27.54	27.54	OUTLET
Velocity	m/sec	56.39	57.58	60.36	63.89	67.45	71.06	74.83	78.83	83.03	87.53	92.40	97.60	103.10	OUTLET
Density	kg/m <sup>3</sup>	2.00	1.96	1.87	1.77	1.67	1.56	1.46	1.32	1.18	1.01	0.80	0.69	0.69	OUTLET
Mach Number		0.1267	0.1296	0.1359	0.1432	0.1518	0.1618	0.1733	0.1863	0.2009	0.2175	0.2363	0.2572	0.2793	OUTLET
Pressure	KPa	401.3	391.3	373.1	352.9	331.6	308.7	283.7	256.1	224.6	186.8	133.6	101.3	101.3	OUTLET
Temperature	°C	19.00	18.96	18.88	18.77	18.64	18.46	18.22	17.86	17.27	16.12	11.86	8.40	8.40	OUTLET
Mass Flow	kg/hr	25.72	25.72	25.72	25.72	25.72	25.72	25.72	25.72	25.72	25.72	25.72	25.72	25.72	OUTLET
Sid Vol Gas Flow	Nm <sup>3</sup> /hr	37.83	37.83	37.83	37.83	37.83	37.83	37.83	37.83	37.83	37.83	37.83	37.83	37.83	OUTLET
Velocity	m/sec	58.06	59.45	62.45	66.03	70.26	75.45	81.12	86.79	93.22	100.44	108.45	117.20	121.70	OUTLET
Density	kg/m <sup>3</sup>	2.67	2.61	2.48	2.35	2.21	2.06	1.89	1.71	1.50	1.25	0.91	0.70	0.70	OUTLET
Mach Number		0.1305	0.1337	0.1405	0.1485	0.1580	0.1697	0.1846	0.2044	0.2327	0.2721	0.3275	0.3980	0.4860	OUTLET
Pressure	KPa	501.3	489.5	465.4	439.9	412.8	383.4	351.2	316.3	276.0	227.5	160.8	101.3	101.3	OUTLET
Temperature	°C	19.00	18.96	18.87	18.73	18.62	18.42	18.07	17.78	17.15	15.92	11.20	2.00	2.00	OUTLET
Mass Flow	kg/hr	32.57	32.57	32.57	32.57	32.57	32.57	32.57	32.57	32.57	32.57	32.57	32.57	32.57	OUTLET
Sid Vol Gas Flow	Nm <sup>3</sup> /hr	47.91	47.91	47.91	47.91	47.91	47.91	47.91	47.91	47.91	47.91	47.91	47.91	47.91	OUTLET
Velocity	m/sec	58.74	60.17	63.28	66.96	71.36	76.81	83.82	93.05	104.45	118.71	139.01	175.45	175.45	OUTLET
Density	kg/m <sup>3</sup>	3.34	3.26	3.10	2.93	2.75	2.56	2.34	2.11	1.84	1.53	1.09	0.71	0.71	OUTLET
Mach Number		0.1320	0.1355	0.1421	0.1503	0.1601	0.1724	0.1881	0.2086	0.2388	0.2891	0.4065	0.6333	0.9171	OUTLET
Pressure	KPa	601.3	587.1	558.1	527.3	494.5	459.2	420.7	377.8	328.5	269.2	186.1	101.3	101.3	OUTLET
Temperature	°C	19.00	18.96	18.87	18.73	18.60	18.40	18.03	17.73	17.07	15.75	11.54	5.02	5.02	OUTLET
Mass Flow	kg/hr	39.38	39.38	39.38	39.38	39.38	39.38	39.38	39.38	39.38	39.38	39.38	39.38	39.38	OUTLET
Sid Vol Gas Flow	Nm <sup>3</sup> /hr	58.04	58.04	58.04	58.04	58.04	58.04	58.04	58.04	58.04	58.04	58.04	58.04	58.04	OUTLET
Velocity	m/sec	59.21	60.63	63.77	67.46	71.90	77.38	84.39	93.84	107.70	131.20	201.80	324.40	324.40	OUTLET
Density	kg/m <sup>3</sup>	4.01	3.92	3.72	3.52	3.30	3.07	2.81	2.53	2.21	1.81	1.18	0.74	0.74	OUTLET
Mach Number		0.1331	0.1363	0.1433	0.1517	0.1617	0.1741	0.1896	0.2106	0.2418	0.2944	0.4125	0.7535	1.2445	OUTLET

Vent Pipe Model Predictions												
0	0.6	1.8	3	4.2	5.4	6.6	7.8	9	10.2	11.4	12	OUTLET
Pressure	0.01%	-0.04%	0.00%	-0.04%	0.02%	0.02%	-0.08%	0.08%	0.14%	0.41%	1.41%	0.02%
Temperature	0.00%	-0.00%	-0.00%	-0.10%	0.00%	0.00%	-0.28%	0.03%	0.07%	0.35%	2.49%	0.56%
Mass Flow	0.00%	-0.01%	-0.02%	-0.02%	0.00%	0.02%	-0.14%	-0.07%	0.04%	0.15%	0.23%	0.14%
Sid Vol Gas Flow	0.00%	-0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Velocity	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%
Density	0.05%	-0.02%	-0.01%	-0.01%	0.00%	-0.04%	-0.04%	-0.04%	-0.04%	0.00%	0.08%	-0.16%
Mach Number	0.16%	0.20%	0.28%	0.34%	0.41%	0.48%	0.55%	0.61%	0.67%	0.73%	0.79%	0.84%

Vent Pipe Model Comparison with HYSYS												
0	0.6	1.8	3	4.2	5.4	6.6	7.8	9	10.2	11.4	12	OUTLET
Pressure	0.01%	-0.04%	0.02%	-0.04%	0.00%	0.03%	-0.06%	0.08%	0.14%	0.41%	1.41%	0.02%
Temperature	0.00%	-0.00%	-0.00%	-0.10%	0.00%	0.00%	-0.28%	0.03%	0.07%	0.35%	2.49%	0.56%
Mass Flow	0.00%	-0.01%	-0.02%	-0.02%	0.00%	0.02%	-0.14%	-0.07%	0.04%	0.15%	0.23%	0.14%
Sid Vol Gas Flow	0.00%	-0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Velocity	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%
Density	0.05%	-0.02%	-0.01%	-0.01%	0.00%	-0.04%	-0.04%	-0.04%	-0.04%	0.00%	0.08%	-0.16%
Mach Number	0.16%	0.20%	0.28%	0.34%	0.41%	0.48%	0.55%	0.61%	0.67%	0.73%	0.79%	0.84%

Table G 12-6: Comparison of vent pipe model predictions with Hysys simulation in pressure range 600 - 1000 KPa gauge for methane

	ASPERN HYSYS Plant see 7.1											
	0	0.6	1.8	3	4.2	5.4	5.6	7.8	9	10.2	11.4	12
Pressure KPa	701.3	684.7	650.9	615.0	576.7	536.5	490.5	446.5	383.0	312.6	194.0	114.8
Temperature °C	19.00	18.96	18.86	18.75	18.60	18.40	18.12	17.71	17.01	16.12	14.10	6.28
Mass Flow kg/hr	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03
Std Vol Gas Flow Nm <sup>3</sup> /hr	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97
Velocity m/sec	59.35	60.78	63.92	67.63	72.08	77.57	84.60	94.08	107.50	131.60	203.70	331.30
Density kg/m <sup>3</sup>	4.68	4.57	4.35	4.11	3.86	3.58	3.29	2.96	2.58	2.11	1.37	0.84
Mach Number	0.1334	0.1366	0.1437	0.1520	0.1621	0.1745	0.1904	0.2119	0.2434	0.2975	0.4698	0.7789
Pressure KPa	801.3	782.5	743.7	702.7	659.0	611.9	560.5	503.4	437.7	357.3	221.9	131.6
Temperature °C	19.00	18.96	18.86	18.74	18.59	18.39	18.12	17.70	16.99	15.49	14.06	6.33
Mass Flow kg/hr	52.86	52.86	52.86	52.86	52.86	52.86	52.86	52.86	52.86	52.86	52.86	52.86
Std Vol Gas Flow Nm <sup>3</sup> /hr	77.90	77.90	77.90	77.90	77.90	77.90	77.90	77.90	77.90	77.90	77.90	77.90
Velocity m/sec	59.41	60.87	64.02	67.73	72.18	77.68	84.72	94.20	108.10	131.70	203.70	330.60
Density kg/m <sup>3</sup>	5.35	5.24	4.98	4.70	4.41	4.10	3.76	3.38	2.98	2.42	1.56	0.96
Mach Number	0.1336	0.1368	0.1439	0.1522	0.1623	0.1747	0.1906	0.2121	0.2437	0.2978	0.4698	0.7772
Pressure KPa	901.3	880.0	836.5	790.4	741.2	688.3	630.6	566.3	492.4	401.9	249.8	148.3
Temperature °C	19.00	18.96	18.86	18.74	18.59	18.39	18.11	17.69	16.98	15.47	14.00	6.42
Mass Flow kg/hr	59.02	59.02	59.02	59.02	59.02	59.02	59.02	59.02	59.02	59.02	59.02	59.02
Std Vol Gas Flow Nm <sup>3</sup> /hr	87.88	87.88	87.88	87.88	87.88	87.88	87.88	87.88	87.88	87.88	87.88	87.88
Velocity m/sec	60.84	62.91	66.58	70.84	75.71	81.18	87.25	93.92	101.19	118.06	176.10	286.10
Density kg/m <sup>3</sup>	6.04	5.90	5.61	5.30	4.97	4.62	4.24	3.81	3.32	2.73	1.76	1.09
Mach Number	0.1337	0.1369	0.1440	0.1524	0.1625	0.1749	0.1908	0.2123	0.2439	0.2980	0.4699	0.7762
Pressure KPa	1001.3	977.8	929.3	878.1	823.5	764.7	700.5	629.1	547.1	446.6	277.7	165.1
Temperature °C	19.00	18.96	18.86	18.74	18.59	18.38	18.10	17.68	16.96	15.44	13.94	6.50
Mass Flow kg/hr	66.38	66.38	66.38	66.38	66.38	66.38	66.38	66.38	66.38	66.38	66.38	66.38
Std Vol Gas Flow Nm <sup>3</sup> /hr	97.83	97.83	97.83	97.83	97.83	97.83	97.83	97.83	97.83	97.83	97.83	97.83
Velocity m/sec	59.54	60.97	64.12	67.84	72.30	77.80	84.88	94.34	108.20	131.90	203.60	329.50
Density kg/m <sup>3</sup>	6.72	6.56	6.24	5.90	5.53	5.14	4.72	4.24	3.70	3.03	1.97	1.21
Mach Number	0.1338	0.1370	0.1441	0.1525	0.1626	0.1750	0.1909	0.2125	0.2446	0.2991	0.4698	0.7751
Pressure KPa	1101.3	1075.0	1022.0	965.8	905.8	841.1	770.5	692.0	601.5	491.3	306.1	182.7
Temperature °C	19.00	18.96	18.86	18.74	18.58	18.38	18.10	17.67	16.95	15.42	13.98	6.40
Mass Flow kg/hr	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15
Std Vol Gas Flow Nm <sup>3</sup> /hr	107.80	107.80	107.80	107.80	107.80	107.80	107.80	107.80	107.80	107.80	107.80	107.80
Velocity m/sec	59.57	60.99	64.15	67.86	72.33	77.83	84.87	94.36	108.20	131.90	203.30	327.90
Density kg/m <sup>3</sup>	7.40	7.23	6.87	6.50	6.10	5.67	5.20	4.67	4.07	3.34	2.17	1.35
Mach Number	0.1338	0.1371	0.1442	0.1526	0.1626	0.1751	0.1910	0.2126	0.2441	0.2982	0.4691	0.7710

	Vent Pipe Model Predictions											
	0	0.6	1.8	3	4.2	5.4	5.6	7.8	9	10.2	11.4	12
Pressure KPa	701.3	684.7	650.9	615.0	576.5	536.5	490.5	446.5	383.0	312.6	194.0	114.8
Temperature °C	19.00	18.96	18.86	18.71	18.50	18.21	17.81	17.02	16.12	14.10	6.28	0.54
Mass Flow kg/hr	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03	46.03
Std Vol Gas Flow Nm <sup>3</sup> /hr	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97	67.97
Velocity m/sec	59.13	60.58	63.76	67.54	72.01	77.61	84.83	94.28	108.25	131.71	188.23	332.31
Density kg/m <sup>3</sup>	5.37	5.24	4.98	4.70	4.41	4.09	3.74	3.37	2.93	2.41	1.69	0.96
Mach Number	0.1328	0.1361	0.1431	0.1514	0.1614	0.1738	0.1898	0.2109	0.2422	0.2949	0.4238	0.7716
Pressure KPa	801.3	780.0	736.5	690.4	641.2	588.3	530.6	466.3	392.4	301.9	149.8	88.3
Temperature °C	19.00	18.96	18.86	18.69	18.59	18.38	17.94	17.69	17.00	15.64	11.27	6.76
Mass Flow kg/hr	59.38	59.38	59.38	59.38	59.38	59.38	59.38	59.38	59.38	59.38	59.38	59.38
Std Vol Gas Flow Nm <sup>3</sup> /hr	87.84	87.84	87.84	87.84	87.84	87.84	87.84	87.84	87.84	87.84	87.84	87.84
Velocity m/sec	59.12	60.57	63.76	67.54	72.03	77.62	84.87	94.31	108.29	131.77	188.29	331.93
Density kg/m <sup>3</sup>	6.05	5.91	5.61	5.30	4.97	4.61	4.22	3.79	3.31	2.72	1.90	1.08
Mach Number	0.1328	0.1360	0.1430	0.1514	0.1613	0.1738	0.1898	0.2108	0.2420	0.2947	0.4234	0.7697
Pressure KPa	1001.3	977.8	929.3	877.3	823.3	764.1	698.3	628.5	547.1	446.2	280.7	165.2
Temperature °C	19.00	18.96	18.86	18.68	18.59	18.38	17.91	17.68	16.98	15.61	11.21	6.86
Mass Flow kg/hr	66.05	66.05	66.05	66.05	66.05	66.05	66.05	66.05	66.05	66.05	66.05	66.05
Std Vol Gas Flow Nm <sup>3</sup> /hr	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.16
Velocity m/sec	59.09	60.54	63.73	67.52	72.01	77.60	84.88	94.31	108.30	131.79	188.29	331.40
Density kg/m <sup>3</sup>	6.74	6.58	6.25	5.90	5.53	5.13	4.69	4.22	3.68	3.02	2.11	1.20
Mach Number	0.1327	0.1359	0.1429	0.1513	0.1611	0.1736	0.1896	0.2106	0.2418	0.2944	0.4238	0.7672
Pressure KPa	1101.3	1075.0	1022.0	965.8	905.8	840.5	768.0	691.7	601.9	493.2	306.9	182.7
Temperature °C	19.00	18.96	18.86	18.68	18.58	18.37	17.89	17.67	16.97	15.58	11.15	6.79
Mass Flow kg/hr	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15	73.15
Std Vol Gas Flow Nm <sup>3</sup> /hr	106.98	106.98	106.98	106.98	106.98	106.98	106.98	106.98	106.98	106.98	106.98	106.98
Velocity m/sec	60.49	60.99	64.18	67.89	72.36	77.86	84.92	94.37	108.36	131.78	188.16	329.48
Density kg/m <sup>3</sup>	7.43	7.25	6.88	6.50	6.09	5.65	5.17	4.65	4.05	3.33	2.33	1.33
Mach Number	0.1325	0.1358	0.1428	0.1511	0.1610	0.1734	0.1895	0.2103	0.2415	0.2940	0.4220	0.7621

	Vent Pipe Model Comparison with HYSYS											
	0	0.6	1.8	3	4.2	5.4	5.6	7.8	9	10.2	11.4	12
Pressure KPa	0.00%	0.01%	-0.02%	-0.08%	-0.44%	-0.88%	-0.21%	-0.07%	-0.02%	0.33%	11.60%	0.00%
Temperature °C	0.00%	-0.01%	-0.02%	-0.22%	-0.22%	-0.02%	-0.27%	0.03%	0.18%	1.16%	178.01%	4.08%
Mass Flow kg/hr	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%	-0.20%
Std Vol Gas Flow Nm <sup>3</sup> /hr	-0.39%	-0.39%	-0.39%	-0.39%	-0.39%	-0.39%	-0.39%	-0.39%	-0.39%	-0.39%	-0.39%	-0.39%
Velocity m/sec	-0.19%	0.15%	0.08%	-0.03%	-0.08%	-0.20%	-0.39%	-0.35%	-0.39%	-0.24%	8.01%	-0.70%
Density kg/m <sup>3</sup>	-0.44%	-0.44%	-0.43%	-0.39%	-0.46%	-0.38%	-0.31%	-0.46%	-0.49%	-0.82%	9.71%	-0.59%
Mach Number	0.00%	0.02%	-0.02%	0.08%	-0.04%	0.08%	-0.26%	-0.07%	-0.01%	0.34%	11.57%	0.00%
Pressure KPa	0.00%	-0.01%	0.01%	-0.21%	0.02%	0.00%	-0.25%	0.01%	0.18%	1.14%	179.18%	4.09%
Temperature °C	-0.30%	-0.30%	-0.30%	-0.30%	-0.30%	-0.30%	-0.30%	-0.30%	-0.30%	-0.30%	-0.30%	-0.30%
Mass Flow kg/hr	-0.49%	-0.49%	-0.49%	-0.49%	-0.49%	-0.49%	-0.49%	-0.49%	-0.49%	-0.49%	-0.49%	-0.49%
Std Vol Gas Flow Nm <sup>3</sup> /hr	-0.52%	-0.48%	-0.40%	-0.25%	-0.22%	-0.10%	0.13%	0.09%	0.14%	0.01%	-7.59%	0.52%
Velocity m/sec	0.23%	0.17%	0.10%	-0.01%	-0.07%	0.21%	-0.13%	0.33%	-0.65%	0.30%	7.91%	0.51%
Density kg/m <sup>3</sup>	-0.59%	-0.54%	-0.55%	-0.52%	-0.59%	-0.50%	-0.40%	-0.57%	-0.63%	-0.96%	9.79%	-0.72%
Mach Number	0.00%	0.00%	-0.02%	-0.09%	-0.03%	-0.08%	-0.26%	-0.07%	-0.01%	0.36%	11.53%	0.00%
Pressure KPa	0.00%	-0.02%	0.00%	-0.20%	-0.01%	-0.03%	-0.25%	0.00%	0.13%	1.07%	182.01%	5.29%
Temperature °C	-0.30%	-0.30%	-0.3									



Table G 12-7: Comparison of vent pipe model predictions with Hysys simulation in pressure range 100 - 500 KPa gauge for DBNGP gas mixture

		ASPEN HYSYS Plant ver.7.1											
		0	0.6	1.8	3	4.5	6.4	7.8	2	10.2	11.4	12	
		INLET										OUTLET	
Length	m	201.3	197.6	189.9	181.7	173.3	164.4	154.9	144.9	134.0	122.1	108.7	101.3
Pressure	K Pa	201.3	197.6	189.9	181.7	173.3	164.4	154.9	144.9	134.0	122.1	108.7	101.3
Temperature	°C	19.00	18.96	18.93	18.89	18.86	18.80	18.71	18.57	18.46	18.27	17.99	17.57
Mass Flow	kg/hr	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99
Std Vol Gas Flow	Nm <sup>3</sup> /hr	15.78	15.79	15.79	15.79	15.79	15.79	15.79	15.78	15.78	15.78	15.78	15.78
Velocity	m/sec	48.37	49.29	51.29	53.65	56.15	59.18	62.76	67.11	72.54	79.59	89.33	95.54
Density	kg/m <sup>3</sup>	1.49	1.46	1.41	1.35	1.29	1.22	1.15	1.08	0.99	0.91	0.81	0.76
Mach Number		0.1156	0.1178	0.1224	0.1280	0.1342	0.1415	0.1501	0.1605	0.1735	0.1905	0.2139	0.2389
Pressure	K Pa	301.3	294.7	281.0	266.6	251.4	235.1	217.4	198.4	176.9	152.0	121.2	101.3
Temperature	°C	19.00	18.97	18.89	18.78	18.69	18.54	18.34	18.06	17.63	16.86	15.00	13.64
Mass Flow	kg/hr	19.80	19.79	19.79	19.79	19.79	19.79	19.79	19.79	19.79	19.79	19.79	19.79
Std Vol Gas Flow	Nm <sup>3</sup> /hr	26.10	26.10	26.10	26.10	26.10	26.10	26.10	26.10	26.10	26.10	26.10	26.10
Velocity	m/sec	53.31	54.54	57.17	60.24	63.86	68.25	73.72	80.81	90.57	104.00	122.60	155.70
Density	kg/m <sup>3</sup>	2.24	2.19	2.09	1.98	1.87	1.75	1.62	1.48	1.32	1.13	0.91	0.77
Mach Number		0.1272	0.1303	0.1366	0.1437	0.1523	0.1628	0.1760	0.1928	0.2161	0.2510	0.3140	0.3744
Pressure	K Pa	401.3	392.0	373.1	352.9	331.6	308.8	283.5	256.3	225.1	188.9	138.8	101.3
Temperature	°C	19.00	18.96	18.88	18.78	18.64	18.47	18.15	17.69	17.34	16.30	14.53	12.86
Mass Flow	kg/hr	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20
Std Vol Gas Flow	Nm <sup>3</sup> /hr	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79
Velocity	m/sec	54.97	56.28	59.13	62.47	66.47	71.36	77.57	85.83	97.66	116.90	141.10	176.00
Density	kg/m <sup>3</sup>	2.99	2.92	2.77	2.63	2.47	2.30	2.11	1.91	1.68	1.41	1.08	0.78
Mach Number		0.1313	0.1344	0.1412	0.1492	0.1588	0.1706	0.1855	0.2033	0.2239	0.2566	0.3107	0.3682
Pressure	K Pa	601.3	589.5	565.4	539.8	512.8	484.1	454.1	421.8	386.4	348.1	306.3	261.3
Temperature	°C	19.00	18.96	18.87	18.73	18.62	18.44	18.08	17.60	17.19	15.99	13.38	10.33
Mass Flow	kg/hr	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49
Std Vol Gas Flow	Nm <sup>3</sup> /hr	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31
Velocity	m/sec	55.69	57.02	59.96	63.41	67.55	72.65	79.16	87.91	100.60	121.00	149.60	186.00
Density	kg/m <sup>3</sup>	3.71	3.65	3.47	3.28	3.08	2.86	2.62	2.36	2.06	1.71	1.32	0.89
Mach Number		0.1329	0.1361	0.1431	0.1514	0.1613	0.1736	0.1892	0.2102	0.2369	0.2719	0.3186	0.3682
Pressure	K Pa	601.3	587.1	568.0	546.9	523.6	498.3	471.6	443.1	414.1	384.1	351.6	316.3
Temperature	°C	19.00	18.96	18.87	18.76	18.61	18.42	18.15	17.76	17.08	15.65	13.41	10.33
Mass Flow	kg/hr	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69
Std Vol Gas Flow	Nm <sup>3</sup> /hr	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98
Velocity	m/sec	56.02	57.36	60.33	63.83	68.03	73.21	79.84	88.77	101.80	124.10	151.10	186.90
Density	kg/m <sup>3</sup>	4.49	4.38	4.17	3.94	3.69	3.43	3.15	2.83	2.47	2.03	1.53	1.02
Mach Number		0.1336	0.1369	0.1440	0.1523	0.1624	0.1748	0.1907	0.2122	0.2407	0.2778	0.3270	0.3806

		Vent Pipe Model Prediction											
		0	0.6	1.8	3	4.5	6.4	7.8	2	10.2	11.4	12	
		INLET										OUTLET	
Length	m	201.3	197.6	189.9	181.7	173.3	164.4	154.9	144.9	134.0	122.1	108.7	101.3
Pressure	K Pa	201.3	197.6	189.9	181.7	173.3	164.4	154.9	144.9	134.0	122.1	108.7	101.3
Temperature	°C	19.00	18.96	18.93	18.89	18.86	18.80	18.71	18.57	18.46	18.27	17.99	17.57
Mass Flow	kg/hr	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99	11.99
Std Vol Gas Flow	Nm <sup>3</sup> /hr	15.78	15.79	15.79	15.79	15.79	15.79	15.79	15.78	15.78	15.78	15.78	15.78
Velocity	m/sec	48.42	49.34	51.33	53.64	56.25	59.28	62.89	67.23	72.69	79.71	89.40	95.85
Density	kg/m <sup>3</sup>	1.49	1.46	1.41	1.35	1.29	1.22	1.15	1.07	0.99	0.91	0.81	0.76
Mach Number		0.1156	0.1177	0.1224	0.1279	0.1341	0.1412	0.1498	0.1601	0.1732	0.1899	0.2131	0.2386
Pressure	K Pa	301.3	294.7	281.0	266.6	251.4	235.1	217.4	198.4	176.9	152.0	121.2	101.3
Temperature	°C	19.00	18.97	18.89	18.78	18.69	18.54	18.34	18.07	17.64	16.92	15.36	13.66
Mass Flow	kg/hr	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80
Std Vol Gas Flow	Nm <sup>3</sup> /hr	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05
Velocity	m/sec	53.31	54.49	57.17	60.27	63.89	68.31	73.85	80.90	90.64	105.25	131.40	165.24
Density	kg/m <sup>3</sup>	2.24	2.19	2.09	1.98	1.87	1.75	1.62	1.48	1.32	1.13	0.91	0.76
Mach Number		0.1272	0.1298	0.1364	0.1437	0.1523	0.1628	0.1760	0.1928	0.2161	0.2510	0.3140	0.3744
Pressure	K Pa	401.3	392.0	373.1	352.9	331.6	308.8	283.5	256.3	225.1	188.9	138.8	101.3
Temperature	°C	19.00	18.96	18.88	18.78	18.64	18.47	18.15	17.69	17.34	16.30	14.53	12.86
Mass Flow	kg/hr	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20	27.20
Std Vol Gas Flow	Nm <sup>3</sup> /hr	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79
Velocity	m/sec	54.97	56.28	59.13	62.47	66.47	71.36	77.57	85.83	97.66	116.90	141.10	176.00
Density	kg/m <sup>3</sup>	2.99	2.92	2.77	2.63	2.47	2.30	2.11	1.91	1.68	1.41	1.08	0.78
Mach Number		0.1309	0.1342	0.1408	0.1488	0.1584	0.1699	0.1851	0.2046	0.2277	0.2781	0.3479	0.4289
Pressure	K Pa	601.3	589.5	565.4	539.8	512.8	484.1	454.1	421.8	386.4	348.1	306.3	261.3
Temperature	°C	19.00	18.96	18.87	18.73	18.62	18.44	18.08	17.60	17.19	15.99	13.38	10.33
Mass Flow	kg/hr	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49	34.49
Std Vol Gas Flow	Nm <sup>3</sup> /hr	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31	45.31
Velocity	m/sec	55.69	56.85	59.80	63.29	67.44	72.60	79.24	87.93	100.63	121.70	149.25	186.00
Density	kg/m <sup>3</sup>	3.71	3.65	3.47	3.28	3.08	2.86	2.62	2.36	2.06	1.71	1.32	0.89
Mach Number		0.1329	0.1366	0.1436	0.1517	0.1606	0.1729	0.1886	0.2092	0.2368	0.2789	0.3298	0.3852
Pressure	K Pa	601.3	587.1	568.0	546.9	523.6	498.3	471.6	443.1	414.1	384.1	351.6	316.3
Temperature	°C	19.00	18.96	18.87	18.76	18.61	18.42	18.15	17.76	17.08	15.65	13.41	10.33
Mass Flow	kg/hr	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69	41.69
Std Vol Gas Flow	Nm <sup>3</sup> /hr	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98	54.98
Velocity	m/sec	56.02	57.36	60.33	63.83	68.03	73.21	79.84	88.77	101.80	124.10	151.10	186.90
Density	kg/m <sup>3</sup>	4.49	4.38	4.17	3.94	3.69	3.43	3.15	2.83	2.47	2.03	1.53	1.02
Mach Number		0.1336	0.1369	0.1440	0.1523	0.1624	0.1748	0.1907	0.2122	0.2407	0.2778	0.3270	0.3806

		Vent Pipe Model Comparison with HYSYS											
		0	0.6	1.8	3	4.5	6.4	7.8	2	10.2	11.4	12	
		INLET										OUTLET	
Length	m	201.3	197.6	189.9	181.7	173.3	164.4	154.9	144.9	134.0	122.1	108.7	101.3
Pressure	K Pa	201.3	197.6	189.9	181.7	173.3	164.4	154.9	144.9	134.0	122.1		

Table G 12-8: Comparison of vent pipe model predictions with Hysys simulation in pressure range 600 - 1000 KPa gauge for DBNGP gas mixture

	ASPEN HYSYS Plant ver.7.1											
	0	0.6	1.8	3	4.5	6.6	7.8	9	10.2	11.4	12	OUTLET
Pressure K Pa	701.3	684.7	650.9	615.0	576.5	535.6	490.7	440.3	383.1	313.9	217.0	116.2
Temperature °C	19.00	18.96	18.87	18.75	18.61	18.41	18.14	17.74	17.06	15.60	11.50	-5.31
Mass Flow kg/hr	48.81	48.81	48.81	48.81	48.81	48.81	48.81	48.81	48.81	48.81	48.81	48.81
Std Vol Gas Flow Nm <sup>3</sup> /hr	64.38	64.38	64.38	64.38	64.38	64.38	64.38	64.38	64.38	64.38	64.38	64.38
Velocity m/sec	56.14	57.49	60.46	63.96	68.17	73.36	80.01	88.96	102.10	124.40	192.10	310.70
Density kg/m <sup>3</sup>	5.25	5.12	4.87	4.60	4.31	4.01	3.68	3.31	2.88	2.37	1.53	0.95
Mach Number	0.1339	0.1371	0.1443	0.1526	0.1627	0.1752	0.1911	0.2127	0.2443	0.2984	0.4700	0.7749
Pressure K Pa	801.3	782.4	743.6	702.1	657.7	611.5	563.2	513.3	473.8	358.8	248.0	132.6
Temperature °C	19.00	18.96	18.86	18.70	18.60	18.40	17.97	17.73	17.06	15.74	11.50	-5.86
Mass Flow kg/hr	55.71	55.71	55.71	55.71	55.71	55.71	55.71	55.71	55.71	55.71	55.71	55.71
Std Vol Gas Flow Nm <sup>3</sup> /hr	73.31	73.31	73.31	73.31	73.31	73.31	73.31	73.31	73.31	73.31	73.31	73.31
Velocity m/sec	55.81	57.18	60.19	63.77	68.00	73.28	80.13	89.05	102.25	124.41	177.74	312.70
Density kg/m <sup>3</sup>	6.02	5.87	5.58	5.27	4.94	4.58	4.19	3.77	3.28	2.70	1.89	1.17
Mach Number	0.1331	0.1363	0.1434	0.1518	0.1617	0.1742	0.1903	0.2113	0.2426	0.2984	0.4741	0.7682
Pressure K Pa	901.3	880.0	836.4	789.6	741.0	687.8	636.6	586.0	542.5	403.6	279.0	149.2
Temperature °C	19.00	18.96	18.86	18.69	18.60	18.40	17.94	17.71	17.04	15.70	11.50	-6.08
Mass Flow kg/hr	62.77	62.77	62.77	62.77	62.77	62.77	62.77	62.77	62.77	62.77	62.77	62.77
Std Vol Gas Flow Nm <sup>3</sup> /hr	82.59	82.59	82.59	82.59	82.59	82.59	82.59	82.59	82.59	82.59	82.59	82.59
Velocity m/sec	55.78	57.15	60.17	63.76	67.99	73.28	80.15	89.06	102.27	124.48	177.81	312.73
Density kg/m <sup>3</sup>	6.78	6.62	6.29	5.93	5.56	5.16	4.72	4.25	3.70	3.04	2.13	1.21
Mach Number	0.1330	0.1362	0.1433	0.1517	0.1616	0.1741	0.1902	0.2111	0.2424	0.2981	0.4737	0.7674
Pressure K Pa	1001.0	977.7	929.4	878.1	823.6	764.8	703.2	638.9	573.3	448.5	310.1	166.0
Temperature °C	19.00	18.96	18.86	18.75	18.60	18.40	17.91	17.70	17.02	15.67	11.36	-6.23
Mass Flow kg/hr	69.82	69.82	69.82	69.82	69.82	69.82	69.82	69.82	69.82	69.82	69.82	69.82
Std Vol Gas Flow Nm <sup>3</sup> /hr	91.88	91.88	91.88	91.88	91.88	91.88	91.88	91.88	91.88	91.88	91.88	91.88
Velocity m/sec	55.74	57.11	60.13	63.72	67.96	73.25	80.14	89.04	102.26	124.46	177.81	312.35
Density kg/m <sup>3</sup>	7.55	7.37	7.00	6.60	6.19	5.75	5.25	4.73	4.12	3.38	2.37	1.35
Mach Number	0.1329	0.1361	0.1432	0.1516	0.1614	0.1739	0.1900	0.2109	0.2421	0.2984	0.4731	0.7682
Pressure K Pa	1101.0	1075.0	1022.0	964.8	905.5	846.5	787.7	729.2	671.8	523.3	341.1	182.7
Temperature °C	19.00	18.96	18.86	18.67	18.59	18.38	17.88	17.69	17.00	15.64	11.30	-6.41
Mass Flow kg/hr	76.88	76.88	76.88	76.88	76.88	76.88	76.88	76.88	76.88	76.88	76.88	76.88
Std Vol Gas Flow Nm <sup>3</sup> /hr	101.17	101.17	101.17	101.17	101.17	101.17	101.17	101.17	101.17	101.17	101.17	101.17
Velocity m/sec	55.08	57.05	60.07	63.67	67.91	73.20	80.11	89.01	102.23	124.44	177.79	312.12
Density kg/m <sup>3</sup>	8.32	8.12	7.71	7.28	6.82	6.33	5.78	5.21	4.53	3.72	2.61	1.48
Mach Number	0.1327	0.1360	0.1430	0.1513	0.1612	0.1737	0.1898	0.2106	0.2418	0.2984	0.4742	0.7673

	Vent Pipe Model Comparison with HYSYS											
	0	0.6	1.8	3	4.5	6.6	7.8	9	10.2	11.4	12	OUTLET
Pressure K Pa	0.00%	0.00%	-0.02%	-0.05%	-0.08%	-0.12%	-0.16%	-0.20%	-0.24%	-0.28%	-0.33%	-0.39%
Temperature °C	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Mass Flow kg/hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.00%	0.00%	-0.02%	-0.04%	-0.06%	-0.08%	-0.10%	-0.12%	-0.14%	-0.16%	-0.18%	-0.20%
Velocity m/sec	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Density kg/m <sup>3</sup>	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Mach Number	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Pressure K Pa	0.00%	0.00%	-0.02%	-0.05%	-0.08%	-0.12%	-0.16%	-0.20%	-0.24%	-0.28%	-0.33%	-0.39%
Temperature °C	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Mass Flow kg/hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.00%	0.00%	-0.02%	-0.04%	-0.06%	-0.08%	-0.10%	-0.12%	-0.14%	-0.16%	-0.18%	-0.20%
Velocity m/sec	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Density kg/m <sup>3</sup>	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Mach Number	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Pressure K Pa	0.00%	0.00%	-0.02%	-0.05%	-0.08%	-0.12%	-0.16%	-0.20%	-0.24%	-0.28%	-0.33%	-0.39%
Temperature °C	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Mass Flow kg/hr	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Std Vol Gas Flow Nm <sup>3</sup> /hr	0.00%	0.00%	-0.02%	-0.04%	-0.06%	-0.08%	-0.10%	-0.12%	-0.14%	-0.16%	-0.18%	-0.20%
Velocity m/sec	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Density kg/m <sup>3</sup>	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%
Mach Number	0.00%	0.00%	-0.01%	-0.02%	-0.03%	-0.04%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.10%

## **Appendix H**

### **13.1 Vent Pipe Model Program**

## Vent Pipe Model <sup>®</sup>

Single Phase Gas Mixture Selected	
Argon;0.0092;Oxygen;0.2096;Nitrogen;0.7812;	

Vent Pipe	
Schedule No.	80
Pipe Size	0.25 inch
Internal diameter	7.66 mm
Internal diameter	0.0077 m
Wall thickness	3.02 mm
Special W thickness	mm
Length	12.0 m
Roughness	0.015 mm

Initial Estimates	
Inlet Mach Number	0.01
Outlet Temperature	19.00 °C 292.15 °K

Thermophysical gas properties calculated from REFPROP NIST computer package;Temperature and Pressure	TP
Vent pipe Model Units:	SI

Gas	Mole %	Normalized Mole %	Mole Fraction
Argon	0.920 %	0.92 %	0.0092
Oxygen	20.960 %	20.96 %	0.2096
Nitrogen	78.120 %	78.12 %	0.7812
	100.00	100.00	1.0000

Units	Inlet Static Pressure, P <sub>1</sub>	Outlet Static Pressure, P <sub>2</sub>	Units	Inlet Static Temperature, T <sub>1</sub>	Outlet Static Temperature
KPa g	500.0	0.0	°C	19.00	-8.73
KPa abs	601.3	101.3	*K	292.15	264.42

### Gas Properties

Pressure Drop	500.0 KPa
Temperature Drop	27.73 °C
Exit Gas Temperature	-8.73 °C
Exit Pipe Wall Temperature	11.51 °C
Exit Recovery Factor	0.725
Inlet Mach Number	0.1287
Outlet Mach Number	0.7268
Max Mass Flowrate	52.73 kg/hr
Std. Vol Flowrate	43.04 m <sup>3</sup> /hr
Flow Condition	Subsonic (0 < M < 0.8)
Stagnation Temperature	19.69 °C
Stagnation Enthalpy	292.27 KJ/kg
Critical Pressure	-30.76 KPa G
Critical Temperature	-30.01 °C
Critical Length	12.08 m
Friction Factor	0.02
Reynold's Number	144883
Exit Velocity	237.75 m/sec

Calculate for gas properties

Calculate

User options on approaching sonic conditions

Inlet Pressure

Outlet Pressure

Vent Length

Take a snap-shot of gas properties

Snap Shot

Figure H 13-1: Vent pipe model user specification sheet



### Newton's Iteration Method for Nonlinear Equations

#### Determinant of Jacobian

#### Multiplication of matrices (Jacobian Matrix)

#### Subtraction of Matrices

Iteration	Old		New		X	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>	M <sub>5</sub>	M <sub>6</sub>	J	F(ξ)	J <sup>-1</sup> F(ξ)	X <sub>new</sub>
	T <sub>1j</sub>	M <sub>1j</sub>	Determinant	T <sub>2j</sub>											
1	292.2	0.01	4712.93	291.74	0.0150										
2	291.74	0.0150	1408.46	291.24	0.0224										
3	291.24	0.0224	424.22	290.14	0.0332										
4	290.14	0.0332	130.37	287.84	0.0488										
5	287.84	0.0488	41.85	283.38	0.0698										
6	283.38	0.0698	14.71	276.19	0.0949										
7	276.19	0.0949	6.15	268.16	0.1179										
8	268.16	0.1179	3.41	263.76	0.1298										
9	263.76	0.1298	2.63	263.21	0.1320										
10	263.21	0.1320	2.51	263.24	0.1321										
11	263.24	0.1321	2.51	263.24	0.1321										
12	263.24	0.1321	2.51	263.24	0.1321										
13	263.24	0.1321	2.51	263.24	0.1321										
14	263.24	0.1321	2.51	263.24	0.1321										
15	263.24	0.1321	2.51	263.24	0.1321										
16	263.24	0.1321	2.51	263.24	0.1321										
17	263.24	0.1321	2.51	263.24	0.1321										
18	263.24	0.1321	2.51	263.24	0.1321										
19	263.24	0.1321	2.51	263.24	0.1321										
20	263.24	0.1321	2.51	263.24	0.1321										

M<sub>1j</sub> ..... 0.13206  
T<sub>2j</sub> ..... 263.236

P<sub>1</sub> P<sub>2</sub> T<sub>1</sub> γ Const A  
601.325 101.325 292.15 1.4113 0.206

f L D  
0.0232896 12 0.00766

<b>Iteration 10</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.56.88	6.6E-01	F(x)=	2.1E-04	263.2	
	0.1321	2.0E-03	-6.0E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		3.3E-02	0.132	
										X <sub>new</sub> =	
											-0.03
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 11</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.36.88	6.6E-01	F(x)=	-1.2E-05	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		2.1E-05	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 12</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.56.88	6.6E-01	F(x)=	1.3E-06	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		-9.6E-11	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 13</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.36.88	6.6E-01	F(x)=	-1.3E-07	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		-1.1E-12	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 14</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.56.88	6.6E-01	F(x)=	1.3E-08	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		-2.1E-14	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 15</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.36.88	6.6E-01	F(x)=	-1.3E-09	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		0.0E+00	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 16</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.56.88	6.6E-01	F(x)=	1.4E-10	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		1.4E-14	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 17</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.36.88	6.6E-01	F(x)=	-1.4E-11	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		-1.4E-14	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 18</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.56.88	6.6E-01	F(x)=	1.4E-12	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		1.4E-14	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 19</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.36.88	6.6E-01	F(x)=	-1.5E-13	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		-1.4E-14	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=
<b>Iteration 20</b>											
X=	263.2	-4.2E-03	-1.7E+00	-4E-03	-2E+00	-2.56.88	6.6E-01	F(x)=	1.5E-14	263.2	
	0.1321	2.0E-03	-5.9E+02	2E-03	-6E+02	-7.8E-04	-1.7E-03		0.0E+00	0.132	
											X <sub>new</sub> =
											0.00
											0.00
											J <sup>-1</sup> F(x)=

Figure H 13-2: Newtons Iteration method for nonlinear equations

### Interpolation of Property Relation

Static Function XYinterpolate(xyarray As Variant, x, y As Single) As Single

Dim n1, M1 As Integer

Dim x1, x2, y1, y2, Ry1x1, Ry1x2, Ry1x1x2, Ry2x1, Ry2x2, Ry2x1x2 As Single

x1 = Application.HLookup(x, xyarray, 1)

n1 = Application.Match(x1, xyarray.Rows(1), 0)

x2 = xyarray.Cells(1, n1 + 1).Value

y1 = Application.VLookup(y, xyarray, 1)

M1 = Application.Match(y1, xyarray.Columns(1), 0)

y2 = xyarray.Cells(M1 + 1, 1).Value

Ry1x1 = xyarray.Cells(M1, n1)

Ry1x2 = xyarray.Cells(M1, n1 + 1)

Ry1x1x2 = (x - x1) / (x2 - x1) \* (Ry1x2 - Ry1x1) + Ry1x1

Ry2x1 = xyarray.Cells(M1 + 1, n1)

Ry2x2 = xyarray.Cells(M1 + 1, n1 + 1)

Ry2x1x2 = (x - x1) / (x2 - x1) \* (Ry2x2 - Ry2x1) + Ry2x1

XYinterpolate = (y - y1) / (y2 - y1) \* (Ry2x1x2 - Ry1x1x2) + Ry1x1x2

End Function

Static Function Log10(x)

Log10 = Log(x) / Log(10)

End Function

### Serghides approximation to Colebrook-White Equation for calculating friction factor:

Function MoodyFrictFactor(Nre, rel\_rough)

If Nre > 2000 Then

a = -2 \* Log10(rel\_rough / 3.7 + 12 / Nre)

b = -2 \* Log10(rel\_rough / 3.7 + 2.51 \* a / Nre)

c = -2 \* Log10(rel\_rough / 3.7 + 2.51 \* b / Nre)

MoodyFrictFactor = (a - (b - a) ^ 2 / (c - 2 \* b + a)) ^ -2

Else

MoodyFrictFactor = 64 / Nre

End If

End Function



### Initial estimate of friction factor using Von-Karman equation

```
Function VonKarmanFrictFactor(rel_rough)
    If rel_rough > 0 Then
        a = 2 * Log10(rel_rough / 3.7)
        b = -1 * a
        c = 1 / b
        VonKarmanFrictFactor = c ^ 2
    Else
        VonKarmanFrictFactor = "Pipe is smooth"
    End If
End Function
```

### Non-Linear equations for predicting $T_2$ and $M_1$

```
Function equation1(press1, press2, temp1, temp2, Compressibility, Gamma, constA, Mach1)
    As Double
        "Main Equation for T2
        equation1 = (temp1 / temp2) - ((1 + (constA * Mach1 * Mach1 * ((press1 * press1) /
        (press2 * press2)) * (temp2 / temp1))) / (1 + (constA * Mach1 * Mach1)))
    End Function
```

```
Function equation2(press1, press2, temp1, temp2, Compressibility, Gamma, constA, Mach1,
    fricf, Lenght, Diameter) As Double
        'Main equation for M1
        equation2 = (((((2 * constA * Compressibility) - (1 / Compressibility) - (3 *
        constA)) * ((Application.In((press1 * press1) / (press2 * press2))) +
        (Application.In(temp2 / temp1)) + (Application.In((1 + (constA * Mach1 * Mach1))
        / (1 + (constA * ((press1 * press1) / (press2 * press2)) * (temp2 / temp1) * Mach1 *
        Mach1)))))) + ((1 / (Mach1 * Mach1)) * (1 - (1 / (((press1 * press1) / (press2 *
        press2)) * (temp2 / temp1)))))) * (Compressibility / Gamma) - ((fricf * Lenght) /
        Diameter)
    End Function
```

Function equation3(press1, press2, temp1, temp2, Compressibility, Gamma, constA, Mach1)  
As Double

'derivative of eqn 1 with respect to T2 which is treated as X1 in our case

$$\text{equation3} = (-1) * ((\text{temp1} / (\text{temp2} * \text{temp2})) + ((\text{a} * \text{Mach1} * \text{Mach1} * ((\text{press1} * \text{press1}) / (\text{press2} * \text{press2})) * (1 / \text{temp1})) / (1 + (\text{constA} * \text{Mach1} * \text{Mach1}))))$$

End Function

Function equation4(press1, press2, temp1, temp2, Compressibility, Gamma, constA, Mach1)  
As Double

'derivative of eqn 1 with respect to mach1 which is treated as X2 in our case

$$\text{equation4} = (-1) * (((1 + (\text{constA} * \text{Mach1} * \text{Mach1})) * (\text{constA} * ((\text{press1} * \text{press1}) / (\text{press2} * \text{press2})) * (\text{temp2} / \text{temp1}) * (2 * \text{Mach1})) - ((1 + (\text{constA} * \text{Mach1} * \text{Mach1} * ((\text{press1} * \text{press1}) / (\text{press2} * \text{press2})) * (\text{temp2} / \text{temp1}))) * (2 * \text{constA} * \text{Mach1}))) / ((1 + (\text{constA} * \text{Mach1} * \text{Mach1})) * (1 + (\text{constA} * \text{Mach1} * \text{Mach1}))))$$

End Function

Function equation5(press1, press2, temp1, temp2, Compressibility, Gamma, constA, Mach1)  
As Double

'derivative of eqn 2 with respect to T2 which is treated as X1 in our case

$$\text{equation5} = (((2 * \text{constA} * \text{Compressibility}) - (1 / \text{Compressibility}) - (3 * \text{constA})) * ((1 / \text{temp2}) - (1 / ((1 / (\text{constA} * ((\text{press1} * \text{press1}) / (\text{press2} * \text{press2})) * (\text{Mach1} * \text{Mach1}) * (1 / \text{temp1}))) + (\text{temp2})))))) + (1 / ((\text{Mach1} * \text{Mach1}) * ((\text{press1} * \text{press1}) / (\text{press2} * \text{press2})) * (\text{temp2} * \text{temp2}) * (1 / \text{temp1})))) * (\text{Compressibility} / \text{Gamma})$$

End Function

Function equation6(press1, press2, temp1, temp2, Compressibility, Gamma, constA, Mach1)  
As Double

'derivative of eqn 2 with respect to mach1 which is treated as X2 in our case

$$\text{equation6} = (((2 * \text{constA} * \text{Mach1} * ((2 * \text{constA} * \text{Compressibility}) - (1 / \text{Compressibility}) - (3 * \text{constA}))) * ((1 / (1 + (\text{constA} * \text{Mach1} * \text{Mach1}))) - (1 / ((1 / ((\text{press1} * \text{press1} * \text{temp2}) / (\text{press2} * \text{press2} * \text{temp1}))) + (\text{constA} * \text{Mach1} * \text{Mach1})))))) - ((2 / (\text{Mach1} * \text{Mach1} * \text{Mach1})) * (1 - (1 / ((\text{press1} * \text{press1} * \text{temp2}) / (\text{press2} * \text{press2} * \text{temp1})))))) * (\text{Compressibility} / \text{Gamma})$$

End Function

## Calculations and Experimental flow comparisons

Option Explicit

```
Public Sub OutletPressureGoalSeek()
```

```
Dim ws As String
```

```
ws = "Controlling sheet"
```

```
Worksheets(ws).Range("AR10").GoalSeek _
```

```
Goal:=Range("outletpressureKPaG").Value + 101.325, _
```

```
ChangingCell:=Worksheets(ws).Range("Error")
```

```
End Sub
```

```
Public Sub experimentflowcal()
```

```
Dim ws, ws1 As String
```

```
Dim rangeIP, rangeOP, rangeMF, rangeIT, rangeOT As Range
```

```
Dim x, StartInletPressure, StartOutletPressure, bob As Variant
```

```
ws = "Controlling sheet"
```

```
ws1 = "Experiment Flow Calculation"
```

```
Set rangeIP = Worksheets(ws1).Range("StartIP:EndIP")
```

```
Set rangeOP = Worksheets(ws1).Range("StartOP:EndOP")
```

```
Set rangeMF = Worksheets(ws1).Range("StartMF:EndMF")
```

```
Set rangeIT = Worksheets(ws1).Range("StartIT:EndIT")
```

```
Set rangeOT = Worksheets(ws1).Range("StartOT:EndOT")
```

```
'StartInletPressure = Worksheets(ws).Range("InletPressureKPaG")
```

```
'StartOutletPressure = Worksheets(ws).Range("OutletPressureKPaG")
```

```
For Each x In rangeIP
```

```
    If x.Value > 150 Then
```

```
        If x.Value < x.Offset(0, 1).Value Then
```

```
            x.Value = ""
```

```
            x.Offset(0, 1).Value = ""
```

```
        Else
```

```
            Worksheets(ws).Range("InletPressureKPaG") = x.Value
```

```
            Worksheets(ws).Range("OutletPressureKPaG") = x.Offset(0, 1).Value
```

```
            Worksheets(ws).Range("InletTemperatureDegC") = x.Offset(0, 3).Value
```

```
'bob = x.Offset(0, 1).Value + 101.325
```

```
'Worksheets(ws).Range("AK2").GoalSeek , _
```

```
' Goal:=bob, _
```

```
' ChangingCell:=Worksheets(ws).Range("Y4")
```

```
Call OutletPressureGoalSeek
```

```
Call SnapShotOfControllingSheet
```

```
End If
End If
Next x

MsgBox "all done"
End Sub
```

### Functions for Vent Pipe Model Program

```
Function Mass_Flux(Mach1, Density, Compressibility, Gamma, R, Temperature) As Double
    Mass_Flux = Mach1 * Density * Application.WorksheetFunction.Power(Compressibility
    * Gamma * R * Temperature, 0.5)
End Function
```

```
Function Mass_Flow(MassFlux, Diameter) As Double
```

```
    Dim Area As Double
```

```
    Area = (Application.WorksheetFunction.pi() / 4) *
```

```
    Application.WorksheetFunction.Power(Diameter, 2)
```

```
    Mass_Flow = MassFlux * Area
```

```
End Function
```

```
Function Velocity(MassFlux, Density)
```

```
    Velocity = MassFlux / Density
```

```
End Function
```

```
Function Mach2(Mach1, Pressure1, Pressure2, Temperature1, Temperature2)
```

```
    Mach2 = Mach1 * (Pressure1 / Pressure2) * Application.WorksheetFunction.Power
    ((Temperature2 / Temperature1), 0.5)
```

```
End Function
```

```
Function Reynolds(Diameter, Velocity, Density, Viscosity)
```

```
    Reynolds = (Diameter * Velocity * Density) / Viscosity
```

```
End Function
```

```
Function Area(Diameter)
```

```
    Area = (Application.WorksheetFunction.pi() / 4) *
```

```
    Application.WorksheetFunction.Power(Diameter, 2)
```

```
End Function
```

## Newton's Iteration Method

```
Public Sub Newton_Iteration_Method()
```

```
Dim ws As String
```

```
Dim a, b, c, d, e, f, Ro, A1, B1, C1, D1, G1, Gi, mu1, P1, P2, T1, Z1, A_Constant,  
Pipe_Rel_Roughness, P_Length, P_Diameter As Variant
```

```
Dim T2i, M1i, M2i, mi, Vi, Rei, fi, Iterations As Variant
```

```
Dim i, j As Variant
```

```
On Error Resume Next
```

```
ws = "Mass Flow Rate"
```

```
P1 = Worksheets(ws).Range("Inlet_Pressure").Value
```

```
P2 = Worksheets(ws).Range("Outlet_Pressure").Value
```

```
T1 = Worksheets(ws).Range("Inlet_Temperature").Value
```

```
Z1 = Worksheets(ws).Range("Inlet_Compressibility").Value
```

```
G1 = Worksheets(ws).Range("Inlet_specific_heat_ratio").Value
```

```
D1 = Worksheets(ws).Range("Inlet_Density").Value
```

```
mu1 = Worksheets(ws).Range("Inlet_Viscosity").Value
```

```
Ro = Worksheets(ws).Range("Gas_Constant").Value
```

```
A_Constant = Worksheets(ws).Range("Inlet_A").Value
```

```
Pipe_Rel_Roughness = Worksheets(ws).Range("Pipe_Roughness").Value /
```

```
Worksheets(ws).Range("Pipe_Diameter").Value
```

```
P_Length = Worksheets(ws).Range("Pipe_Length").Value
```

```
P_Diameter = Worksheets(ws).Range("Pipe_Diameter").Value
```

```
'Initial estimates
```

```
T2i = Worksheets(ws).Range("Inlet_Temperature").Value
```

```
M1i = 0.01
```

```
fi = VonKarmanFrictFactor(Pipe_Rel_Roughness)
```

```
Iterations = 10
```

```
For i = 1 To Iterations
```

```
For j = 1 To 20
```

```
a = equation3(P1, P2, T1, T2i, Z1, G1, A_Constant, M1i)
```

```
c = equation4(P1, P2, T1, T2i, Z1, G1, A_Constant, M1i)
```

```
b = equation5(P1, P2, T1, T2i, Z1, G1, A_Constant, M1i)
```

```
d = equation6(P1, P2, T1, T2i, Z1, G1, A_Constant, M1i)
```

```
e = equation1(P1, P2, T1, T2i, Z1, G1, A_Constant, M1i)
```

```
f = equation2(P1, P2, T1, T2i, Z1, G1, A_Constant, M1i, fi, P_Length, P_Diameter)
```

```
A1 = d * ((a * d) - (b * c))
```

```
B1 = b / ((b * c) - (a * d))
```

```
C1 = c / ((b * c) - (a * d))
```

```
D1 = a / ((a * d) - (b * c))
```

```
T2i = T2i - ((A1 * e) + (B1 * f))
```

```
M1i = M1i - ((B1 * e) + (D1 * f))
```

```

j = j + 1
Next j
'New friction factor using moody
  Gi = Mass_Flux(M1i, D1, Z1, G1, Ro, T2i)
  mi = Mass_Flow(Gi, P_Diameter)
  Vi = Velocity(Gi, D1)
  Rei = Reynolds(P_Diameter, Vi, D1, mu1)
  fi = MoodyFrictFactor(Rei, Pipe_Rel_Roughness)
Next i
M2i = Mach2(M1i, P1, P2, T1, T2i)
MsgBox M2i
End Sub

```

### Snap-Shot Module

```
Public Sub SnapShotOfControllingSheet()
```

```
Dim ws, ws1, cell As String
```

```

ws = "Snap Shot"
ws1 = "Controlling sheet"
cell = Worksheets(ws).Range("A8").Address
'cell = "SnapShotDateTime"

```

```

On Error Resume Next
Err.Clear

```

```

Worksheets(ws).Range(cell).End(xlDown).Offset(1, 0).Value = Date
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 0).NumberFormat = "dd-mmm' yy"
Worksheets(ws).Range(cell).End(xlDown).Offset(1, 0).NumberFormat = "dd-mmm' yy"

```

```

Worksheets(ws).Range(cell).End(xlDown).Offset(0, 1).Value = Range("PipeScheduleNo")
Worksheets(ws).Range(cell).End(xlDown).Offset(1, 0).NumberFormat = "general"

```

```

Worksheets(ws).Range(cell).End(xlDown).Offset(0, 2).Value = Range("PipeSizeInch")
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 2).NumberFormat = "0.000"

```

```

Worksheets(ws).Range(cell).End(xlDown).Offset(0, 3).Value = Range("PipeLenghtm")
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 3).NumberFormat = "0.000"

```

```

Worksheets(ws).Range(cell).End(xlDown).Offset(0,4).Value = Range("SurfaceRoughness").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 4).NumberFormat = "0.000"

```

```

Worksheets(ws).Range(cell).End(xlDown).Offset(0,5).Value = Range("InletPressureKPaG").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 5).NumberFormat = "0.00"

```

```

Worksheets(ws).Range(cell).End(xlDown).Offset(0,6).Value = Range("OutletPressureKPaG").Value

```



```

Worksheets(ws).Range(cell).End(xlDown).Offset(0, 6).NumberFormat = "0.00"

Worksheets(ws).Range(cell).End(xlDown).Offset(0,7).Value           =
Range("PressureDrop").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 7).NumberFormat = "0.00"

Worksheets(ws).Range(cell).End(xlDown).Offset(0,8).Value           =
Range("InletTemperatureDegC").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 8).NumberFormat = "0.000"

Worksheets(ws).Range(cell).End(xlDown).Offset(0,9).Value           =
Range("OutletTemperatureDegC").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 9).NumberFormat = "0.000"

Worksheets(ws).Range(cell).End(xlDown).Offset(0, 10).Value = Range("InletMach").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 10).NumberFormat = "0.0000"

Worksheets(ws).Range(cell).End(xlDown).Offset(0,11).Value           =
Range("OutletMach").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 11).NumberFormat = "0.000"

Worksheets(ws).Range(cell).End(xlDown).Offset(0,12).Value           =
Range("PipeMaxMassFlowrate").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 12).NumberFormat = "0.000"

Worksheets(ws).Range(cell).End(xlDown).Offset(0,13).Value           =
Range("PipeMaxNormalFlowrate").Value
Worksheets(ws).Range(cell).End(xlDown).Offset(0, 13).NumberFormat = "0.000"

'MsgBox "Values entered on Snap Shot Spreadsheet"

End Sub

```

**Program for determining thermodynamic properties from REFPROP (Lemmon, Huber, and McLinden 2009). Formatted accordingly for vent pipe model by Farhan Rajiwate**

Option Explicit

Private Const FluidsDirectory As String = "fluids\"

Private Const MixturesDirectory As String = "mixtures\"

Private Const MaxComps As Integer = 20

Private Declare Sub SETUPdll Lib "REFPROP.DLL" (i As Long, ByVal hfld As String, ByVal hfmix As String, ByVal hrf As String, ierr As Long, ByVal herr As String, ln1 As Long, ln2 As Long, ln3 As Long, ln4 As Long)

Private Declare Sub SETREFdll Lib "REFPROP.DLL" (ByVal hrf As String, ixflag As Long, x0 As Double, h0 As Double, s0 As Double, t0 As Double, p0 As Double, ierr As Long, ByVal herr As String, ln1 As Long, ln2 As Long)

Private Declare Sub SETMIXdll Lib "REFPROP.DLL" (ByVal hmxnme As String, ByVal hfmix As String, ByVal hrf As String, ncc As Long, ByVal hfile As String, x As Double, ierr As Long, ByVal herr As String, ln1 As Long, ln2 As Long, ln3 As Long, ln4 As Long, ln5 As Long)

Private Declare Sub SETMODdll Lib "REFPROP.DLL" (i As Long, ByVal htype As String, ByVal hmix As String, ByVal hcomp As String, ierr As Long, ByVal herr As String, ln1 As Long, ln2 As Long, ln3 As Long, ln4 As Long)

Private Declare Sub GERG04dll Lib "REFPROP.DLL" (nc As Long, iflag As Long, ierr As Long, ByVal herr As String, ln1 As Long)

Private Declare Sub TPRHODll Lib "REFPROP.DLL" (t As Double, p As Double, x As Double, j As Long, i As Long, d As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub THERM2dll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, p As Double, e As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, Z As Double, hjt As Double, aH As Double, G As Double, kappa As Double, beta As Double, dPdD As Double, d2PdD2 As Double, dPdT As Double, dDdT As Double, dDdP As Double, spare1 As Double, spare2 As Double, spare3 As Double, spare4 As Double)

Private Declare Sub THERM3dll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, kappa As Double, beta As Double, isenk As Double, kt As Double, betas As Double, bs As Double, kkt As Double, thrott As Double, pi As Double, spht As Double)

Private Declare Sub THERMdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, p As Double, e As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, hjt As Double)

Private Declare Sub THERM0dll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, p As Double, e As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, a As Double, G As Double)

Private Declare Sub ENTROdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, s As Double)

Private Declare Sub ENTHALdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, h As Double)

Private Declare Sub CVCPdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, cv As Double, cp As Double)

Private Declare Sub PRESSdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, p As Double)

Private Declare Sub AGdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, a As Double, G As Double)

Private Declare Sub DPDDdll Lib "REFPROP.DLL" (t As Double, rho As Double, x As Double, dPd As Double)

Private Declare Sub DPDD2dll Lib "REFPROP.DLL" (t As Double, rho As Double, x As Double, d2Pd2 As Double)

Private Declare Sub DPDTdll Lib "REFPROP.DLL" (t As Double, rho As Double, x As Double, dPdT As Double)

Private Declare Sub DDDPdll Lib "REFPROP.DLL" (t As Double, rho As Double, x As Double, dDdP As Double)

Private Declare Sub DDDTdll Lib "REFPROP.DLL" (t As Double, rho As Double, x As Double, dDdT As Double)

Private Declare Sub DHD1dll Lib "REFPROP.DLL" (t As Double, rho As Double, x As Double, dHdT\_D As Double, dHdT\_P As Double, dHdD\_T As Double, dHdD\_P As Double, dHdP\_T As Double, dHdP\_D As Double)

Private Declare Sub SATTdll Lib "REFPROP.DLL" (t As Double, x As Double, i As Long, p As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub SATPdll Lib "REFPROP.DLL" (p As Double, x As Double, i As Long, t As Double, D1 As Double, Dv As Double, xliq As Double, xvap As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub SATDdll Lib "REFPROP.DLL" (d As Double, x As Double, kph As Long, kr As Long, t As Double, p As Double, D1 As Double, Dv As Double, xliq As Double, xvap As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub SATHdll Lib "REFPROP.DLL" (h As Double, x As Double, kph As Long, nroot As Long, k1 As Long, T1 As Double, P1 As Double, D1 As Double, k2 As Long, T2 As Double, P2 As Double, d2 As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub SATEdll Lib "REFPROP.DLL" (e As Double, x As Double, kph As Long, nroot As Long, k1 As Long, T1 As Double, P1 As Double, D1 As Double, k2 As Long, T2 As Double, P2 As Double, d2 As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub SATSdll Lib "REFPROP.DLL" (s As Double, x As Double, kph As Long, nroot As Long, k1 As Long, T1 As Double, P1 As Double, D1 As Double, k2 As Long, T2 As Double, P2 As Double, d2 As Double, k3 As Long, t3 As Double, p3 As Double, d3 As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub CV2PKdll Lib "REFPROP.DLL" (icomp As Long, t As Double, rho As Double, cv2p As Double, csat As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub CSATKdll Lib "REFPROP.DLL" (icomp As Long, t As Double, kph As Long, p As Double, rho As Double, csat As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub DPTSATKdll Lib "REFPROP.DLL" (icomp As Long, t As Double, kph As Long, p As Double, rho As Double, csat As Double, dpdtsat As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub TPFLSHdll Lib "REFPROP.DLL" (t As Double, p As Double, x As Double, d As Double, D1 As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub TDFLSHdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, p As Double, D1 As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub PDFLSHdll Lib "REFPROP.DLL" (p As Double, d As Double, x As Double, t As Double, D1 As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub PHFLSHdll Lib "REFPROP.DLL" (p As Double, h As Double, x As Double, t As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub PSFLSHdll Lib "REFPROP.DLL" (p As Double, s As Double, x As Double, t As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, h As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub PEFLSHdll Lib "REFPROP.DLL" (p As Double, e As Double, x As Double, t As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub THFLSHdll Lib "REFPROP.DLL" (t As Double, h As Double, x As Double, i As Long, p As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub TSFLSHdll Lib "REFPROP.DLL" (t As Double, s As Double, x As Double, i As Long, p As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, h As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub TEFLSHdll Lib "REFPROP.DLL" (t As Double, e As Double, x As Double, i As Long, p As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub DHFLSHdll Lib "REFPROP.DLL" (d As Double, h As Double, x As Double, t As Double, p As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub DSFLSHdll Lib "REFPROP.DLL" (d As Double, s As Double, x As Double, t As Double, p As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, e As Double, h As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub DEFLSHdll Lib "REFPROP.DLL" (d As Double, e As Double, x As Double, t As Double, p As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub HSFLSHdll Lib "REFPROP.DLL" (h As Double, s As Double, Z As Double, t As Double, p As Double, d As Double, DI As Double, Dv As Double, xliq As

Double, xvap As Double, q As Double, e As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub ESFLSHdll Lib "REFPROP.DLL" (e As Double, s As Double, Z As Double, t As Double, p As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, h As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub CCRITdll Lib "REFPROP.DLL" (t As Double, p As Double, V As Double, x As Double, cs As Double, ts As Double, Ds As Double, ps As Double, ws As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub FPVdll Lib "REFPROP.DLL" (t As Double, d As Double, p As Double, x As Double, f As Double)

'private Declare Sub SPECGRdll Lib "REFPROP.DLL" (t As Double, d As Double, p As Double, Gr As Double)

Private Declare Sub TQFLSHdll Lib "REFPROP.DLL" (t As Double, q As Double, x As Double, kq As Long, p As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, e As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub PQFLSHdll Lib "REFPROP.DLL" (p As Double, q As Double, x As Double, kq As Long, t As Double, d As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, e As Double, h As Double, s As Double, cv As Double, cp As Double, w As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub ABFL1dll Lib "REFPROP.DLL" (a As Double, b As Double, x As Double, i As Long, ByVal ab As String, dmin As Double, dmax As Double, t As Double, p As Double, d As Double, ierr As Long, ByVal herr As String, ln1 As Long, ln2 As Long)

Private Declare Sub ABFL2dll Lib "REFPROP.DLL" (a As Double, b As Double, x As Double, kq As Long, ksat As Long, ByVal ab As String, tbub As Double, tdew As Double, pbub As Double, pdew As Double, Dlbub As Double, Dvdew As Double, ybub As Double, xdew As Double, t As Double, p As Double, DI As Double, Dv As Double, x As Double, y As Double, q As Double, ierr As Long, ByVal herr As String, ln As Long, ln2 As Long)

Private Declare Sub DBFL2dll Lib "REFPROP.DLL" (d As Double, b As Double, x As Double, i As Long, ByVal ab As String, t As Double, p As Double, DI As Double, Dv As Double, xliq As Double, xvap As Double, q As Double, ierr As Long, ByVal herr As String, ln As Long, ln2 As Long)

Private Declare Sub CRITPdll Lib "REFPROP.DLL" (x As Double, tc As Double, pc As Double, dc As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub VIRBdll Lib "REFPROP.DLL" (t As Double, x As Double, b As Double)

Private Declare Sub DBDTdll Lib "REFPROP.DLL" (t As Double, x As Double, dbt As Double)

Private Declare Sub VIRCdll Lib "REFPROP.DLL" (t As Double, x As Double, c As Double)

Private Declare Sub TRNPRdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, eta As Double, tcx As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub FGCTYdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, f As Double)

Private Declare Sub DIELECDll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, de As Double)

Private Declare Sub SURFTdll Lib "REFPROP.DLL" (t As Double, d As Double, x As Double, sigma As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub SURTENDll Lib "REFPROP.DLL" (t As Double, rhoL As Double, rhoV As Double, xl As Double, xv As Double, sigma As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub MELTTdll Lib "REFPROP.DLL" (t As Double, x As Double, p As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub MLTH2Odll Lib "REFPROP.DLL" (t As Double, P1 As Double, P2 As Double)

Private Declare Sub MELTPdll Lib "REFPROP.DLL" (p As Double, x As Double, t As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub SUBLTdll Lib "REFPROP.DLL" (t As Double, x As Double, p As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub SUBLPdll Lib "REFPROP.DLL" (p As Double, x As Double, t As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub WMOLDll Lib "REFPROP.DLL" (x As Double, wm As Double)

Private Declare Sub XMASSdll Lib "REFPROP.DLL" (xmol As Double, xkg As Double, wmix As Double)

Private Declare Sub XMOLEDll Lib "REFPROP.DLL" (xkg As Double, xmol As Double, wmix As Double)

Private Declare Sub QMASSdll Lib "REFPROP.DLL" (qmol As Double, xl As Double, xv As Double, qkg As Double, xlkg As Double, xvkg As Double, wliq As Double, wvap As Double, ierr As Long, ByVal herr As String, ln As Long)



Private Declare Sub QMOLEdll Lib "REFPROP.DLL" (qkg As Double, x1kg As Double, xvkg As Double, qmol As Double, xl As Double, xv As Double, wliq As Double, wvap As Double, ierr As Long, ByVal herr As String, ln As Long)

Private Declare Sub INFOdll Lib "REFPROP.DLL" (icomp As Long, wmm As Double, ttrp As Double, tnbpt As Double, tc As Double, pc As Double, dc As Double, Zc As Double, acf As Double, dip As Double, Rgas As Double)

Private Declare Sub LIMITXdll Lib "REFPROP.DLL" (ByVal htyp As String, t As Double, d As Double, p As Double, x As Double, tmin As Double, tmax As Double, dmax As Double, pmax As Double, ierr As Long, ByVal herr As String, ln1 As Long, ln2 As Long)

Private Declare Sub LIMITKdll Lib "REFPROP.DLL" (ByVal htyp As String, icomp As Long, t As Double, d As Double, p As Double, tmin As Double, tmax As Double, dmax As Double, pmax As Double, ierr As Long, ByVal herr As String, ln1 As Long, ln2 As Long)

Private Declare Sub SETKTVdll Lib "REFPROP.DLL" (icomp As Long, jcomp As Long, ByVal hmodij As String, fij As Double, ByVal hfmix As String, ierr As Long, ByVal herr As String, ln1 As Long, ln2 As Long, ln3 As Long)

Private Declare Sub GETKTVdll Lib "REFPROP.DLL" (icomp As Long, jcomp As Long, ByVal hmodij As String, fij As Double, ByVal hfmix As String, ByVal hfij As String, ByVal hbinp As String, ByVal hmxrul As String, ln1 As Long, ln2 As Long, ln3 As Long, ln4 As Long, ln5 As Long)

Private Declare Sub GETFIJdll Lib "REFPROP.DLL" (ByVal hmodij As String, fij As Double, ByVal hfij As String, ByVal hmxrul As String, ln1 As Long, ln2 As Long, ln3 As Long)

Private Declare Sub PREOSdll Lib "REFPROP.DLL" (i As Long)

Private Declare Sub SETAGAdll Lib "REFPROP.DLL" (ierr As Long, ByVal herr As String, ln1 As Long)

'Used to call Refprop:

Private herr As String \* 255, herr2 As String \* 255, hfmix As String \* 255, hfmix2 As String \* 255, hrf As String \* 3, htyp As String \* 3, hmxnme As String \* 255

Private hfld As String \* 10000

Private nc As Long, phase As Long

Private x(1 To MaxComps) As Double, xliq(1 To MaxComps) As Double, xvap(1 To MaxComps) As Double, xmm(1 To MaxComps) As Double, xkg(1 To MaxComps) As Double, xmol(1 To MaxComps) As Double, wmix As Double

Private ierr As Long, ierr2 As Long, kq As Long, kr As Long

Private t As Double, p As Double, d As Double, DI As Double, Dv As Double, q As Double, wm As Double, tz As Double, pz As Double, dz As Double, dd As Double

Private e As Double, h As Double, s As Double, Cvcalc As Double, Cpcalc As Double, w As Double

Private tmin As Double, tmax As Double, dmax As Double, pmax As Double

Private tc As Double, pc As Double, dc As Double

Private tbub As Double, tdew As Double, pbub As Double, pdew As Double, DIbub As Double, Dvdew As Double, ybub(1 To MaxComps) As Double, xdew(1 To MaxComps) As Double

Private eta As Double, tcx As Double, sigma As Double, hjt As Double, de As Double

Private wmm As Double, ttrp As Double, tnbpt As Double, Zc As Double, acf As Double, dip As Double, Rgas As Double

Private tUnits(10) As String, taUnits(10) As String, pUnits(10) As String, dUnits(10) As String, vUnits(10) As String, hUnits(10) As String, sUnits(10) As String, wUnits(10) As String, visUnits(10) As String, tcxUnits(10) As String, stUnits(10) As String

Private tUnits2 As String, taUnits2 As String, pUnits2 As String, dUnits2 As String, vUnits2 As String, hUnits2 As String, sUnits2 As String, wUnits2 As String, visUnits2 As String, tcxUnits2 As String, stUnits2 As String

Private FldOld As String

Private Z As Double, aHelm As Double, Gibbs As Double, xkappa As Double, beta As Double

Private dPdD As Double, d2PdD2 As Double, dPdT As Double, dDdT As Double, dDdP As Double

Private spare1 As Double, spare2 As Double, spare3 As Double, spare4 As Double

Private Const CtoK = 273.15 'Exact conversion

Private Const FtoR = 459.67 'Exact conversion

Private Const RtoK = 5 / 9 'Exact conversion

Private Const HtoS = 3600 'Exact conversion

Private Const ATMtoMPa = 0.101325 'Exact conversion

Private Const BARtoMPa = 0.1 'Exact conversion

Private Const KGfToN = 98.0665 / 10 'Exact conversion

Private Const INtoM = 0.0254 'Exact conversion

Private Const FTtoM = 12 \* INtoM 'Exact conversion

```

Private Const LBMtoKG = 0.45359237      'Exact conversion
Private Const CALtoJ = 4.184           'Exact conversion (tc)
'private Const CALtoJ = 4.1868         'Exact conversion (IT) (Use this one only with
pure water)
Private Const MMHGtoMPa = ATMtoMPa / 760 'Exact conversion
Private Const INH2OtoMPa = 0.000249082

```

```

Private Const BTUtoKJ = CALtoJ * LBMtoKG * RtoK
Private Const LBFtoN = LBMtoKG * KGfToN
Private Const IN3toM3 = INtoM * INtoM * INtoM
Private Const FT3toM3 = FTtoM * FTtoM * FTtoM
Private Const GALLONtoM3 = IN3toM3 * 231
Private Const PSIAtoMPa = LBMtoKG / INtoM / INtoM * KGfToN / 1000000
Private Const FTLBFtoJ = FTtoM * LBFtoN
Private Const HPtoW = 550 * FTLBFtoJ
Private Const BTUtoW = BTUtoKJ * 1000
Private Const LBFTtoNM = LBFtoN / FTtoM
Private CompFlag As Integer

```

```

Function Setup(FluidName)

```

```

    Dim a As String, ab As String, FluidNme As String, FlNme As String

```

```

    Dim i As Integer, sum As Double, sc As Integer, ncc As Integer, nc2 As Long, mass As
Integer

```

```

    Dim hRef As Double, sRef As Double, Tref As Double, pref As Double

```

```

    Dim htype As String * 3, hmix As String * 3, hcomp As String * 60

```

```

    Dim RPPrefix As String, FluidsPrefix As String, MixturesPrefix As String

```

```

    Dim xtemp(1 To MaxComps) As Double

```

```

    ierr = 0

```

```

    herr = ""

```

```

    FlNme = FluidName

```

```

If InStr(FluidName, "error") Then Exit Function
If InStr(FluidName, "Inputs are out of range") Then Exit Function
If FluidName = FldOld Then Exit Function
FldOld = ""
Call CheckName(FluidName)
RPPrefix = Environ("RPPrefix")
If RPPrefix = "" Then
    FluidsPrefix = FluidsDirectory
    MixturesPrefix = MixturesDirectory
Else
    FluidsPrefix = RPPrefix & "\" & FluidsDirectory
    MixturesPrefix = RPPrefix & "\" & MixturesDirectory
End If
hrf = "DEF"
hfmix = FluidsPrefix & "hmx.bnc"
On Error GoTo ErrorHandler:
ChDrive (Application.ActiveWorkbook.Path)
ChDir (Application.ActiveWorkbook.Path)
On Error GoTo 0
a = ""
For i = 1 To MaxComps: xtemp(i) = 0: Next
mass = 0
If InStr(UCase(FluidName), ".MIX") Then
    'Open MixturesPrefix & FluidName For Input As #1
    'Line Input #1, ab
    'Line Input #1, ab
    'Input #1, nc2
    'For i = 1 To nc2
    ' Line Input #1, ab

```

```

' a = a & FluidsPrefix & ab & "|"
'Next
'For i = 1 To nc2
' Input #1, xtemp(i)
'Next
'Close 1
'hfld = a

hmxnme = MixturesPrefix & FluidName

Call SETMIXdll(hmxnme, hfmix, hrf, nc2, hfld, xtemp(1), ierr, herr, 255&, 255&, 3&,
10000&, 255&)

ElseIf InStr(FluidName, ",") Or InStr(FluidName, ";") Then

FluidNme = Trim(FluidName)

If InStr(FluidNme, ";") Then sc = 1 Else sc = 0

If UCase(Right(FluidNme, 4)) = "MASS" Then mass = 1: FluidNme =
Trim(Left(FluidNme, Len(FluidNme) - 4))

nc2 = 0

Do

If sc = 0 Then i = InStr(FluidNme, ",") Else i = InStr(FluidNme, ";")

If i = 0 Then i = Len(FluidNme) + 1

nc2 = nc2 + 1

If nc2 > MaxComps Then ierr = 1: herr = Trim2("Too many components"): Exit
Function

ab = Trim(Left(FluidNme, i - 1))

Call CheckName(ab)

If InStr(LCase(ab), ".fld") = 0 Then ab = ab + ".fld"

a = a & FluidsPrefix & ab & "|"

FluidNme = Mid(FluidNme, i + 1)

If sc = 0 Then i = InStr(FluidNme, ",") Else i = InStr(FluidNme, ";")

If i = 0 Then i = Len(FluidNme) + 1

xtemp(nc2) = CDBl(Left(FluidNme, i - 1))

```

```

FluidNme = Trim(Mid(FluidNme, i + 1))
Loop Until FluidNme = ""
sum = 0
For i = 1 To nc2: sum = sum + xtemp(i): Next
If sum <= 0 Then ierr = 1: herr = Trim2("Composition not set"): Exit Function
For i = 1 To nc2: xtemp(i) = xtemp(i) / sum: Next
hfld = a
If nc2 < 1 Then ierr = 1: herr = Trim2("Setup failed"): Exit Function
'To load the GERG-2004 pure fluid equations of state rather than the defaults
'that come with Refprop, call the GERG04dll routine with a 1 as the second input.
'Call GERG04dll(nc2, 1&, ierr, herr, 255&)
Call SETUPdll(nc2, hfld, hfmix, hrf, ierr, herr, 10000&, 255&, 3&, 255&)
ElseIf InStr(FluidName, "/" ) <> 0 And InStr(FluidName, "(" ) <> 0 Then
FluidNme = Trim(FluidName)
If UCase(Right(FluidNme, 4)) = "MASS" Then mass = 1: FluidNme =
Trim(Left(FluidNme, Len(FluidNme) - 4))
nc2 = 0
Do
i = InStr(FluidNme, "/" )
If InStr(FluidNme, "(" ) < i Then i = InStr(FluidNme, "(" )
If i = 0 Then i = Len(FluidNme) + 1
nc2 = nc2 + 1
If nc2 > MaxComps Then ierr = 1: herr = Trim2("Too many components"): Exit
Function
ab = Trim(Left(FluidNme, i - 1))
Call CheckName(ab)
If InStr(LCase(ab), ".fld") = 0 Then ab = ab + ".fld"
a = a & FluidsPrefix & ab & "|"
FluidNme = Trim(Mid(FluidNme, i))
If Left(FluidNme, 1) = "/" Then FluidNme = Trim(Mid(FluidNme, 2))

```

```

Loop Until Left(FluidNme, 1) = "("
FluidNme = Mid(FluidNme, 2)
If Right(FluidNme, 1) = ")" Then FluidNme = Trim(Left(FluidNme, Len(FluidNme) - 1))
ncc = 0
Do
  i = InStr(FluidNme, "/")
  If i = 0 Then i = Len(FluidNme) + 1
  ncc = ncc + 1
  If ncc > MaxComps Then ierr = 1: herr = Trim2("Too many components"): Exit
Function
  xtemp(ncc) = CDBl(Left(FluidNme, i - 1))
  FluidNme = Mid(FluidNme, i + 1)
Loop Until FluidNme = ""
sum = 0
For i = 1 To nc2: sum = sum + xtemp(i): Next
If sum <= 0 Then ierr = 1: herr = Trim2("Composition not set"): Exit Function
For i = 1 To nc2: xtemp(i) = xtemp(i) / sum: Next
hfld = a
If nc2 < 1 Then ierr = 1: herr = Trim2("Setup failed"): Exit Function
'To load the GERG-2004 pure fluid equations of state rather than the defaults
'that come with Refprop, call the GERG04dll routine with a 1 as the second input.
'Call GERG04dll(nc2, 1&, ierr, herr, 255&)
Call SETUPdll(nc2, hfld, hfmix, hrf, ierr, herr, 10000&, 255&, 3&, 255&)
Else
  nc2 = 1
  If InStr(LCase(FluidName), ".fld") = 0 And InStr(LCase(FluidName), ".ppf") = 0 Then
FluidName = FluidName + ".fld"
  If InStr(FluidName, "\") Then
    hfld = FluidName
  Else

```



```

    hfld = FluidsPrefix & FluidName
End If

'...Use call to SETMOD to change the equation of state for any of the
'....pure components from the default (recommended) values.
'....This should only be implemented by an experienced user.
If InStr(LCase(hfld), "argon") <> 0 And nc2 = 1 Then
' hcomp = "FE1": htype = "EOS": hmix = hcomp
' Call SETMODdll(nc2, htype, hmix, hcomp, ierr, herr, 3&, 3&, 60&, 255&)
End If

Call SETUPdll(nc2, hfld, hfmix, hrf, ierr, herr, 10000&, 255&, 3&, 255&)
End If

If mass Then
    For i = 1 To nc2
        xkg(i) = xtemp(i)
    Next
    Call XMOLEdll(xkg(1), xtemp(1), wmix)
End If

If ierr <= 0 Then
    nc = nc2      'If setup was successful, load new values of nc and x()
    For i = 1 To nc
        x(i) = xtemp(i)
    Next
    Setup = FluidName
    FldOld = FINme
    'Use the following line to calculate enthalpies and entropies on a reference state

```

'based on the currently defined mixture, or to change to some other reference state.

'The routine does not have to be called, but doing so will cause calculations

'to be the same as those produced from the graphical interface for mixtures.

Call SETREFdll(hrf, 2&, x(1), hRef, sRef, Tref, pref, ierr, herr, 3&, 255&)

Else

Setup = Trim2(herr)

FldOld = ""

End If

Exit Function

ErrorHandler:

Resume Next

End Function

Sub CheckName(FluidName)

Restart:

If Left(FluidName, 1) = Chr(34) Then

FluidName = Mid(FluidName, 2): GoTo Restart

End If

If Right(FluidName, 1) = Chr(34) Then

FluidName = Left(FluidName, Len(FluidName) - 1): GoTo Restart

End If

If UCase(FluidName) = "AIR" Then FluidName =  
"nitrogen;7812;argon;0092;oxygen;2096"

If UCase(FluidName) = "CARBON DIOXIDE" Then FluidName = "CO2"

If UCase(FluidName) = "CARBON MONOXIDE" Then FluidName = "CO"

If UCase(FluidName) = "CARBONYL SULFIDE" Then FluidName = "COS"

If UCase(FluidName) = "CYCLOHEXANE" Then FluidName = "CYCLOHEX"

If UCase(FluidName) = "CYCLOPROPANE" Then FluidName = "CYCLOPRO"

If UCase(FluidName) = "DEUTERIUM" Then FluidName = "D2"

```

If UCase(FluidName) = "HEAVY WATER" Then FluidName = "D2O"
If UCase(FluidName) = "HYDROGEN SULFIDE" Then FluidName = "H2S"
If UCase(FluidName) = "IBUTANE" Then FluidName = "ISOBUTAN"
If UCase(FluidName) = "ISOBUTANE" Then FluidName = "ISOBUTAN"
If UCase(FluidName) = "ISOPENTANE" Then FluidName = "IPENTANE"
If UCase(FluidName) = "NEOPENTANE" Then FluidName = "NEOPENTN"
If UCase(FluidName) = "ISOHEXANE" Then FluidName = "IHEXANE"
If UCase(FluidName) = "NITROUS OXIDE" Then FluidName = "N2O"
If UCase(FluidName) = "PARAHYDROGEN" Then FluidName = "PARAHYD"
If UCase(FluidName) = "PROPYLENE" Then FluidName = "PROPYLEN"
If UCase(FluidName) = "SULFUR HEXAFLUORIDE" Then FluidName = "SF6"
End Sub

```

```

Sub CalcSetup(FluidName, InpCode, Units, Prop1, Prop2)
    Call Setup(FluidName)
    If ierr > 0 Then Exit Sub
    Call ConvertUnits(InpCode, Units, Prop1, Prop2)
    herr = ""
    q = 0: t = 0: p = 0: d = 0: D1 = 0: Dv = 0: e = 0: h = 0: s = 0: Cvcalc = 0: Cpcalc = 0: w = 0
End Sub

```

```

Sub CalcProp(FluidName, InpCode, ByVal Units, ByVal Prop1, ByVal Prop2)
    Dim iflag1 As Integer, iflag2 As Integer
    ThisWorkbook.Activate
    q = 0: t = 0: p = 0: d = 0: D1 = 0: Dv = 0: e = 0: h = 0: s = 0: Cvcalc = 0: Cpcalc = 0: w = 0
    If IsMissing(Prop1) Then iflag1 = 1
    If iflag1 = 0 Then
        If Len(Trim(Prop1)) = 0 Then iflag1 = 2
    End If

```

```

    If iflag1 = 0 Then If CDBl(Prop1) = 0 And Prop1 <> "0" Then ierr = 1: herr =
Trim2("Invalid input: ") + Prop1: Exit Sub

End If

If IsMissing(Prop2) Then iflag2 = 1

If iflag2 = 0 Then

    If Len(Trim(Prop2)) = 0 Then iflag2 = 2

    If iflag2 = 0 Then If CDBl(Prop2) = 0 And Prop2 <> "0" Then ierr = 1: herr =
Trim2("Invalid input: ") + Prop2: Exit Sub

End If

If IsMissing(InpCode) Then InpCode = ""

Call CalcSetup(FluidName, InpCode, Units, Prop1, Prop2)

If UCase(Left(InpCode, 4)) = "CRIT" Then

    Call CRITPdll(x(1), t, p, d, ierr, herr, 255&)

    If ierr = 0 Then Call THERMdll(t, d, x(1), pc, e, h, s, Cvcalc, Cpcalc, w, hjt)

    Exit Sub

ElseIf UCase(Left(InpCode, 4)) = "TRIP" Then

    If nc <> 1 Then ierr = 1: herr = Trim2("Can only return triple point for a pure fluid"): Exit
Sub

    Call INFOdll(1, wmm, t, tnbpt, tc, pc, dc, Zc, acf, dip, Rgas)

    Call SATTdll(t, x(1), 1, p, d, Dv, xliq(1), xvap(1), ierr, herr, 255&)

    If ierr = 0 Then Call THERMdll(t, d, x(1), pc, e, h, s, Cvcalc, Cpcalc, w, hjt)

    Exit Sub

End If

If iflag1 Then ierr = 1: herr = Trim2("Inputs are missing"): Exit Sub

If ierr > 0 Then Exit Sub

If InpCode <> "" Then Call Calc(InpCode, Prop1, Prop2, iflag1, iflag2)

End Sub

Sub Calc(InputCode, Prop1, Prop2, iflag1, iflag2)

```

```

Dim a As String, Input1 As String, Input2 As String, InpCode, i As Integer, pp As Double
ierr = 0
herr = ""
InpCode = Trim(UCase(InputCode))
Input2 = ""
Input1 = Left(InpCode, 1)
If Len(InpCode) = 2 Then Input2 = Mid(InpCode, 2, 1)
If Len(InpCode) = 3 And Right(InpCode, 1) = "&" Then Input2 = Mid(InpCode, 2, 1)
If Left(InpCode, 2) = "TP" Or Left(InpCode, 2) = "PT" Then Input2 = Mid(InpCode, 2, 1)

If Input1 = "T" Then t = Prop1: If iflag1 >= 1 Then GoTo Error1
If Input1 = "P" Then p = Prop1: If iflag1 >= 1 Then GoTo Error1
If Input1 = "D" Then d = Prop1: If iflag1 >= 1 Then GoTo Error1
If Input1 = "V" And Prop1 <> 0 And Len(InpCode) = 2 Then d = 1 / Prop1: Mid(InpCode,
1, 1) = "D": If iflag1 >= 1 Then GoTo Error1
If Input1 = "E" Then e = Prop1: If iflag1 >= 1 Then GoTo Error1
If Input1 = "H" Then h = Prop1: If iflag1 >= 1 Then GoTo Error1
If Input1 = "S" Then s = Prop1: If iflag1 >= 1 Then GoTo Error1
If Input1 = "Q" Then q = Prop1: If iflag1 >= 1 Then GoTo Error1
If Input2 = "T" Then t = Prop2: If iflag2 >= 1 Then GoTo Error2
If Input2 = "P" Then p = Prop2: If iflag2 >= 1 Then GoTo Error2
If Input2 = "D" Then d = Prop2: If iflag2 >= 1 Then GoTo Error2
If Input2 = "V" And Prop2 <> 0 And Len(InpCode) = 2 Then d = 1 / Prop2: Mid(InpCode,
2, 1) = "D": If iflag2 >= 1 Then GoTo Error2
If Input2 = "E" Then e = Prop2: If iflag2 >= 1 Then GoTo Error2
If Input2 = "H" Then h = Prop2: If iflag2 >= 1 Then GoTo Error2
If Input2 = "S" Then s = Prop2: If iflag2 >= 1 Then GoTo Error2
If Input2 = "Q" Then q = Prop2: If iflag2 >= 1 Then GoTo Error2

phase = 2

```

```

If Len(InpCode) > 1 Then If UCase(Mid(InpCode, 2, 1)) = "L" Then phase = 1

For i = 1 To nc
    xliq(i) = 0: xvap(i) = 0
Next

If Left(InpCode, 1) = "T" And t <= 0 Then herr = Trim2("Input temperature is zero"): Exit Sub

'Calculate saturation values given temperature
If InpCode = "TL" Or InpCode = "TLIQ" Or InpCode = "TVAP" Then
    Call SATTdll(t, x(1), phase, p, Dl, Dv, xliq(1), xvap(1), ierr, herr, 255&)
    If (p = 0 Or Dl = 0) And ierr = 0 Then ierr = 1: herr = Trim2("Inputs are out of range"): Exit Sub
    d = Dl: q = 0
    If phase = 2 Then d = Dv: q = 1
    Call THERMdll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, hjt)
'Calculate saturation values given pressure
ElseIf InpCode = "PL" Or InpCode = "PLIQ" Or InpCode = "PVAP" Then
    Call SATPdll(p, x(1), phase, t, Dl, Dv, xliq(1), xvap(1), ierr, herr, 255&)
    If (p = 0 Or Dl = 0) And ierr = 0 Then ierr = 1: herr = Trim2("Inputs are out of range"): Exit Sub
    d = Dl: q = 0
    If phase = 2 Then d = Dv: q = 1
    Call THERMdll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, hjt)
'Calculate saturation values given density
ElseIf InpCode = "DL" Or InpCode = "DLIQ" Or InpCode = "DVAP" Then
    Call SATDdll(d, x(1), 1&, kr, t, p, Dl, Dv, xliq(1), xvap(1), ierr, herr, 255&)
    Call THERMdll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, hjt)
    q = kr - 1
ElseIf InpCode = "TPL" Or InpCode = "PTL" Then
    Call TPRHODll(t, p, x(1), 1&, 0&, d, ierr, herr, 255&)

```

```

DI = d: Dv = d: q = 990
Call THERMdll(t, d, x(1), pp, e, h, s, Cvcalc, Cpcalc, w, hjt)
ElseIf InpCode = "TPV" Or InpCode = "PTV" Then
Call TPRHODll(t, p, x(1), 2&, 0&, d, ierr, herr, 255&)
DI = d: Dv = d: q = 990
Call THERMdll(t, d, x(1), pp, e, h, s, Cvcalc, Cpcalc, w, hjt)
ElseIf InpCode = "TP" Or InpCode = "PT" Then
Call TPFLSHdll(t, p, x(1), d, DI, Dv, xliq(1), xvap(1), q, e, h, s, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "TD" Or InpCode = "DT" Then
Call TDFLSHdll(t, d, x(1), p, DI, Dv, xliq(1), xvap(1), q, e, h, s, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "TD&" Or InpCode = "DT&" Then
'Do not perform any flash calculation here
Call THERMdll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, hjt)
q = 990
ElseIf InpCode = "TH" Or InpCode = "HT" Then
Call THFLSHdll(t, h, x(1), 2&, p, d, DI, Dv, xliq(1), xvap(1), q, e, s, Cvcalc, Cpcalc, w,
ierr, herr, 255&)
ElseIf InpCode = "TS" Or InpCode = "ST" Then
Call TSFLSHdll(t, s, x(1), 1&, p, d, DI, Dv, xliq(1), xvap(1), q, e, h, Cvcalc, Cpcalc, w,
ierr, herr, 255&)
ElseIf InpCode = "TE" Or InpCode = "ET" Then
Call TEFLSHdll(t, e, x(1), 2&, p, d, DI, Dv, xliq(1), xvap(1), q, h, s, Cvcalc, Cpcalc, w,
ierr, herr, 255&)
ElseIf InpCode = "TQ" Or InpCode = "QT" Then
Call TQFLSHdll(t, q, x(1), 1&, p, d, DI, Dv, xliq(1), xvap(1), e, h, s, Cvcalc, Cpcalc, w,
ierr, herr, 255&)
ElseIf InpCode = "PD" Or InpCode = "DP" Then
Call PDFLSHdll(p, d, x(1), t, DI, Dv, xliq(1), xvap(1), q, e, h, s, Cvcalc, Cpcalc, w, ierr,
herr, 255&)

```



```

ElseIf InpCode = "PH" Or InpCode = "HP" Then
    Call PHFLSHdll(p, h, x(1), t, d, Dl, Dv, xliq(1), xvap(1), q, e, s, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "PS" Or InpCode = "SP" Then
    Call PSFLSHdll(p, s, x(1), t, d, Dl, Dv, xliq(1), xvap(1), q, e, h, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "PE" Or InpCode = "EP" Then
    Call PEFLSHdll(p, e, x(1), t, d, Dl, Dv, xliq(1), xvap(1), q, h, s, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "PQ" Or InpCode = "QP" Then
    Call PQFLSHdll(p, q, x(1), 1&, t, d, Dl, Dv, xliq(1), xvap(1), e, h, s, Cvcalc, Cpcalc, w,
ierr, herr, 255&)
ElseIf InpCode = "DH" Or InpCode = "HD" Then
    Call DHFLSHdll(d, h, x(1), t, p, Dl, Dv, xliq(1), xvap(1), q, e, s, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "DS" Or InpCode = "SD" Then
    Call DSFLSHdll(d, s, x(1), t, p, Dl, Dv, xliq(1), xvap(1), q, e, h, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "DE" Or InpCode = "ED" Then
    Call DEFLSHdll(d, e, x(1), t, p, Dl, Dv, xliq(1), xvap(1), q, h, s, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "HS" Or InpCode = "SH" Then
    Call HSFLSHdll(h, s, x(1), t, p, d, Dl, Dv, xliq(1), xvap(1), q, e, Cvcalc, Cpcalc, w, ierr,
herr, 255&)
ElseIf InpCode = "TMELT" Then
    Call MELTTdll(t, x(1), p, ierr, herr, 255&)
    If ierr = 0 Then Call TPFLSHdll(t, p, x(1), d, Dl, Dv, xliq(1), xvap(1), q, e, h, s, Cvcalc,
Cpcalc, w, ierr, herr, 255&)
ElseIf InpCode = "PMELT" Then
    If p = 0 Then ierr = 1: herr = Trim2("Input pressure is zero"): Exit Sub
    Call MELTPdll(p, x(1), t, ierr, herr, 255&)

```

```
    If ierr = 0 Then Call TPFLSHdll(t, p, x(1), d, D1, Dv, xliq(1), xvap(1), q, e, h, s, Cvcalc, Cpcalc, w, ierr, herr, 255&)
```

```
  ElseIf InpCode = "TSUBL" Then
```

```
    Call SUBLTdll(t, x(1), p, ierr, herr, 255&)
```

```
    If ierr = 0 And p = 0 Then ierr = 1: herr = Trim2("No sublimation line available")
```

```
    If ierr = 0 Then
```

```
      q = 1
```

```
      d = p / 8.314472 / t
```

```
      Call TPRHodll(t, p, x(1), 2&, 1&, d, ierr, herr, 255&)
```

```
      Call THERMdll(t, d, x(1), pp, e, h, s, Cvcalc, Cpcalc, w, hjt)
```

```
    End If
```

```
  ElseIf InpCode = "PSUBL" Then
```

```
    If p = 0 Then ierr = 1: herr = Trim2("Input pressure is zero"): Exit Sub
```

```
    Call SUBLPdll(p, x(1), t, ierr, herr, 255&)
```

```
    If ierr = 0 And t = 0 Then ierr = 1: herr = Trim2("No sublimation line available")
```

```
    If ierr = 0 Then
```

```
      q = 1
```

```
      d = p / 8.314472 / t
```

```
      Call TPRHodll(t, p, x(1), 2&, 1&, d, ierr, herr, 255&)
```

```
      Call THERMdll(t, d, x(1), pp, e, h, s, Cvcalc, Cpcalc, w, hjt)
```

```
    End If
```

```
  Else
```

```
    ierr = 1: herr = Trim2("Invalid input code")
```

```
  End If
```

```
  If (q <= 0.000001 Or q >= 0.999999) And Cvcalc = -9999980 Then Call THERMdll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, hjt)
```

```
  Exit Sub
```

```
Error1:
```

```
  ierr = 1: herr = Trim2("First property missing"): Exit Sub
```

```
Error2:
```

```

ierr = 1: herr = Trim2("Second property missing"): Exit Sub
End Sub

Function Temperature(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Temperature = ConvertUnits("-T", Units, t, 0)
End Function

Function Pressure(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Pressure = ConvertUnits("-P", Units, p, 0)
End Function

Function Density(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Density = ConvertUnits("-D", Units, d, 0)
End Function

Function CompressibilityFactor(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Call INFOdll(1, wmm, ttrp, tnbpt, tc, pc, dc, Zc, acf, dip, Rgas)
    CompressibilityFactor = p / d / t / Rgas
End Function

Function LiquidDensity(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    If ierr <> 0 Then LiquidDensity = Trim2(herr): Exit Function
    If q < 0 Or q > 1 Then
        LiquidDensity = Trim2("Inputs are single phase")
    Else
        CompFlag = 1
        LiquidDensity = ConvertUnits("-D", Units, D1, 0)
    End If
End Function

```

```

    CompFlag = 0
End If
End Function

Function VaporDensity(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    If ierr <> 0 Then VaporDensity = Trim2(herr): Exit Function
    If q < 0 Or q > 1 Then
        VaporDensity = Trim2("Inputs are single phase")
    Else
        CompFlag = 2
        VaporDensity = ConvertUnits("-D", Units, Dv, 0)
        CompFlag = 0
    End If
End Function

Function Volume(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Dim V As Double
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Volume = 0
    If d <= 0 Then Volume = Trim2("Density is zero"): Exit Function
    V = 1 / d
    Volume = ConvertUnits("-V", Units, V, 0)
End Function

Function Energy(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Energy = ConvertUnits("-H", Units, e, 0)
End Function

```

```
Function Enthalpy(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Enthalpy = ConvertUnits("-H", Units, h, 0)
End Function
```

```
Function Entropy(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Entropy = ConvertUnits("-S", Units, s, 0)
End Function
```

```
Function IsochoricHeatCapacity(FluidName, InpCode, Optional Units, Optional Prop1,
Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    IsochoricHeatCapacity = ConvertUnits("-S", Units, Cvcalc, 0)
End Function
```

```
Function cv(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    cv = ConvertUnits("-S", Units, Cvcalc, 0)
End Function
```

```
Function IsobaricHeatCapacity(FluidName, InpCode, Optional Units, Optional Prop1,
Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    IsobaricHeatCapacity = ConvertUnits("-S", Units, Cpcalc, 0)
End Function
```

```
Function cp(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    cp = ConvertUnits("-S", Units, Cpcalc, 0)
```

End Function

```
Function SpeedOfSound(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
```

```
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
```

```
    SpeedOfSound = ConvertUnits("-W", Units, w, 0)
```

End Function

```
Function Sound(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
```

```
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
```

```
    Sound = ConvertUnits("-W", Units, w, 0)
```

End Function

```
Function LatentHeat(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
```

```
    Dim hl As Double, hv As Double
```

```
    InpCode = Trim(UCase(InpCode))
```

```
    If Left(InpCode, 1) = "T" Then
```

```
        Call CalcSetup(FluidName, "T", Units, Prop1, Prop2)
```

```
        If ierr <> 0 Then LatentHeat = Trim2(herr): Exit Function
```

```
        If nc <> 1 Then LatentHeat = Trim2("Can only be calculated for pure fluids"): Exit Function
```

```
        Call INFOdll(1, wmm, ttrp, tnbpt, tc, pc, dc, Zc, acf, dip, Rgas)
```

```
        t = Prop1
```

```
        If t <= 0 Then LatentHeat = Trim2("Input temperature is zero"): Exit Function
```

```
        If t > tc Then LatentHeat = Trim2("Temperature is greater than the critical point temperature"): Exit Function
```

```
        Call SATTDll(t, x(1), 1&, p, Dl, Dv, xliq(1), xvap(1), ierr, herr, 255&)
```

```
        If (p = 0 Or Dl = 0) And ierr = 0 Then ierr = 1: LatentHeat = Trim2("Inputs are out of range"): Exit Function
```

```
    ElseIf Left(InpCode, 1) = "P" Then
```

```

Call CalcSetup(FluidName, "P", Units, Prop1, Prop2)
If ierr <> 0 Then LatentHeat = Trim2(herr): Exit Function

If nc <> 1 Then LatentHeat = Trim2("Can only be calculated for pure fluids"): Exit
Function

Call INFOdll(1, wmm, ttrp, tnbpt, tc, pc, dc, Zc, acf, dip, Rgas)

p = Prop1

If p <= 0 Then LatentHeat = Trim2("Input pressure is zero"): Exit Function

If p > pc Then LatentHeat = Trim2("Pressure is greater than the critical point pressure"):
Exit Function

Call SATPdll(p, x(1), 1&, t, D1, Dv, xliq(1), xvap(1), ierr, herr, 255&)

If (t = 0 Or D1 = 0) And ierr = 0 Then ierr = 1: LatentHeat = Trim2("Inputs are out of
range"): Exit Function

Else

LatentHeat = Trim2("Valid inputs are only 'T' or 'P'"): Exit Function

End If

If ierr <> 0 Then LatentHeat = Trim2(herr): Exit Function

Call THERMdll(t, D1, x(1), p, e, hl, s, Cvcalc, Cpcalc, w, hjt)

Call THERMdll(t, Dv, x(1), p, e, hv, s, Cvcalc, Cpcalc, w, hjt)

LatentHeat = ConvertUnits("-H", Units, hv - hl, 0)

End Function

```

```

Function HeatOfVaporization(FluidName, InpCode, Optional Units, Optional Prop1,
Optional Prop2)

HeatOfVaporization = LatentHeat(FluidName, InpCode, Units, Prop1, Prop2)

End Function

```

```

Function JouleThompson(FluidName, InpCode, Optional Units, Optional Prop1, Optional
Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

Call THERMdll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, hjt)

JouleThompson = ConvertUnits("-J", Units, hjt, 0)

```



End Function

Function IsentropicExpansionCoef(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

Call THERMdll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, hjt)

Call INFOdll(1, wmm, ttrp, tnbpt, tc, pc, dc, Zc, acf, dip, Rgas)

Call WMOLdll(x(1), wm)

If d = 0 Then

IsentropicExpansionCoef =  $w^2 / R_{gas} / t * wm * 0.001$

Else

IsentropicExpansionCoef =  $w^2 * d / p * wm * 0.001$

End If

End Function

Function IsothermalCompressibility(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

Call THERM2dll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, Z, hjt, aHelm, Gibbs, xkappa, beta, dPdD, d2PdD2, dPdT, dDdT, dDdP, spare1, spare2, spare3, spare4)

IsothermalCompressibility = Trim2("Infinite")

If d > 1E-20 And Not (xkappa = -9999990 Or xkappa > 1E+15) Then  
IsothermalCompressibility = 1 / ConvertUnits("-P", Units, 1 / xkappa, 0)

End Function

Function VolumeExpansivity(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

Call THERM2dll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, Z, hjt, aHelm, Gibbs, xkappa, beta, dPdD, d2PdD2, dPdT, dDdT, dDdP, spare1, spare2, spare3, spare4)

VolumeExpansivity = 1 / ConvertUnits("-A", Units, 1 / beta, 0)

End Function

Function AdiabaticCompressibility(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

Call THERM2dll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, Z, hjt, aHelm, Gibbs, xkappa, beta, dPdD, d2PdD2, dPdT, dDdT, dDdP, spare1, spare2, spare3, spare4)

Call WMOLdll(x(1), wm)

AdiabaticCompressibility = Trim2("Infinite")

If d > 1E-20 And w <> 0 Then AdiabaticCompressibility = 1 / ConvertUnits("-P", Units, 1 / (1 / d / w ^ 2 / wm \* 1000), 0)

End Function

Function AdiabaticBulkModulus(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

Call THERM2dll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, Z, hjt, aHelm, Gibbs, xkappa, beta, dPdD, d2PdD2, dPdT, dDdT, dDdP, spare1, spare2, spare3, spare4)

Call WMOLdll(x(1), wm)

If p = 0 Then

AdiabaticBulkModulus = 0

Else

AdiabaticBulkModulus = ConvertUnits("-P", Units, w ^ 2 \* d \* wm \* 0.001, 0)

End If

End Function

Function IsothermalExpansionCoef(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

Call THERM2dll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, Z, hjt, aHelm, Gibbs, xkappa, beta, dPdD, d2PdD2, dPdT, dDdT, dDdP, spare1, spare2, spare3, spare4)

```

Call WMOLdll(x(1), wm)
If p = 0 Then
    IsothermalExpansionCoef = 1
Else
    IsothermalExpansionCoef = d / p * dPdD
End If
End Function

```

```

Function IsothermalBulkModulus(FluidName, InpCode, Optional Units, Optional Prop1,
Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    Call THERM2dll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, Z, hjt, aHelm, Gibbs, xkappa,
beta, dPdD, d2PdD2, dPdT, dDdT, dDdP, spare1, spare2, spare3, spare4)
    Call WMOLdll(x(1), wm)
    If p = 0 Then
        IsothermalBulkModulus = 0
    Else
        IsothermalBulkModulus = ConvertUnits("-P", Units, d * dPdD, 0)
    End If
End Function

```

```

Function Quality(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    If ierr > 0 Then Quality = Trim2(herr): Exit Function
    Quality = q
    If q = 990 Then Quality = Trim2("Not calculated")
    If q = 998 Then Quality = Trim2("Superheated vapor with T>Tc")
    If q = 999 Then Quality = Trim2("Supercritical state (T>Tc, p>pc)")
    If q = -998 Then Quality = Trim2("Subcooled liquid with p>pc")

```

End Function

```
Function LiquidMoleFraction(FluidName, Optional InpCode, Optional Units, Optional Prop1, Optional Prop2, Optional i)
```

```
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
```

```
    If ierr > 0 Then LiquidMoleFraction = Trim2(herr): Exit Function
```

```
    If i < 1 Or i > nc Then LiquidMoleFraction = Trim2("Constituent number out of range"): Exit Function
```

```
    If q < 0 Or q > 1 Then
```

```
        LiquidMoleFraction = x(i)
```

```
    Else
```

```
        LiquidMoleFraction = xliq(i)
```

```
    End If
```

```
    If nc = 1 Then LiquidMoleFraction = Trim2("Not applicable for a pure fluid")
```

End Function

```
Function VaporMoleFraction(FluidName, Optional InpCode, Optional Units, Optional Prop1, Optional Prop2, Optional i)
```

```
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
```

```
    If ierr > 0 Then VaporMoleFraction = Trim2(herr): Exit Function
```

```
    If i < 1 Or i > nc Then VaporMoleFraction = Trim2("Constituent number out of range"): Exit Function
```

```
    If q < 0 Or q > 1 Then
```

```
        VaporMoleFraction = x(i)
```

```
    Else
```

```
        VaporMoleFraction = xvap(i)
```

```
    End If
```

```
    If nc = 1 Then VaporMoleFraction = Trim2("Not applicable for a pure fluid")
```

End Function

```

Function Viscosity(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    If ierr > 0 Then Viscosity = Trim2(herr): Exit Function
    If t = 0 Or d = 0 Then Viscosity = Trim2("Inputs out of range"): Exit Function
    Call TRNPRPdll(t, d, x(1), eta, tcx, ierr2, herr2, 255&)
    If q > 0.000001 And q < 1 - 0.000001 Then eta = -9999999
    Viscosity = ConvertUnits("-U", Units, eta, 0)
    If eta = 0 Then Viscosity = Trim2("Unable to calculate property")
End Function

```

```

Function ThermalConductivity(FluidName, InpCode, Optional Units, Optional Prop1,
Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    If ierr > 0 Then ThermalConductivity = Trim2(herr): Exit Function
    If t = 0 Or d = 0 Then ThermalConductivity = Trim2("Inputs out of range"): Exit Function
    Call TRNPRPdll(t, d, x(1), eta, tcx, ierr2, herr2, 255&)
    If q > 0.000001 And q < 1 - 0.000001 Then tcx = -9999999
    ThermalConductivity = ConvertUnits("-K", Units, tcx, 0)
    If tcx = 0 Then ThermalConductivity = Trim2("Unable to calculate property")
End Function

```

```

Function Prandtl(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)
    Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)
    If ierr > 0 Then Prandtl = Trim2(herr): Exit Function
    If t = 0 Or d = 0 Then Prandtl = Trim2("Inputs out of range"): Exit Function
    Call TRNPRPdll(t, d, x(1), eta, tcx, ierr2, herr2, 255&)
    If q > 0.000001 And q < 1 - 0.000001 Then Prandtl = Trim2("Undefined"): Exit Function
    If tcx = 0 Or eta = 0 Then Prandtl = Trim2("Unable to calculate property")

```

Call THERMdll(t, d, x(1), p, e, h, s, Cvcalc, Cpcalc, w, hjt)

Call WMOLdll(x(1), wm)

Prandtl = eta \* Cpcalc / tcx / wm / 1000

End Function

Function SurfaceTension(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

If ierr > 0 Then SurfaceTension = Trim2(herr): Exit Function

If t = 0 Then SurfaceTension = Trim2("Input temperature is zero"): Exit Function

If q >= 0 And q <= 1 Then

Call SURFTdll(t, Dl, xliq(1), sigma, ierr2, herr2, 255&)

Else

Call SURFTdll(t, d, x(1), sigma, ierr2, herr2, 255&)

End If

SurfaceTension = ConvertUnits("-N", Units, sigma, 0)

If sigma = 0 Or ierr2 <> 0 Then SurfaceTension = Trim2("Inputs out of range")

End Function

Function DielectricConstant(FluidName, InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcProp(FluidName, InpCode, Units, Prop1, Prop2)

If ierr > 0 Then DielectricConstant = Trim2(herr): Exit Function

If q > 0.000001 And q < 1 - 0.000001 Then DielectricConstant = Trim2("Undefined"): Exit Function

If t = 0 Then DielectricConstant = Trim2("Inputs out of range"): Exit Function

Call DIELECDll(t, d, x(1), de)

DielectricConstant = de

End Function

```
Function MolarMass(FluidName, Optional InpCode, Optional Units, Optional Prop1,  
Optional Prop2)
```

```
    Call CalcSetup(FluidName, "", Units, Prop1, Prop2)
```

```
    Call WMOLdll(x(1), wm)
```

```
    MolarMass = wm
```

```
End Function
```

```
Function MoleFraction(FluidName, i)
```

```
    Call CalcProp(FluidName, "", "", 0, 0)
```

```
    If ierr > 0 Then MoleFraction = Trim2(herr): Exit Function
```

```
    If i < 1 Or i > nc Then MoleFraction = Trim2("Constituent number out of range"): Exit  
Function
```

```
    MoleFraction = x(i)
```

```
    If nc = 1 Then MoleFraction = Trim2("Not applicable for a pure fluid")
```

```
End Function
```

```
Function MassFraction(FluidName, i)
```

```
    Call CalcProp(FluidName, "", "", 0, 0)
```

```
    If ierr > 0 Then MassFraction = Trim2(herr): Exit Function
```

```
    If i < 1 Or i > nc Then MassFraction = Trim2("Constituent number out of range"): Exit  
Function
```

```
    Call XMASSdll(x(1), xmm(1), wm)
```

```
    MassFraction = xmm(i)
```

```
    If nc = 1 Then MassFraction = Trim2("Not applicable for a pure fluid")
```

```
End Function
```

'Change molar composition to mass composition

'Prop1 - Prop20 are the molar values for the components in the mixture.

'i specifies which component's mole fraction is returned. If zero, the molar mass is returned



Function Mole2Mass(FluidName, i, Prop1, Prop2, Optional Prop3, Optional Prop4, Optional Prop5, Optional Prop6, Optional Prop7, Optional Prop8, Optional Prop9, Optional Prop10, Optional Prop11, Optional Prop12, Optional Prop13, Optional Prop14, Optional Prop15, Optional Prop16, Optional Prop17, Optional Prop18, Optional Prop19, Optional Prop20)

Dim j As Integer, xkg2(1 To MaxComps) As Double, xmol2(1 To MaxComps) As Double, wmix2 As Double, sum As Double

For j = 1 To MaxComps: xmol2(j) = 0: Next

xmol2(1) = Prop1

xmol2(2) = Prop2

If Not IsMissing(Prop3) Then xmol2(3) = Prop3

If Not IsMissing(Prop4) Then xmol2(4) = Prop4

If Not IsMissing(Prop5) Then xmol2(5) = Prop5

If Not IsMissing(Prop6) Then xmol2(6) = Prop6

If Not IsMissing(Prop7) Then xmol2(7) = Prop7

If Not IsMissing(Prop8) Then xmol2(8) = Prop8

If Not IsMissing(Prop9) Then xmol2(9) = Prop9

If Not IsMissing(Prop10) Then xmol2(10) = Prop10

If Not IsMissing(Prop11) Then xmol2(11) = Prop11

If Not IsMissing(Prop12) Then xmol2(12) = Prop12

If Not IsMissing(Prop13) Then xmol2(13) = Prop13

If Not IsMissing(Prop14) Then xmol2(14) = Prop14

If Not IsMissing(Prop15) Then xmol2(15) = Prop15

If Not IsMissing(Prop16) Then xmol2(16) = Prop16

If Not IsMissing(Prop17) Then xmol2(17) = Prop17

If Not IsMissing(Prop18) Then xmol2(18) = Prop18

If Not IsMissing(Prop19) Then xmol2(19) = Prop19

If Not IsMissing(Prop20) Then xmol2(20) = Prop20

Call CalcSetup(FluidName, "", "", 0, 0)

If ierr > 0 Then Mole2Mass = Trim2(herr): Exit Function

If i < 0 Or i > nc Then Mole2Mass = Trim2("Index out of Range (greater than number of components in mixture)": Exit Function

```

sum = 0
For j = 1 To nc
    sum = sum + xmol2(j)
Next
If Abs(sum - 1) > 0.0001 Then Mole2Mass = Trim2("Composition does not sum to 1"): Exit
Function
Call XMASSdll(xmol2(1), xkg2(1), wmix2)
If i = 0 Then 'Molar mass of mixture
    Mole2Mass = wmix2
Else 'Mass fraction
    Mole2Mass = xkg2(i)
End If
End Function

```

'Change mass composition to molar composition

'Prop1 - Prop20 are the mass values for the components in the mixture.

'i specifies which component's mass fraction is returned. If zero, the molar mass is returned

Function Mass2Mole(FluidName, i, Prop1, Prop2, Optional Prop3, Optional Prop4, Optional Prop5, Optional Prop6, Optional Prop7, Optional Prop8, Optional Prop9, Optional Prop10, Optional Prop11, Optional Prop12, Optional Prop13, Optional Prop14, Optional Prop15, Optional Prop16, Optional Prop17, Optional Prop18, Optional Prop19, Optional Prop20)

Dim j As Integer, xkg2(1 To MaxComps) As Double, xmol2(1 To MaxComps) As Double, wmix2 As Double, sum As Double

For j = 1 To MaxComps: xkg2(j) = 0: Next

xkg2(1) = Prop1

xkg2(2) = Prop2

If Not IsMissing(Prop3) Then xkg2(3) = Prop3

If Not IsMissing(Prop4) Then xkg2(4) = Prop4

If Not IsMissing(Prop5) Then xkg2(5) = Prop5

If Not IsMissing(Prop6) Then xkg2(6) = Prop6

If Not IsMissing(Prop7) Then xkg2(7) = Prop7

```

If Not IsMissing(Prop8) Then xkg2(8) = Prop8
If Not IsMissing(Prop9) Then xkg2(9) = Prop9
If Not IsMissing(Prop10) Then xkg2(10) = Prop10
If Not IsMissing(Prop11) Then xkg2(11) = Prop11
If Not IsMissing(Prop12) Then xkg2(12) = Prop12
If Not IsMissing(Prop13) Then xkg2(13) = Prop13
If Not IsMissing(Prop14) Then xkg2(14) = Prop14
If Not IsMissing(Prop15) Then xkg2(15) = Prop15
If Not IsMissing(Prop16) Then xkg2(16) = Prop16
If Not IsMissing(Prop17) Then xkg2(17) = Prop17
If Not IsMissing(Prop18) Then xkg2(18) = Prop18
If Not IsMissing(Prop19) Then xkg2(19) = Prop19
If Not IsMissing(Prop20) Then xkg2(20) = Prop20
Call CalcSetup(FluidName, "", "", 0, 0)
If ierr > 0 Then Mass2Mole = Trim2(herr): Exit Function
If i < 0 Or i > nc Then Mass2Mole = Trim2("Index out of Range (greater than number of
components in mixture)": Exit Function
sum = 0
For j = 1 To nc
    sum = sum + xkg2(j)
Next
If Abs(sum - 1) > 0.0001 Then Mass2Mole = Trim2("Composition does not sum to 1"): Exit
Function
Call XMOLEdll(xkg2(1), xmol2(1), wmix2)
If i = 0 Then 'Molar mass of mixture
    Mass2Mole = wmix2
Else 'Mole fraction
    Mass2Mole = xmol2(i)
End If
End Function

```

Function EOSMax(FluidName, Optional InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcSetup(FluidName, "", Units, Prop1, Prop2)

If nc > 1 Then

Call LIMITXdll("EOS", 300#, 0#, 0#, x(1), tmin, tmax, dmax, pmax, ierr2, herr2, 3&, 255&)

Else

Call LIMITKdll("EOS", 1, 300#, 0#, 0#, tmin, tmax, dmax, pmax, ierr2, herr2, 3&, 255&)

End If

If IsMissing(InpCode) Then InpCode = ""

If InpCode = "P" Or InpCode = "p" Then

EOSMax = ConvertUnits("-P", Units, pmax, 0)

ElseIf InpCode = "D" Or InpCode = "d" Then

EOSMax = ConvertUnits("-D", Units, dmax, 0)

Else

EOSMax = ConvertUnits("-T", Units, tmax, 0)

End If

End Function

Function EOSMin(FluidName, Optional InpCode, Optional Units, Optional Prop1, Optional Prop2)

Call CalcSetup(FluidName, "", Units, Prop1, Prop2)

If nc > 1 Then

Call LIMITXdll("EOS", 300#, 0#, 0#, x(1), tmin, tmax, dmax, pmax, ierr2, herr2, 3&, 255&)

Else

Call LIMITKdll("EOS", 1, 300#, 0#, 0#, tmin, tmax, dmax, pmax, ierr2, herr2, 3&, 255&)

End If

If IsMissing(InpCode) Then InpCode = ""

```

If InpCode = "P" Or InpCode = "p" Then
    EOSMin = 0
ElseIf InpCode = "D" Or InpCode = "d" Then
    EOSMin = 0
Else
    EOSMin = ConvertUnits("-T", Units, tmin, 0)
End If
End Function

```

```

Function ErrorCode(InputCell)
    ErrorCode = ierr
End Function

```

```

Function ErrorString(InputCell)
    ErrorString = Trim2(ierr)
End Function

```

```

Function Trim2(a)

```

'All error messages call this routine to add the pound sign (#) to the beginning of the line.

'If you do not want this error code, simply remove the ["#" +] piece below.

'It can also be changed to any other symbol(s) you desire.

```

If Left(a, 1) <> "#" Then
    Trim2 = "#" + Trim(a)
Else
    Trim2 = Trim(a)
End If
End Function

```

Function UnitConvert(InputValue, UnitType As String, OldUnits As String, NewUnits As String)

'InputValue is the value to be converted from OldUnits to NewUnits

'UnitType is one of the following letters (one character only in most cases):

'UnitType	Unit name	SI units
' T	Temperature	K
' P	Pressure	Pa
' D	Density or specific volume	mol/m <sup>3</sup> or kg/m <sup>3</sup> (or m <sup>3</sup> /mol or m <sup>3</sup> /kg)
' H	Enthalpy or specific energy	J/mol or J/kg
' S	Entropy or heat capacity	J/mol-K or J/kg-K
' W	Speed of sound	m/s
' U	Viscosity	Pa-s
' K	Thermal conductivity	W/m-K
' JT	Joule Thompson	K/Pa
' L	Length	m
' A	Area	m <sup>2</sup>
' V	Volume	m <sup>3</sup>
' M	Mass	kg
' F	Force	N
' E	Energy	J
' Q	Power	W
' N	Surface tension	N/m

' Gage pressures can be used by adding "\_g" to the unit, e.g., "MPa\_g"

Dim Value As Double, Tpe As String, Unit1 As String, Unit2 As String

Dim Drcr As Integer, Gage As Integer, Vacm As Integer

Dim MolWt As Double, Rgas As Double

```

If Not IsNumeric(InputValue) Then UnitConvert = 0: Exit Function
If NewUnits = "" Then UnitConvert = InputValue: Exit Function

Value = InputValue
Tpe = UCase(Trim(UnitType))
Unit1 = UCase(Trim(OldUnits))
Unit2 = UCase(Trim(NewUnits))

Rgas = 8.314472
Call WMOLdll(x(1), wm)
If CompFlag = 1 Then Call WMOLdll(xliq(1), wm)
If CompFlag = 2 Then Call WMOLdll(xvap(1), wm)
MolWt = wm

For Drct = 1 To -1 Step -2
'-----
' Temperature Conversion
'-----

If Tpe = "T" Then
    If Unit1 = "K" Then
    ElseIf Unit1 = "C" Then
        Value = Value + Drct * CtoK
    ElseIf Unit1 = "R" Then
        Value = Value * RtoK ^ Drct
    ElseIf Unit1 = "F" Then
        If Drct = 1 Then
            'Value = RtoK * (Value + FtoR)  'Does not give exactly zero at 32 F
            Value = (Value - 32) * RtoK + CtoK
        Else
            'Value = Value / RtoK - FtoR  'Does not give exactly 32 at 273.15 K

```



Value = (Value - CtoK) / RtoK + 32

End If

Else

UnitConvert = Trim2("Undefined input unit"): Exit Function

End If

'-----

' Pressure Conversion

'-----

ElseIf Tpe = "P" Then

Gage = InStr(Unit1, "GAGE")

Vacm = InStr(Unit1, "VACM")

If Gage = 0 Then Gage = InStr(Unit1, "\_G")

If Vacm = 0 Then Vacm = InStr(Unit1, "\_V")

If Gage <> 0 And Drct = -1 Then Value = Value - ATMtoMPa

If Vacm <> 0 And Drct = -1 Then Value = ATMtoMPa - Value

If Gage <> 0 Then Unit1 = Trim(Left(Unit1, Gage - 1))

If Vacm <> 0 Then Unit1 = Trim(Left(Unit1, Vacm - 1))

If Unit1 = "PA" Then

Value = Value / 1000000 ^ Drct

ElseIf Unit1 = "KPA" Then

Value = Value / 1000 ^ Drct

ElseIf Unit1 = "MPA" Then

Value = Value

ElseIf Unit1 = "GPA" Then

Value = Value \* 1000 ^ Drct

ElseIf Unit1 = "BAR" Then

Value = Value \* BARtoMPa ^ Drct

ElseIf Unit1 = "KBAR" Then

```

Value = Value * (BARtoMPa * 1000) ^ Drct
ElseIf Unit1 = "ATM" Then
    Value = Value * ATMtoMPa ^ Drct
ElseIf Unit1 = "KGF/CM^2" Or Unit1 = "KG/CM^2" Or Unit1 = "ATA" Or Unit1 =
"AT" Or Unit1 = "ATMA" Then
    Value = Value * (KGFtoN / 100) ^ Drct
ElseIf Unit1 = "PSI" Or Unit1 = "PSIA" Then
    Value = Value * PSIAtoMPa ^ Drct
ElseIf Unit1 = "PSF" Then
    Value = Value * (PSIAtoMPa / 144) ^ Drct
ElseIf Unit1 = "MMHG" Or Unit1 = "TORR" Then
    Value = Value * MMHGtoMPa ^ Drct
ElseIf Unit1 = "CMHG" Then
    Value = Value * (MMHGtoMPa * 10) ^ Drct
ElseIf Unit1 = "INHG" Then
    Value = Value * (MMHGtoMPa * INtoM * 1000) ^ Drct
ElseIf Unit1 = "INH2O" Then
    Value = Value * INH2OtoMPa ^ Drct
ElseIf Unit1 = "PSIG" Then
    If Drct = 1 Then
        Value = PSIAtoMPa * Value + ATMtoMPa
    Else
        Value = (Value - ATMtoMPa) / PSIAtoMPa
    End If
Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function
End If
If Gage <> 0 And Drct = 1 Then Value = Value + ATMtoMPa
If Vacm <> 0 And Drct = 1 Then Value = ATMtoMPa - Value

```

```

'-----
' Density Conversion
'-----

ElseIf Tpe = "D" Then
  If Value = 0 Then Value = 1E-50
  If Unit1 = "MOL/DM^3" Or Unit1 = "MOL/L" Or Unit1 = "KMOL/M^3" Then
  ElseIf Unit1 = "MOL/CM^3" Or Unit1 = "MOL/CC" Then
    Value = Value * 1000 ^ Drct
  ElseIf Unit1 = "MOL/M^3" Then
    Value = Value / 1000 ^ Drct
  ElseIf Unit1 = "KG/M^3" Then
    Value = Value / MolWt ^ Drct
  ElseIf Unit1 = "KG/DM^3" Or Unit1 = "KG/L" Then
    Value = Value * (1000 / MolWt) ^ Drct
  ElseIf Unit1 = "G/DM^3" Or Unit1 = "G/L" Then
    Value = Value * (1 / MolWt) ^ Drct
  ElseIf Unit1 = "G/CC" Or Unit1 = "G/CM^3" Or Unit1 = "G/ML" Then
    Value = Value * (1000 / MolWt) ^ Drct
  ElseIf Unit1 = "G/DM^3" Then
    Value = Value * (1 / MolWt) ^ Drct
  ElseIf Unit1 = "LBM/FT^3" Or Unit1 = "LB/FT^3" Then
    Value = Value * (LBMtoKG / FT3toM3 / MolWt) ^ Drct
  ElseIf Unit1 = "LBMOL/FT^3" Then
    Value = Value * (LBMtoKG / FT3toM3) ^ Drct
  ElseIf Unit1 = "SLUG/FT^3" Then
    Value = Value * (LBMtoKG / FT3toM3 / MolWt * KGFtoN / FTtoM) ^ Drct
  ElseIf Unit1 = "LB/GAL" Then
    Value = Value * (LBMtoKG / GALLONtoM3 / MolWt) ^ Drct

```

```

'-----
' Specific Volume Conversion
'-----

ElseIf Unit1 = "DM^3/MOL" Or Unit1 = "L/MOL" Or Unit1 = "M^3/KMOL" Then
    Value = 1 / Value

ElseIf Unit1 = "CM^3/MOL" Or Unit1 = "CC/MOL" Or Unit1 = "ML/MOL" Then
    Value = 1000 / Value

ElseIf Unit1 = "M^3/MOL" Then
    Value = 1 / Value / 1000

ElseIf Unit1 = "M^3/KG" Then
    Value = 1 / Value / MolWt

ElseIf Unit1 = "DM^3/KG" Or Unit1 = "L/KG" Then
    Value = 1000 / Value / MolWt

ElseIf Unit1 = "CC/G" Or Unit1 = "CM^3/G" Or Unit1 = "ML/G" Then
    Value = 1000 / Value / MolWt

ElseIf Unit1 = "DM^3/G" Then
    Value = 1 / Value / MolWt

ElseIf Unit1 = "FT^3/LBM" Or Unit1 = "FT^3/LB" Then
    Value = 1 / Value * (LBMtoKG / FT3toM3 / MolWt)

ElseIf Unit1 = "FT^3/LBMOL" Then
    Value = 1 / Value * (LBMtoKG / FT3toM3)

ElseIf Unit1 = "FT^3/SLUG" Then
    Value = 1 / Value * (LBMtoKG / FT3toM3 / MolWt * KGftoN / FTtoM)

Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function

End If

If Abs(Value) < 1E-30 Then Value = 0

```

-----  
' Specific Energy and Enthalpy Conversions  
-----

```
ElseIf Tpe = "H" Then
  If Unit1 = "J/MOL" Or Unit1 = "KJ/KMOL" Then
    ElseIf Unit1 = "KJ/MOL" Then
      Value = Value * 1000 ^ Drct
    ElseIf Unit1 = "MJ/MOL" Then
      Value = Value * 1000000 ^ Drct
    ElseIf Unit1 = "KJ/KG" Or Unit1 = "J/G" Then
      Value = MolWt ^ Drct * Value
    ElseIf Unit1 = "J/KG" Then
      Value = (MolWt / 1000) ^ Drct * Value
    ElseIf Unit1 = "M^2/S^2" Then
      Value = (MolWt / 1000) ^ Drct * Value
    ElseIf Unit1 = "FT^2/S^2" Then
      Value = (MolWt / 1000 * FTtoM ^ 2) ^ Drct * Value
    ElseIf Unit1 = "CAL/MOL" Or Unit1 = "KCAL/KMOL" Then
      Value = CALtoJ ^ Drct * Value
    ElseIf Unit1 = "CAL/G" Or Unit1 = "KCAL/KG" Then
      Value = (CALtoJ * MolWt) ^ Drct * Value
    ElseIf Unit1 = "BTU/LBM" Or Unit1 = "BTU/LB" Then
      Value = (BTUtoKJ / LBMtoKG * MolWt) ^ Drct * Value
    ElseIf Unit1 = "BTU/LBMOL" Then
      Value = (BTUtoKJ / LBMtoKG) ^ Drct * Value
    Else
      UnitConvert = Trim2("Undefined input unit"): Exit Function
    End If
```

-----  
' Entropy and Heat Capacity Conversions  
-----

```
ElseIf Tpe = "S" Then
  If Unit1 = "J/MOL-K" Or Unit1 = "KJ/KMOL-K" Then
    Value = Value
  ElseIf Unit1 = "KJ/MOL-K" Then
    Value = Value * 1000 ^ Drct
  ElseIf Unit1 = "KJ/KG-K" Or Unit1 = "J/G-K" Then
    Value = MolWt ^ Drct * Value
  ElseIf Unit1 = "J/KG-K" Then
    Value = (MolWt / 1000) ^ Drct * Value
  ElseIf Unit1 = "BTU/LBM-R" Or Unit1 = "BTU/LB-R" Then
    Value = (BTUtoKJ / LBMtoKG / RtoK * MolWt) ^ Drct * Value
  ElseIf Unit1 = "BTU/LBMOL-R" Then
    Value = (BTUtoKJ / LBMtoKG / RtoK) ^ Drct * Value
  ElseIf Unit1 = "CAL/G-K" Or Unit1 = "CAL/G-C" Or Unit1 = "KCAL/KG-K" Or Unit1
= "KCAL/KG-C" Then
    Value = (CALtoJ * MolWt) ^ Drct * Value
  ElseIf Unit1 = "CAL/MOL-K" Or Unit1 = "CAL/MOL-C" Then
    Value = CALtoJ ^ Drct * Value
  ElseIf Unit1 = "FT-LBF/LBMOL-R" Then
    Value = (FTLBFtoJ / LBMtoKG / RtoK / 1000) ^ Drct * Value
  ElseIf Unit1 = "CP/R" Then
    Value = Rgas ^ Drct * Value * 1000
  Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function
  End If
```

-----  
' Speed of Sound Conversion  
-----

```
ElseIf Tpe = "W" Then
  If Unit1 = "M/S" Then
    ElseIf Unit1 = "M^2/S^2" Then
      Value = Sqr(Value)
    ElseIf Unit1 = "CM/S" Then
      Value = Value / 100 ^ Drct
    ElseIf Unit1 = "KM/H" Then
      Value = Value * (1000 / HtoS) ^ Drct
    ElseIf Unit1 = "FT/S" Then
      Value = Value * FTtoM ^ Drct
    ElseIf Unit1 = "IN/S" Then
      Value = Value * INtoM ^ Drct
    ElseIf Unit1 = "MILE/H" Or Unit1 = "MPH" Then
      Value = Value * (INtoM * 63360 / HtoS) ^ Drct
    ElseIf Unit1 = "KNOT" Then
      Value = Value * 0.5144444444 ^ Drct
    ElseIf Unit1 = "MACH" Then
      Value = Value * Sqr(1.4 * 298.15 * 8314.51 / 28.95853816) ^ Drct
  Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function
  End If
```

-----  
' Viscosity Conversion  
-----

```
ElseIf Tpe = "U" Then
```



```

If Unit1 = "PA-S" Or Unit1 = "KG/M-S" Then
ElseIf Unit1 = "MPA-S" Then    'Note: This is milliPa-s, not MPa-s
    Value = Value / 1000 ^ Drct
ElseIf Unit1 = "UPA-S" Then
    Value = Value / 1000000 ^ Drct
ElseIf Unit1 = "G/CM-S" Or Unit1 = "POISE" Then
    Value = Value / 10 ^ Drct
ElseIf Unit1 = "CENTIPOISE" Then
    Value = Value / 1000 ^ Drct
ElseIf Unit1 = "MILLIPOISE" Or Unit1 = "MPOISE" Then
    Value = Value / 10000 ^ Drct
ElseIf Unit1 = "MICROPOISE" Or Unit1 = "UPOISE" Then
    Value = Value / 10000000 ^ Drct
ElseIf Unit1 = "LBM/FT-S" Or Unit1 = "LB/FT-S" Then
    Value = Value * (LBMtoKG / FTtoM) ^ Drct
ElseIf Unit1 = "LBF-S/FT^2" Then
    Value = Value * (LBFtoN / FTtoM ^ 2) ^ Drct
ElseIf Unit1 = "LBM/FT-H" Or Unit1 = "LB/FT-H" Then
    Value = Value * (LBMtoKG / FTtoM / HtoS) ^ Drct
Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function
End If

```

```

'-----
' Thermal Conductivity Conversion
'-----

```

```

ElseIf Tpe = "K" Then
    If Unit1 = "MW/M-K" Then
    ElseIf Unit1 = "W/M-K" Then

```

```

Value = Value * 1000 ^ Drct
ElseIf Unit1 = "G-CM/S^3-K" Then
Value = Value / 100 ^ Drct
ElseIf Unit1 = "KG-M/S^3-K" Then
Value = Value * 1000 ^ Drct
ElseIf Unit1 = "CAL/S-CM-K" Then
Value = Value * (CALtoJ * 100000) ^ Drct
ElseIf Unit1 = "KCAL/HR-M-K" Then
Value = Value * (CALtoJ * 100000 * 1000 / 100 / 3600) ^ Drct
ElseIf Unit1 = "LBM-FT/S^3-F" Or Unit1 = "LB-FT/S^3-F" Then
Value = Value * (1000 * LBMtoKG * FTtoM / RtoK) ^ Drct
ElseIf Unit1 = "LBF/S-F" Then
Value = Value * (1000 * LBFtoN / RtoK) ^ Drct
ElseIf Unit1 = "BTU/H-FT-F" Then
Value = Value * (1000 * BTUtoW / HtoS / FTtoM / RtoK) ^ Drct
Else
UnitConvert = Trim2("Undefined input unit"): Exit Function
End If

```

```

'-----
' Joule-Thomson Conversion
'-----

```

```

ElseIf Tpe = "JT" Then
If Unit1 = "K/MPA" Or Unit1 = "C/MPA" Then
ElseIf Unit1 = "K/KPA" Or Unit1 = "C/KPA" Then
Value = Value * 1000 ^ Drct
ElseIf Unit1 = "K/PA" Or Unit1 = "C/PA" Then
Value = Value * 1000000 ^ Drct
ElseIf Unit1 = "C/ATM" Then

```

```

    Value = Value / ATMtoMPa ^ Drct
ElseIf Unit1 = "C/BAR" Then
    Value = Value / BARtoMPa ^ Drct
ElseIf Unit1 = "K/PSI" Or Unit1 = "K/PSIA" Then
    Value = Value / PSIAtoMPa ^ Drct
ElseIf Unit1 = "F/PSI" Or Unit1 = "F/PSIA" Or Unit1 = "R/PSIA" Then
    Value = Value / (PSIAtoMPa / RtoK) ^ Drct
Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function
End If

```

```

'-----
' Length Conversion
'-----

```

```

ElseIf Tpe = "L" Then
    If Unit1 = "METER" Or Unit1 = "M" Then
        ElseIf Unit1 = "DM" Then
            Value = Value / 10 ^ Drct
        ElseIf Unit1 = "CM" Then
            Value = Value / 100 ^ Drct
        ElseIf Unit1 = "MM" Then
            Value = Value / 1000 ^ Drct
        ElseIf Unit1 = "KM" Then
            Value = Value * 1000 ^ Drct
        ElseIf Unit1 = "INCH" Or Unit1 = "IN" Then
            Value = Value * INtoM ^ Drct
        ElseIf Unit1 = "FOOT" Or Unit1 = "FT" Then
            Value = Value * FTtoM ^ Drct
        ElseIf Unit1 = "YARD" Or Unit1 = "YD" Then

```

```

Value = Value * (INtoM * 36) ^ Drct
ElseIf Unit1 = "MILE" Or Unit1 = "MI" Then
Value = Value * (INtoM * 63360) ^ Drct
ElseIf Unit1 = "LIGHT YEAR" Then
Value = Value * 9.46055E+15 ^ Drct
ElseIf Unit1 = "ANGSTROM" Then
Value = Value / 10000000000# ^ Drct
ElseIf Unit1 = "FATHOM" Then
Value = Value * (FTtoM * 6) ^ Drct
ElseIf Unit1 = "MIL" Then
Value = Value * (INtoM / 1000) ^ Drct
ElseIf Unit1 = "ROD" Then
Value = Value * (INtoM * 16.5 * 12) ^ Drct
ElseIf Unit1 = "PARSEC" Then
Value = Value * (30837400000000# * 1000) ^ Drct
Else
UnitConvert = Trim2("Undefined input unit"): Exit Function
End If

```

```

'-----
' Area Conversion
'-----

```

```

ElseIf Tpe = "A" Then
If Unit1 = "METER^2" Or Unit1 = "M^2" Then
ElseIf Unit1 = "CM^2" Then
Value = Value / 10000 ^ Drct
ElseIf Unit1 = "MM^2" Then
Value = Value / 1000000 ^ Drct
ElseIf Unit1 = "KM^2" Then

```

```

Value = Value * 1000000 ^ Drct
ElseIf Unit1 = "INCH^2" Or Unit1 = "IN^2" Then
Value = Value * (INtoM ^ 2) ^ Drct
ElseIf Unit1 = "FOOT^2" Or Unit1 = "FT^2" Then
Value = Value * (FTtoM ^ 2) ^ Drct
ElseIf Unit1 = "YARD^2" Or Unit1 = "YD^2" Then
Value = Value * ((INtoM * 36) ^ 2) ^ Drct
ElseIf Unit1 = "MILE^2" Or Unit1 = "MI^2" Then
Value = Value * ((INtoM * 63360) ^ 2) ^ Drct
ElseIf Unit1 = "ACRE" Then
Value = Value * ((INtoM * 36) ^ 2 * 4840) ^ Drct
ElseIf Unit1 = "BARN" Then
Value = Value * 1E-28 ^ Drct
ElseIf Unit1 = "HECTARE" Then
Value = Value * 10000 ^ Drct
Else
UnitConvert = Trim2("Undefined input unit"): Exit Function
End If

```

```

'-----
' Volume Conversion (Note: not specific volume)
'-----

```

```

ElseIf Tpe = "V" Then
If Unit1 = "METER^3" Or Unit1 = "M^3" Then
ElseIf Unit1 = "CM^3" Then
Value = Value / 1000000 ^ Drct
ElseIf Unit1 = "LITER" Or Unit1 = "L" Or Unit1 = "DM^3" Then
Value = Value / 1000 ^ Drct
ElseIf Unit1 = "INCH^3" Or Unit1 = "IN^3" Then

```

```

Value = Value * IN3toM3 ^ Drct
ElseIf Unit1 = "FOOT^3" Or Unit1 = "FT^3" Then
    Value = Value * (IN3toM3 * 12 ^ 3) ^ Drct
ElseIf Unit1 = "YARD^3" Or Unit1 = "YD^3" Then
    Value = Value * (IN3toM3 * 36 ^ 3) ^ Drct
ElseIf Unit1 = "GALLON" Or Unit1 = "GAL" Then
    Value = Value * GALLONtoM3 ^ Drct
ElseIf Unit1 = "QUART" Or Unit1 = "QT" Then
    Value = Value * (GALLONtoM3 / 4) ^ Drct
ElseIf Unit1 = "PINT" Or Unit1 = "PT" Then
    Value = Value * (GALLONtoM3 / 8) ^ Drct
ElseIf Unit1 = "CUP" Then
    Value = Value * (GALLONtoM3 / 16) ^ Drct
ElseIf Unit1 = "OUNCE" Then
    Value = Value * (GALLONtoM3 / 128) ^ Drct
ElseIf Unit1 = "TABLESPOON" Or Unit1 = "TBSP" Then
    Value = Value * (GALLONtoM3 / 256) ^ Drct
ElseIf Unit1 = "TEASPOON" Or Unit1 = "TSP" Then
    Value = Value * (GALLONtoM3 / 768) ^ Drct
ElseIf Unit1 = "CORD" Then
    Value = Value * (FT3toM3 * 128) ^ Drct
ElseIf Unit1 = "BARREL" Then
    Value = Value * (GALLONtoM3 * 42) ^ Drct
ElseIf Unit1 = "BOARD FOOT" Then
    Value = Value * (IN3toM3 * 144) ^ Drct
ElseIf Unit1 = "BUSHEL" Then
    Value = Value * 0.03523907016688 ^ Drct
Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function

```

End If

'-----  
' Mass Conversion  
'-----

```
ElseIf Tpe = "M" Then
  If Unit1 = "KG" Then
    ElseIf Unit1 = "G" Then
      Value = Value / 1000 ^ Drct
    ElseIf Unit1 = "MG" Then      'milligram
      Value = Value / 1000000 ^ Drct
    ElseIf Unit1 = "LBM" Or Unit1 = "LB" Then
      Value = Value * LBMtoKG ^ Drct
    ElseIf Unit1 = "GRAIN" Then
      Value = Value * (LBMtoKG / 7000) ^ Drct
    ElseIf Unit1 = "SLUG" Then
      Value = Value * (KGFtoN * LBMtoKG / FTtoM) ^ Drct
    ElseIf Unit1 = "TON" Then
      Value = Value * (LBMtoKG * 2000) ^ Drct
    ElseIf Unit1 = "TONNE" Then
      Value = Value * 1000 ^ Drct
    Else
      UnitConvert = Trim2("Undefined input unit"): Exit Function
    End If
```

'-----  
' Force Conversion  
'-----

```
ElseIf Tpe = "F" Then
```



```

If Unit1 = "NEWTON" Or Unit1 = "N" Then
ElseIf Unit1 = "MN" Then 'milliNewtons
    Value = Value / 1000 ^ Drct
ElseIf Unit1 = "KGF" Then
    Value = Value * KGFtoN ^ Drct
ElseIf Unit1 = "DYNE" Then
    Value = Value / 100000 ^ Drct
ElseIf Unit1 = "LBF" Then
    Value = Value * LBFtoN ^ Drct
ElseIf Unit1 = "POUNDAL" Then
    Value = Value * (LBMtoKG * FTtoM) ^ Drct
ElseIf Unit1 = "OZF" Then
    Value = Value * (LBFtoN / 16) ^ Drct
Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function
End If

```

```

'-----
' Energy Conversion
'-----

```

```

ElseIf Tpe = "E" Then
    If Unit1 = "JOULE" Or Unit1 = "J" Then
    ElseIf Unit1 = "KJ" Then
        Value = Value * 1000 ^ Drct
    ElseIf Unit1 = "MJ" Then
        Value = Value * 1000000 ^ Drct
    ElseIf Unit1 = "KW-H" Then
        Value = Value * (HtoS * 1000) ^ Drct
    ElseIf Unit1 = "CAL" Then

```

```

    Value = CALtoJ ^ Drct * Value
ElseIf Unit1 = "KCAL" Then
    Value = Value * (CALtoJ * 1000) ^ Drct
ElseIf Unit1 = "ERG" Then
    Value = Value / 10000000 ^ Drct
ElseIf Unit1 = "BTU" Then
    Value = Value * (BTUtoKJ * 1000) ^ Drct
ElseIf Unit1 = "FT-LBF" Then
    Value = Value * FTLBFtoJ ^ Drct
Else
    UnitConvert = Trim2("Undefined input unit"): Exit Function
End If

```

```

'-----
' Power Conversion
'-----

```

```

ElseIf Tpe = "Q" Then
    If Unit1 = "WATT" Or Unit1 = "W" Then
        ElseIf Unit1 = "KWATT" Or Unit1 = "KW" Then
            Value = Value * 1000 ^ Drct
        ElseIf Unit1 = "BTU/S" Then
            Value = Value * BTUtoW ^ Drct
        ElseIf Unit1 = "BTU/MIN" Then
            Value = Value * (BTUtoW / 60) ^ Drct
        ElseIf Unit1 = "BTU/H" Then
            Value = Value * (BTUtoW / HtoS) ^ Drct
        ElseIf Unit1 = "CAL/S" Then
            Value = Value * CALtoJ ^ Drct
        ElseIf Unit1 = "KCAL/S" Then

```

```

Value = Value * (CALtoJ * 1000) ^ Drct
ElseIf Unit1 = "CAL/MIN" Then
Value = Value * (CALtoJ / 60) ^ Drct
ElseIf Unit1 = "KCAL/MIN" Then
Value = Value * (CALtoJ / 60 * 1000) ^ Drct
ElseIf Unit1 = "FT-LBF/S" Then
Value = Value * FTLBFtoJ ^ Drct
ElseIf Unit1 = "FT-LBF/MIN" Then
Value = Value * (FTLBFtoJ / 60) ^ Drct
ElseIf Unit1 = "FT-LBF/H" Then
Value = Value * (FTLBFtoJ / HtoS) ^ Drct
ElseIf Unit1 = "HP" Then
Value = Value * HPtoW ^ Drct
Else
UnitConvert = Trim2("Undefined input unit"): Exit Function
End If

```

```

'-----
' Surface Tension Conversion
'-----

```

```

ElseIf Tpe = "N" Then
If Unit1 = "N/M" Then
ElseIf Unit1 = "MN/M" Then
Value = Value / 1000 ^ Drct
ElseIf Unit1 = "DYNE/CM" Or Unit1 = "DYN/CM" Then
Value = Value / 1000 ^ Drct
ElseIf Unit1 = "LBF/FT" Then
Value = Value * LBFTtoNM ^ Drct
Else

```

```

    UnitConvert = Trim2("Undefined input unit"): Exit Function
End If
End If
Unit1 = Unit2
Next Drct
UnitConvert = Value
End Function

```

```

Sub SetupUnits(i)

```

'Warning: If any of these are changed (to make them the default) after the program has run,  
' you will need to exit Excel and restart it so that it reinitializes

```

'Refprop Units

```

```

tUnits2 = "K"
taUnits2 = "K"
pUnits2 = "kPa"
dUnits2 = "mol/dm^3"
vUnits2 = "dm^3/mol"
hUnits2 = "J/mol"
sUnits2 = "J/mol-K"
wUnits2 = "m/s"
visUnits2 = "uPa-s"
tcxUnits2 = "W/m-K"
stUnits2 = "N/m"

```

```

'Default units: (SI)

```

```

tUnits(0) = "K"
taUnits(0) = "K"
pUnits(0) = "MPa"

```

dUnits(0) = "kg/m^3"

vUnits(0) = "m^3/kg"

hUnits(0) = "kJ/kg"

sUnits(0) = "kJ/kg-K"

wUnits(0) = "m/s"

visUnits(0) = "uPa-s"

tcxUnits(0) = "mW/m-K"

stUnits(0) = "mN/m"

'Default units but with K switch to C (SI with C)

tUnits(5) = "C"

taUnits(5) = "K"

pUnits(5) = "MPa"

dUnits(5) = "kg/m^3"

vUnits(5) = "m^3/kg"

hUnits(5) = "kJ/kg"

sUnits(5) = "kJ/kg-K"

wUnits(5) = "m/s"

visUnits(5) = "uPa-s"

tcxUnits(5) = "mW/m-K"

stUnits(5) = "mN/m"

'Default units on a molar basis (Molar SI)

tUnits(6) = "K"

taUnits(6) = "K"

pUnits(6) = "MPa"

dUnits(6) = "mol/dm^3"

vUnits(6) = "dm^3/mol"

hUnits(6) = "J/mol"

sUnits(6) = "J/mol-K"

wUnits(6) = "m/s"

```

visUnits(6) = "uPa-s"
tcxUnits(6) = "mW/m-K"
stUnits(6) = "mN/m"
'mks (mks)
tUnits(1) = "K"
taUnits(1) = "K"
pUnits(1) = "kPa"
dUnits(1) = "kg/m^3"
vUnits(1) = "m^3/kg"
hUnits(1) = "kJ/kg"
sUnits(1) = "kJ/kg-K"
wUnits(1) = "m/s"
visUnits(1) = "uPa-s"
tcxUnits(1) = "W/m-K"
stUnits(1) = "mN/m"
'cgs (cgs)
tUnits(2) = "K"
taUnits(2) = "K"
pUnits(2) = "MPa"
dUnits(2) = "g/cm^3"
vUnits(2) = "cm^3/g"
hUnits(2) = "J/g"
sUnits(2) = "J/g-K"
wUnits(2) = "cm/s"
visUnits(2) = "uPa-s"
tcxUnits(2) = "mW/m-K"
stUnits(2) = "dyn/cm"
'English (E)
tUnits(3) = "F"      'See comments above

```

```

taUnits(3) = "R"
pUnits(3) = "psia"
dUnits(3) = "lbm/ft^3"
vUnits(3) = "ft^3/lbm"
hUnits(3) = "Btu/lbm"
sUnits(3) = "Btu/lbm-R"
wUnits(3) = "ft/s"
visUnits(3) = "lbm/ft-s"
tcxUnits(3) = "Btu/h-ft-F"
stUnits(3) = "lbf/ft"
'Mixed (M)
tUnits(4) = "K"
taUnits(4) = "K"
pUnits(4) = "psia"
dUnits(4) = "g/cm^3"
vUnits(4) = "cm^3/g"
hUnits(4) = "J/g"
sUnits(4) = "J/g-K"
wUnits(4) = "m/s"
visUnits(4) = "uPa-s"
tcxUnits(4) = "mW/m-K"
stUnits(4) = "mN/m"
End Sub

```

```
Function ConvertUnits(InpCode, Units, Prop1, Prop2)
```

```
Dim i As Integer, at As String, bt As String, tConv As Double, DefaultUnits As Integer
```

```
If IsMissing(InpCode) Then InpCode = ""
```

```
If IsMissing(Units) Then Units = ""
```

```

If IsMissing(Prop1) Then Prop1 = 0
If IsMissing(Prop2) Then Prop2 = 0
If ierr > 0 Then ConvertUnits = Trim2(herr): Exit Function
If tUnits2 = "" Then
    Call SetupUnits(0) 'If Default units are changed, this needs to be called again. Normally it
    is skipped after the first entry
End If

'Change the 0 in the following line to 3 for default English units, 1 for mks, or 2 for cgs, etc.
DefaultUnits = 0
i = DefaultUnits

'Do not change the order of the next 7 statements
If Left(UCase(Units), 2) = "SI" Then i = 0          'SI
If UCase(Units) = "SI WITH C" Or UCase(Units) = "C" Then i = 5 'SI with C
If Left(UCase(Units), 1) = "M" Then i = 4          'Mixed
If UCase(Units) = "MOLAR SI" Then i = 6          'Molar SI
If UCase(Units) = "MKS" Then i = 1                'mks
If UCase(Units) = "CGS" Then i = 2                'cgs
If Left(UCase(Units), 1) = "E" Then i = 3        'English

at = UCase(Left(InpCode, 1))
bt = UCase(Mid(InpCode, 2, 1))

If at = "-" Then
    ConvertUnits = Prop1
    If Prop1 >= -9999999 And Prop1 <= -9999900 Then
        If Prop1 = CLng(Prop1) Then
            ConvertUnits = Trim2("Undefined")
        Exit Function
    End If
End If

```



```

If Len(Trim(Prop1)) > 0 Then
    If bt = "T" Then ConvertUnits = UnitConvert(Prop1, "T", tUnits2, tUnits(i))
    If bt = "A" Then ConvertUnits = UnitConvert(Prop1, "T", taUnits2, taUnits(i))
    If bt = "P" Then ConvertUnits = UnitConvert(Prop1, "P", pUnits2, pUnits(i))
    If bt = "D" Then ConvertUnits = UnitConvert(Prop1, "D", dUnits2, dUnits(i))
    If bt = "V" Then ConvertUnits = UnitConvert(Prop1, "D", vUnits2, vUnits(i))
    If bt = "H" Or bt = "E" Then ConvertUnits = UnitConvert(Prop1, "H", hUnits2, hUnits(i))
    If bt = "S" Then ConvertUnits = UnitConvert(Prop1, "S", sUnits2, sUnits(i))
    If bt = "W" Then ConvertUnits = UnitConvert(Prop1, "W", wUnits2, wUnits(i))
    If bt = "U" Then ConvertUnits = UnitConvert(Prop1, "U", visUnits2, visUnits(i))
    If bt = "K" Then ConvertUnits = UnitConvert(Prop1, "K", tcxUnits2, tcxUnits(i))
    If bt = "N" Then ConvertUnits = UnitConvert(Prop1, "N", stUnits2, stUnits(i))
End If

If bt = "J" Then
    tConv = 1
    If tUnits(i) = "R" Or tUnits(i) = "F" Then tConv = 1 / RtoK
    ConvertUnits = Prop1 * tConv / UnitConvert(1, "P", "kPa", pUnits(i))
End If

Else
    If Len(Trim(Prop1)) > 0 Then
        If at = "T" Then Prop1 = UnitConvert(Prop1, "T", tUnits(i), tUnits2)
        If at = "A" Then Prop1 = UnitConvert(Prop1, "T", taUnits(i), taUnits2)
        If at = "P" Then Prop1 = UnitConvert(Prop1, "P", pUnits(i), pUnits2)
        If at = "D" Then Prop1 = UnitConvert(Prop1, "D", dUnits(i), dUnits2)
        If at = "V" Then Prop1 = UnitConvert(Prop1, "D", vUnits(i), vUnits2)
        If at = "H" Or at = "E" Then Prop1 = UnitConvert(Prop1, "H", hUnits(i), hUnits2)
        If at = "S" Then Prop1 = UnitConvert(Prop1, "S", sUnits(i), sUnits2)
        If at = "W" Then Prop1 = UnitConvert(Prop1, "W", wUnits(i), wUnits2)
        If at = "U" Then Prop1 = UnitConvert(Prop1, "U", visUnits(i), visUnits2)
    
```

```

If at = "K" Then Prop1 = UnitConvert(Prop1, "K", tcxUnits(i), tcxUnits2)
If at = "N" Then Prop1 = UnitConvert(Prop1, "N", stUnits(i), stUnits2)
End If

If Len(Trim(Prop2)) > 0 Then
  If bt = "T" Then Prop2 = UnitConvert(Prop2, "T", tUnits(i), tUnits2)
  If bt = "A" Then Prop2 = UnitConvert(Prop2, "T", taUnits(i), taUnits2)
  If bt = "P" Then Prop2 = UnitConvert(Prop2, "P", pUnits(i), pUnits2)
  If bt = "D" Then Prop2 = UnitConvert(Prop2, "D", dUnits(i), dUnits2)
  If bt = "V" Then Prop2 = UnitConvert(Prop2, "D", vUnits(i), vUnits2)
  If bt = "H" Or bt = "E" Then Prop2 = UnitConvert(Prop2, "H", hUnits(i), hUnits2)
  If bt = "S" Then Prop2 = UnitConvert(Prop2, "S", sUnits(i), sUnits2)
  If bt = "W" Then Prop2 = UnitConvert(Prop2, "W", wUnits(i), wUnits2)
  If bt = "U" Then Prop2 = UnitConvert(Prop2, "U", visUnits(i), visUnits2)
  If bt = "K" Then Prop2 = UnitConvert(Prop2, "K", tcxUnits(i), tcxUnits2)
  If bt = "N" Then Prop2 = UnitConvert(Prop2, "N", stUnits(i), stUnits2)
End If
End If
End Function

```

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