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Experimental study on the effect of a heated plume within vented enclosures

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

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ABSTRACT

This thesis presents an experimental study on the effect of a heated plume within vented enclosures. The characteristics of a heated plume within enclosures are studied using controlled and systematic experiments, simulating the movement of heated air due to the development of fire within a room.

A short enclosure (Case CS1) and a tall enclosure (Case CS2) were subjected to two heating configurations representing natural and forced convection heat transfer. The cross-sectional dimension of the enclosures, and the heating power were maintained the same for both cases in order to compare the plume effects due to the change of height. For each case, different combinations of top ventilation were also considered for the present experiments.

The air temperature and pressure within the enclosure were measured with suitable thermocouples and pressure probes, specially fabricated and mounted on racks that were positioned at three locations: (i) at 100 mm above the base of the enclosure; (ii) middle of the enclosure; and (iii) at 100 mm below the ceiling of the enclosure. The ceiling temperature profile was also obtained to determine the ceiling jet impingement.

The experimental results show that for both case studies – CS1 and CS2, for the same heat transfer mechanism (natural or forced convection), the hot air temperature within the enclosure is decreased due to an increase in the number and size of vents. Hot air is exhausted quicker into the ambient and the exchange rate of hot air inside the enclosure and cool air from the ambient is increased. It was found that natural convection mechanism led to a higher ceiling and air temperature distribution than forced convection. The short enclosure had a higher ceiling temperature compared to the tall enclosure. Correlations for ceiling temperature distribution for short and tall enclosures are also provided. The study has resulted in obtaining valuable conclusions for the effect of a heated plume within a vented enclosure.

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NOMENCLATURE

English Symbols

A_v	area of the vent, m^2
C_D	discharge coefficient
H	height of the enclosure, m
H_s	height of the short enclosure, m
H_t	height of the tall enclosure, m
H_v	height of the vent, m
P	pressure, Pa
Q	power of the heater, W
r	distance on the ceiling from the centre point of the plume impingement, m
T	temperature, °C
T_{ceil}	ceiling temperature, °C
T_∞	ambient temperature, °C
V	velocity of air within the enclosure, m/s
$\dot{V}$	volumetric flowrate of air, m^3/s
W	width of the enclosure, m
W_v	width of the vent, m

CHAPTER 1
INTRODUCTION

1.1 Background

The term 'building fire' refers to any accidental fire that occurs in a living compartment. In addition to extensive structural damages, building fire may lead to significant issues affecting the health and safety of its occupants. Fire victims typically suffer from asphyxiation and poisoning caused by the emission of hot and toxic fumes released as a result of building fire. These precede even the burn injuries caused by an increase in the surrounding temperature. From a financial perspective, for example, insurance claims due to fire damages in buildings could possibly run into billions of dollars.

A building fire not only produces smoke; it also generates hot air, which mixes with the existing air in the building's air vents which amplifies and spreads the fire. In order to combat the severity of fire in buildings, it is important to understand the flow and heat transfer characteristics of heated air within buildings. Specific ventilation systems can be strategically planned and installed with prior knowledge of the movement and characteristics of heated air. This knowledge greatly assists in deciding the layout of the location of fire alarms and sprinklers within a given room. Efficient ventilation systems help to increase the expulsion of hot gases, thus minimizing and ultimately avoiding potential asphyxiation and burn injuries. It is also important to take into account any methods for natural ventilation when planning to construct the building. Natural ventilation exists within pathways, doors and windows, and even in the free space located in elevator shafts and escape routes. Hence, possessing an understanding of the pattern of air movement and ventilation exhaust patterns allows for safer building constructions.

In the present study, experiments are carried out in enclosures that are used to simulate rooms in a building. This is vital in order to understand the flow and heat transfer characteristics of hot air movement within the room, and through its ventilations. The results of the study provide an enhanced understanding of the temperature and velocity distribution patterns of hot air within the enclosure and ceiling temperature distribution. This in turn enables the prediction of heat and fluid flow characteristics of hot air movement within rooms in the event of a building fire.

1.2 Significance of Fire Research

Fire is the result of an oxygenated chemical reaction of combustible materials when temperatures reach an optimal temperature beyond the flash point. It is also accompanied with the release of energy in the form of heat and light. The beneficial use of controlled fire (creation and use) can be found in thermal power generation plants, various manufacturing industries, transportation, and in daily household use. However, uncontrolled fire causes significant issues which affect the health and safety of the occupants in buildings and results in widespread property damage. Therefore, it is very important to understand the mechanisms of fire development, its detection, and control. One of the important aspects is to obtain knowledge of the air movement within a room or building.

Increasing human population and the development of infrastructure in every part of the world has contributed to the land shortage problem. This has resulted in the construction of multi-storied dwellings, and office spaces. Apart from this, there are numerous shopping malls, hotels and theme parks that are built everywhere. All of which have a common purpose of using minimum space (land) that not only caters for a large number of people, but reduces the cost of living. Moreover, the rapid growth of modern building technology has introduced new risk factors concerning the spread of smoke and fire. Aside from individual rooms, these buildings consist of staircases, elevators, and corridors. With all these factors to take into account, it has become increasingly difficult and complex to analyze the movement (inlet and outlet) of air during fire, temperature distribution and propagation.

In recent years, the development of fire engineering has been growing rapidly. The topic of building fire has been the main focus in the advancement of understanding and research on building fire. The analysis conducted on the topic of the development of fires, and its propagation within buildings had been studied using a wide variety of computational models. Generally, these models can be classified either as probabilistic or deterministic. Probabilistic models focus on the statistical predictions about the transition from one stage of fire growth to another, while deterministic models use the theory underlying the physical and chemical principles involved in fires. Some experimental work which deals with one or other aspects of the development of fires is also available.

1.2.1 Fire Development within an Enclosure

Fires can exist in several forms, either as a tiny flame flickering on a candle, or an immense flame that uncontrollably ablaze through the forest. Although vastly different in size, they essentially originate the same way. They both require the following three components: oxygen from air, a combustible material, and heat. When all are combined, it produces a chemical reaction, which is accompanied with energy to be released in the form of heat and light. An insufficient supply of any one component will lead to the fire dying out. It is also important to note that the combustion process is highly interactive with the surroundings, and the quantitative estimation of the processes involved is often complex.

Oxygen, one of the essential elements for combustion process is easily obtained from the atmosphere. A continuous supply of oxygen, fuel and temperature are necessities in sustaining a fire. One of the best ways to illustrate this point is a candle. Once it ignites, it burns continuously using oxygen from air, solid wax as fuel, generating heat and light. The burning of the candle continues until the wick of the candle burns away, thereby removing the fuel.

An enclosure fire strongly depends on its surroundings for the supply of oxygen, combustible material, and heat. The development of an enclosure fire is very much dependent on the enclosure geometry, ventilation, and the type and quantity of fuel available within the enclosure. The various stages involved in the burning processes are discussed below.

At its initial stage, when a sufficient mixture of fuel, oxygen and heat are combined, a fire is ignited. This ignition involves a chemical process that produces an exothermic reaction characterized by an increase in temperature above the ambient.

At this stage, the fire is small; that means that, its airflow, buoyancy and pressure differences are limited. This stage is referred to as fuel-controlled as the environment does not have any effect on the combustion process of the fire. After ignition, the fire continuously grows, enlarges and produces an increasing amount of energy. Depending on the available fuel type, fire can grow either at a rapid or slow pace. In a rapidly growing fire, especially with flaming combustion, the fire tends to spread over a surface, and continuously enlarge itself. In some circumstances, the heat flux generated is large enough to transfer to the surrounding areas and ignite another fuel package (i.e. furniture or books) nearby. However, there are some exceptional cases where the flame is small, for example a burning incense stick. The growth period in this case of fire is long and energy releases are at a very low rate. This type of fire will not have a big impact towards its surroundings and may die down before even reaching subsequent stages.

Flashover is the conversion from the growth stage to a fully developed fire. At this stage, the total surface of the fuel package (i.e. furniture or books) within the enclosure will be involved in a fire. There is no exact point for flashover. Generally, the flashover can occur when the temperature reaches approximately 500-600 °C, or when the radiation to the floor of the enclosure (enclosure) is about 15-20 kW/m^2.

Fully developed fires occur when the combustion process reaches its highest energy release rate. In most cases, all of the fuel package within the enclosure will burn and contribute to the combustion process. The enclosure temperature at this point will reach its highest point in the range of approximately 700-1200 °C. At this stage, the process is limited only by the supply of oxygen and therefore, ventilations and openings have a tremendous influence on the process. When the opening is small, air exchange rate through the opening is limited, thus leaving high temperature un-burnt gases to build-up. As these hot gases leave the enclosure, oxygen from the atmosphere gets into the enclosure, this causes mixing and creates a flammable mixture. When this mixture ignites, it causes the flame to stretch out (extend) through the opening.

The energy release rate will decrease and the temperature will drop after some time. This decay in combustible process occurs when most of the available fuel is well consumed. Shortly after, the combustible process starts to decay. The system is then no longer controlled by the supply of oxygen or incoming airflow, but by the quantity of fuel that is available to sustain the process. The burning process is deemed to be complete when the fuel is completely burnt.

1.2.2 Phenomena Occurring During Combustion Process

In general, the complete burning process will experience the stages as discussed earlier. The growth of a fire is restricted due to the enclosure geometry, ventilation, the type and amount of fuel available. With this aside, several other phenomena can be observed during the process of combustion. The following section describes the common phenomenon that occurs during the process of combustion.

After the ignition of fuel, the fire starts to grow, producing energy in the form of heat and light. This results in the air above the flame also getting heated. As cold air surrounds the hot air, the less dense hot air will rise upwardly as a plume, thus building up on the ceiling. In other words, the buoyancy force is one that causes the hot air to rise up entrains the cold air from the surroundings into the flame, to replace the hot air. As the burning process might not be complete, toxic gases and small particles are produced. These are the products from the combustion process mix with hot air, and rise to the ceiling.

As the hot gases and mixture of combustion products rise and impinge on the ceiling, a layer of hot gases start to form under the ceiling. The gases will spread across the ceiling as a momentum-driven circular jet. The velocity, temperature and the spread of the jet is important in fire engineering as these are used to calculate the time response for smoke detectors or sprinklers installed in the ceiling at different locations.

When the combustion process reaches its potential stage, it uses the maximum amount of oxygen available to generate maximum heat. Therefore, ventilation and openings play a vital role in affecting the combustion process and in the amount of heat generated. Ventilation openings are located on walls which are closer to the ceiling. In the presence of a vent on the wall, the hot gas layer descends from the ceiling and exits through the vent. Simultaneously, cold air will flow inside through the lower part of the vent, creating a bi-directional heat exchange through the opening. However, if several openings on the wall exits, uni-directional flow can occur across some openings. That is, either hot air is flowing out to the ambient, or cold gases flowing from the outside the enclosure. This phenomenon occurs due to the presence of a pressure difference and buoyancy force within the enclosure.

If no openings exist in the enclosure, the hot layer that builds up under the ceiling will soon descend toward the flame region and after a period of time, it will cover the flame. As the air entrained into the flame contains minimum oxygen, the fire may die out. This phenomenon is called oxygen starvation. Even though the energy release rate is low, the pyrolysis may continue at a relatively high rate. At this time, should any opening become available, such as a window breakage, then the cold air will entrain to the system, thus re-igniting the fire.

When the cold air entrained into the enclosure mixes with the unburned pyrolysis product, a highly flammable mixture is generated. At its worst, either a small ignition or a smoldering fire is created, both of which will ignite the mixture. This then leads to an explosion or exceedingly rapid burning of the gases, and sometimes expels the burning gases out through the opening. This phenomenon is termed back draft and is extremely hazardous. Usually, a backdraft will only last for a short period of time (i.e. a few seconds).

During the combustion process, the generated energy is transferred to the surrounding area mainly through the three heat transfer mechanisms: conduction, convection and radiation. The heat is transferred to the ceiling by radiation and convection from the rising plume of hot gases that is built up under the ceiling.

1.2.3 Factors Influencing Fire Development in an Enclosure

As mentioned earlier, to form a complete combustion process, there is a need to have three essential elements: oxygen, heat and fuel. Therefore, the magnitude of the energy produced, the temperature, and the time duration of the fire are influenced by these three main factors. Any changes of the enclosure set-up or fuel supplies will have a significant impact on the combustion process. Therefore, this section will discuss the factors affecting the combustion process.

Ignition sources play an important role in the combustion process. This is because without the first ignition of fuel, fire will never burn. The ignition energy can take one of the three following forms, mechanical, electrical or chemical. The greater the energy of the source, the quicker the fire grows on the fuel source. In addition, the location of the fuel source plays an important role. As the energy of fire is transferred from bottom to the top, fire positioned at the bottom of a surface may cause rapid upward spreading of flames and fire growth. However, if the source of fire is positioned at the top, the fire will grow slower in a downward position.

The fuel system is another aspect that influences the combustion process. The burning process is strongly dependent on the material type, the enclosed fuel location and its surface area. Generally, the burning fuel can be categorized into solid, liquid and gases. The most common fuel material in building fire appears in its solid state, such as furniture, books, furnishings, wooden wall, and plastic. Wooden furniture has much slower burning rate, but lasts longer. It has a constant heat generation but a lower energy and temperature. Alternatively, plastic equipment or furniture burns rapidly at a shorter period of time.

Besides this, the position of the fuel package also influences the burning rate, temperature and height of flame. When the fuel package is placed in the middle of the enclosure, ambient air manages to entrain from all directions. However, when the fuel package is placed against the wall, the air entrainment into the system is limited, resulting in a higher temperature and higher flame height. In addition, if two or more fuel packages are positioned near to each other, it will increase the flame height and accelerate the burning process. The nearer the fuel packages are to each other, the easier they contribute to the burning fire.

Ventilations and openings on the wall of enclosure have significant effect on the process, especially during the flash over and in the presence of a fully developed fire. If the openings are large enough, air exchange can happen quickly enough, and the combustion process can take place rapidly and optimally. However, for small openings along the wall, the burning process is limited due to nominal oxygen availability. The fire will burn at a slower rate. At this stage, the fire is said to be ventilation-controlled. If the enclosure is closed with minimal leakage, the fire will become oxygen deprived and may self-extinguish.

1.3 Ceiling Jet and Ventilated Enclosure Fire

The classical representation of houses or office buildings is always co-related to the design of enclosures with one or more openings such as windows and doors. These openings are connected to the ambient or adjacent rooms and are termed as vents. They allow the air to flow into or out of the enclosure, and exchange with the surroundings. During building fire, the ventilation geometry, locations and its characteristics have a very strong effect on the fire growth and the temperature rises, as sufficient of supply of fresh air into the combustion process lead to a higher burning rate. The time required for the fire to reach the fully developed stage is shortened.

The effect of ventilation system brings up two main properties of the enclosure: (i) pressure difference across the vent, and (ii) the gas temperature difference across the vent. With a physical insight on the effect of these factors and their values, an engineer will be able to determine the characteristics of hot gases exiting the enclosure, or cold air entering the enclosure.

At its initial stage, building fire grows and produces a rising amount of energy thus causing the fire to spread. The enclosure has very minimal effect on the fire and air properties change very slowly due to the fire. When the fire grows from the ignition stage to a fully developed stage, it generates a very high-energy rate and increases the surrounding air temperature. The pressure of the air within the enclosure changes, and controls the flow of gases into and out through the vent.

During a building fire, the air above the flame gets heated and expands. As the density decreases, the hot gases move upwards and accumulate under the enclosure ceiling. This layer is known as a thick hot smoke layer. As the air begins to heat up and push away from the flame, the fire will have a lower pressure compared to the surroundings. Thus, the lower temperature and higher pressure of the ambient air will entrain the cold air into the fire. Simultaneously, the hot air near the ceiling moves away from the fire and mixes with the ambient air. As the hot air separates itself from the heat source, the temperature starts to drop and the mixed hot air travels downward along the side of the wall to the bottom of the enclosure. This cool air will then again get entrained into the fire. This creates an air circulation within the enclosure and a hot smoke layer builds up from under the ceiling. Figure 1.1 shows the schematic of the fire and plume development within an enclosure.

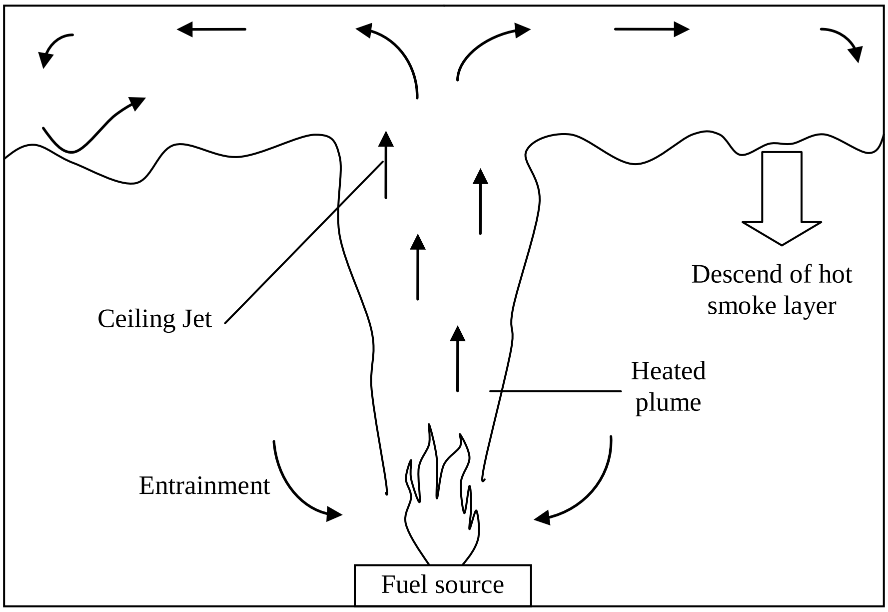


Figure 1.1 Schematic of a fire plume and hot smoke layer build-up in an enclosure.

With appropriate ventilation, the enclosure is able to reduce the impact of the growing hot gas layer from developing beneath the ceiling of a fire enclosure. This is achieved by allowing the hot gases to flow out to the ambient, thereby reducing the growth rate of the smoke layer thickness and temperature.

The gases will begin to flow through the vent either to an adjacent room or to the ambient when the enclosure contains one or more vents. Varying air pressures across this vent, and the formation of a neutral plane separating the layer of hot and cold gases controls the flow of gases across the vents. Hot gases will flow out through the upper part of the neutral plane and the cold gases will flow in through the lower part. The pressure difference between both planes is zero and is referred to as the reference height in vented enclosures.

The rise of temperature accompanied by a hot smoky layer will significantly increase the hazardous condition for human safety and reduces visibility. This makes it difficult for people to find an escape route. Also, the structural elements are at a danger of collapsing due to the temperature rise, the thermal feedback to fuel sources or other combustible objects and thermal influence on the detection of fire and the activation of sprinkler systems. This limits the effectiveness of firemen when rescuing victims and movement during evacuation.

From the ignition stage to becoming a fully developed fire, the temperature of hot air can rise from room temperature up to about 1200 ^{o}C. The time taken for the fire from the ignition stage to become a fully developed fire can range from 30 minutes to 3 hours. This process is strongly limited by the availability of oxygen, fuel source, fuel types and location within the enclosure. With sufficient oxygen supply, the combustion can occur at a more rapid pace.

The combustion process has a high energy release rate. When energy release rate is known, the conservation equations of mass and energy will allow the gas temperature to be calculated. The availability of oxygen depends on the size of the vent that is open to the surroundings. When large ventilation is present, the hot air can escape quickly to the ambient, and cold air can entrain into the flame. In the case of insufficient ventilation, the hot smoke layer will soon descend towards the flame and eventually cover the flame, and the fire may get extinguished due to a lack of oxygen supply.

1.4 Scope of the Present Work

The aim of the present study is to investigate the flow and heat transfer characteristics of a heated plume within enclosures by simulating hot air movement occurring in a building fire environment. Experiments have been performed on two scaled-down models of enclosures, at the laboratory level, to understand the flow and heat transfer effects. The study considers the effect of both natural convection and forced convection flow patterns within a small and a large enclosure with and without ventilation.

The following are the objectives of the present research that help to achieve the aim:

- to design and construct suitable enclosures and ventilation;
- to perform systematic experiments on the enclosures with specified thermal and flow boundary conditions simulating natural and forced convection heat transfer;
- to analyze the results in order to provide a better understanding of the movement of heated plume within enclosures at different heights and explore its characteristics with ventilation conditions; and,
- to predict the effect of plume heating of the ceiling.

1.5 Structure of the Thesis

The background, introduction, aims and objectives of the research were described in this introductory chapter of the thesis. These are important in providing the motivational factor behind this research and why is it important to understand the heat and fluid flow characteristics, enabling a better design of rooms in a building for fire proofing.

Before going into the design and experiment chapters of this thesis, a review of available literature related to this topic is provided in Chapter 2. This review provides a good background of previous studies in the area related to the current study, which helped in the organization of the current study. Chapter 3 presents the development of experimental models and test rig, material selection, instruments used, the experimental procedure, and flow visualization studies.

Chapters 4, 5 and 6 present the results, and provide discussion of results obtained from the experiments carried out in the present work. Comparison and discussion of natural convection and forced convection cases are brought up in these chapters as well. The conclusions from the present study are given in Chapter 7.

1.6 Summary

This chapter provided an introduction of the problem, aim and objectives of the present study. An outline of the structure of the thesis was also presented. The next chapter provides a review of literature.

CHAPTER 2
REVIEW OF LITERATURE

2.1 Introduction

A review of previous work in the area of building fires in an enclosure will be presented in this chapter. This review includes the importance of the knowledge of flow and heat transfer characteristics, ventilation parameters and boundary conditions. This study strives to contribute to a better understanding towards developing the scope of work of the present study.

2.2 Review of Previous Studies

Marshall [1] had studied the flow of smoke and hot gases in open shafts with a separated fire compartment and open shafts. The air that was entrained into the fire compartment was measured and isolated from flowing into the shaft. Hot gases flowing out of the shaft were also monitored to enable the amount of air entrainment within the shaft to be determined. In the open shaft, only the hot smoke layer from fire compartment was allowed to flow through. The experiment showed that the gases clung to the wall as they flowed up the shaft. Both ends of the plume were bounded by the two side walls of the shaft and therefore only one face of the plume was exposed to the cold air. In this study, a vertical wall was acting as the central dividing axis of the plume with one side representing the real plume, and the other as a ghost plume. The experimental mass flow rate showed a good agreement to the theoretical mass flow rate.

Steckler et al. [2] studied the heated air flow induced by fire in a compartment at the developed fire stage. The compartment had various openings and experiments were conducted with varying heat source locations and measured the corresponding opening flow rate. They also obtained the equation of mass flow rate through the opening as a function of fire strength, opening geometries and fire location. The results collected were compared to the calculated idealized flows. They found that the fire was at its greatest when it was allocated nearest to the opening and it decreased with distance away from the opening. The fire plume entrainment profiles were similar to free-standing plume models except for small opening as the entrainment rates is twice or three times greater than the rates predicted by the free standing plume model.

Azevedo and Sparrow [3] numerically and experimentally studied the heat transfer and fluid flow in a vertical and one side-heated channel with fluid entering it through a vent from the unheated wall. These experiments were conducted with water as fluids. They found that the presence of the vent will result in a decrease in the mass flow rate entering the opening of the channel. However this does not significantly impact the total mass flow drawn into the channel. Nusselt numbers for the channel were found to be insensitive to both the vent opening size and its location of the vent and the experimental results corroborate with the numerical results.

Tanaka et al. [4] conducted full-scale experiments on building fires for determining the burning conditions to be applied for toxicity tests. The full-scale experimental model consisted of two rooms that were interconnected: the fire room and an adjacent room. The adjacent room was opened to the ambient with a fixed doorway. The tests were conducted with different opening widths of the door (29, 44, 59 and 89 cm) of the burn room. A burner of size 60 cm × 60 cm was located at the centre of burn room, and had different gas flow rates. The result showed a close relation between the temperature elevation and the oxygen depletion in the burn room. At the beginning stage of burning, the heat transfer within the burn room had strong correlation between the temperature rise and oxygen concentration.

Epstein [5] experimentally studied exchange flow through horizontal opening between two compartments by using brine and water as working fluids. The buoyancy driven exchange flow pattern was observed for a single opening and two openings system. Experiments were conducted by changing the opening ratios L/D where L is the length of opening and D is the diameter of the opening. Results show that with single opening, the flow rate decrease with increase of L/D and flow pattern change from oscillatory exchange flow at very small L/D ratio to Bernoulli flow and turbulent diffusion flow regime at high L/D ratio. For the two-opening case, the flow changed from unidirectional flow to bidirectional flow at higher density differences due to the buoyancy-driven force.

Cooper [6] developed an algorithm and associated computer subroutine in modeling a two-layer zone type compartment to predict the instantaneous rate of convective heat transfer from the fire plume to the ceiling surface. Also presented is the simulation of convective heat transfer to the walls and ceiling which accounts for the effect of fire location.

Yu and Joshi [7] numerically studied three-dimensional laminar natural convection in vented enclosure. Five different vent configurations were allocated at the four different walls on the enclosure with Rayleigh numbers ranging from 10^4 to 10^6. The result on single vent configuration, top vent and right vent were giving similar cooling effect of the heat source but, the flow and temperature pattern had very large discrepancies. The vent on the side wall only managed to cool the heat source up to certain limits comparing to top and right wall and the vent at bottom wall had almost no effect on the cooling of the heat source. The largest cooling effect is the result of the combination of vents on the top and right walls.

Zhuman and George [8] had worked on the same model two years later. The research was carried out with comparing an indoor air quality analysis network model, CONTAMW with the past analysis and experimental results. CONTAMW was developed to determine airflow and contaminant concentrations in each compartment of a building and also used to model smoke control systems in a multi-story building. From the results, Zhuman and George found out large differences between the predicted results as compared to the measured results. However, the two-zone model or ordinary differential equations (ODEs) was found to have given better results with the experimental data than the network model.

In the experimental study on mass flow through a horizontal vent in an enclosure due to pressure and density differences by Tan and Jaluria [9], fresh and saline water were used to simulate the flow across the horizontal vent due to the pressure and buoyancy effect. Under zero pressure, the difference between the density of fresh and saline water generated bidirectional fluid flows across the vent, due to buoyancy effects. When increasing the pressure in the lower region, the flow gradually shifted to form a unidirectional flow. For pressure differences less than the critical value, the buoyancy effects are comparable to the pressure effect and the resulting flow rate is a consequence of the two opposing effects. The use of Bernoulli's equation is only appropriate when the pressure differences are much larger than a critical value with appropriate discharge coefficient, C_D.

Shim et al. [10] performed an interferometric investigation of natural convection in a partially opened enclosure with a discrete heat source. The test model had an opening in the right vertical wall, heat source at the bottom surface and a divider at the top wall. The effects caused by changing the opening length, divider height from the ceiling, and temperature of heat source were taken into consideration. Throughout the experimental investigation, they found out that when the opening length on wall was small, the opening did not have any significant effect on the air flow from the heat source. The test model gave a symmetrical temperature distribution along the x-axis. Besides, the divider that separated the model into two sections prevented the development of upward flow from the heat source. The model without the divider had higher temperature distribution than the one with a longer divider. Thus, they concluded that the flow rates of the incoming air increased with a larger opening on the wall, smaller divider height and higher heat source temperature.

A two-zone fire growth and smoke movement model for multi-compartment building was studied by Zhuman and George (2000) [11]. They evaluated the risks of building fires in a compartment with both fire and smoke, and a compartment without fire and smoke with different physical models and numerical methods. From Zhuman, the compartment with fire or smoke was more suitable to solve with two zone ordinary differential equations (ODEs) while for the compartment without fire and smoke, non-linear algebraic equations based on mass conservation was used. The four independent solution variables used were pressure, enthalpy of upper layer, mass of upper and lower layers denoted as P_i, H_i, m_U and m_L. Results predicted from numerical modeling were then compared with the experimental data. The overall results proved the similarity among the numerical and experimental data especially for the upper layer gas temperature, interface height and vent flow rate.

Darmono [12] numerically studied the smoke spreading and temperature gradient of burning compartment with an additional compartment below the ceiling. This additional compartment aimed as smoke reservoir collected the smoke from burning compartment and not infiltrated into the adjacent room. This also created a clear route for occupants to escape using evacuation route. Darmono found that by adding an additional compartment under the ceiling, the smoke and hot layer will eventually move upwardly due to the buoyancy force and gets stored in the compartment. From the time elapsed for temperature rise and height of smoke layer, it clearly showed that it took a longer period for smoke to build up in the burning compartment. This provided more time for the occupants to evacuate from the building or burning room.

Chow et al. [13] experimentally studied mechanical smoke system in an atrium to analyze the correlation between heat release rate and mass loss rate of fuel source to the forced convection of the atrium. They observed that with a higher heat release rate, the smoke layer interface descended lower and the smoke layer temperature increased. By increasing the exhaust rate to drag out the hot smoke, it will reduce the smoke layer build-up. However, these were limited up to a certain heat release rate of the fuel source.

Chow and Zou [14] used Fire Dynamics Simulator (FDS), a computational fluid dynamics software (CFD), to simulate the doorway flow rates induced by a room fire, and derived the correlations. These results were compared to the experiments reported by Tanaka et al. [4], which were in good agreement to the empirical correlation equations.

Yii et al. [15] had conducted a series of reduced-scale experimental fire to study the behavior of fire compartment with door opening and roof opening. The experimental model was a square enclosure with two openings representing the door and roof. During the experiment, various setups of roof opening were selected to find the characteristics of vent flows through the door opening as a function of the roof vent opening area. The experiment was conducted with an internal post-flashover fire which was located at the wall furthest from the door opening. The experimental results shows the mass flow rate of air into the enclosure increased linearly as the size of roof vent opening increased. A set of vent flow formulations based on Bernoulli equation and hydrostatic principle were presented as well.

Chow and Yin [16] had numerically simulated the smoke movement in a compartment fire for fire plume and air flow pattern. The common research on smoke movement and hot air movement always assumed that they were the same. However, smoke is visible suspension of solid or liquid particles resulting from combustion such as carbon dioxide and unburned or partially burned fuel. In this simulation, Chow and Yin had used different particle size to predict the particle trajectories and smoke plume pattern. They concluded that both the temperature and momentum of smoke were dominant by the air flow since the propagation of particles depended on the air flow pattern.

Hadjisophocleous and Fu [17] used a computational program - Fire risk evaluation and Cost Assessment Model (FireCAM) to determine the fire growth within a fire compartment. They used zone-type fire growth model to predict the fire growth and the risk. In pre-flashover stage, a two-zone modeling was applied to the fire compartment, and single-zone model was applied for the compartment fire at post-flashover stage. The experimental data showed good agreement with the computational results.

Mariani and Coelho [18] numerically studied natural convection heat transfer system in partially open enclosures by varying the location of heat source at three different heights of the test enclosure. Effect of natural convection due to the Rayleigh number (Ra) and Nusselt number (Nu) were analyzed. They found that with higher Rayleigh number, temperature in the enclosure will decrease while the Nusselt number increases. In addition, the results showed that the position of local heat source influences the fluid dynamics of air and the heat transfer within the enclosures.

Sleiti [19] numerically studied the vent aspect ratio effect on the air flowing through a horizontal vent due to buoyancy force in a vertical rectangular enclosure divided into two chambers by a horizontal partition. The upper chamber contains cold air and lower chamber contains hot air. The study found that the flow exchange increases with larger ratio of slot width of the opening to the thickness of the partition. Also, when the slot width was very small, a ratio of 0.5 to the thickness of the partition, there were no flow exchange between the two chambers as the viscous forces were as large as buoyancy forces.

From a review of literature, it can be seen that the topic of building fire research involves consideration of fluid flow and heat transfer characteristics, which in turn are a result to the heating of air and its movement within the enclosure (compartment). This is the topic of interest for the present research, wherein the characteristics of a heated plume is explored in detail, for two enclosures – short and tall, and for natural and forced convection situations.

A survey of literature of previous research on this topic shows that researchers were mainly focusing on the overall gas and particle flow within the enclosure, hot air temperature and flow rate flowing into and out of the enclosure through the vents and overall heating properties. The lack of the actual temperature distribution values on different sections at different heights (within the enclosure) from the heat source due to the effect of different locations of the vents had not been carried out in detail. Therefore, the current research will be focusing on this area of finding the actual temperature distribution on different sections of the enclosure such that a better understanding and estimation of the temperature can be obtained. Meanwhile, previous researchers had not compared the differences between natural convection and forced convection temperature distribution within the enclosure with the same modeling under the same heating properties. Therefore, the current research will carry out the comparison between natural convection and forced convection heat transfer mechanisms within the same enclosure, and for different enclosures for the same heating levels.

2.3 Summary

This chapter provided a review of literature for the research related to building fire and ventilation properties, re-iterating the scope of present work mentioned earlier in Chapter 1. The next chapter describes the experiment set up, the models used and instrumentation.

CHAPTER 3
DESCRIPTION OF THE PHYSICAL GEOMETRY

3.1 Introduction

A comprehensive review of literature relevant to the present research work was presented in Chapter 2. The present research examines the thermo-fluid characteristics of air flow in an enclosure with an internally supplied heat source, simulating the movement of hot gases in a room fire environment. The focus of the research includes the flow of air in and out through the vents in the enclosure, the effects of the heat source, estimation of temperature, velocity, and pressure distribution of hot air at different levels within the enclosure. Two enclosures were designed and fabricated in order to carry out the required experiments. The enclosures were designed in such a way that they could be attached to the same test rig with minimal modifications, for both natural convection and forced convection experiments. All experiments were carried out at the Thermodynamics Laboratory at Curtin University of Technology.

3.2 Description of the Test Rig

The main components of the test rig consist of the short and tall enclosures, heaters, and instrumentation. The following sections describe the enclosures and other components of this test rig in greater detail.

3.2.1 Short and Tall Enclosures

Two enclosures were considered for the natural convection and forced convection experiments carried out in this thesis. The enclosures were named short enclosure and tall enclosure. Both enclosures had a square cross-section, but differed in their height. A photograph of the short enclosure used in the experiments is shown in Figure 3.1, and a schematic of the short enclosure in Figure 3.2. The short enclosure had inner dimensions measuring 0.6 m (length) × 0.6 m (width) × 0.6 m (height). The walls of the enclosure were made of Perspex, considering the requirement for low thermal conductivity walls (typically the case for rooms in buildings), and for the need for flow visualization. This short enclosure represented approximately a 1/5th scale model, compared to the typical size of a standard room in a building. The top wall of the enclosure was named as the ceiling and the bottom wall was named as the base of the enclosure. The vertical and horizontal walls were joined by custom-made removable frame brackets to allow for modifications as required for the experiments.

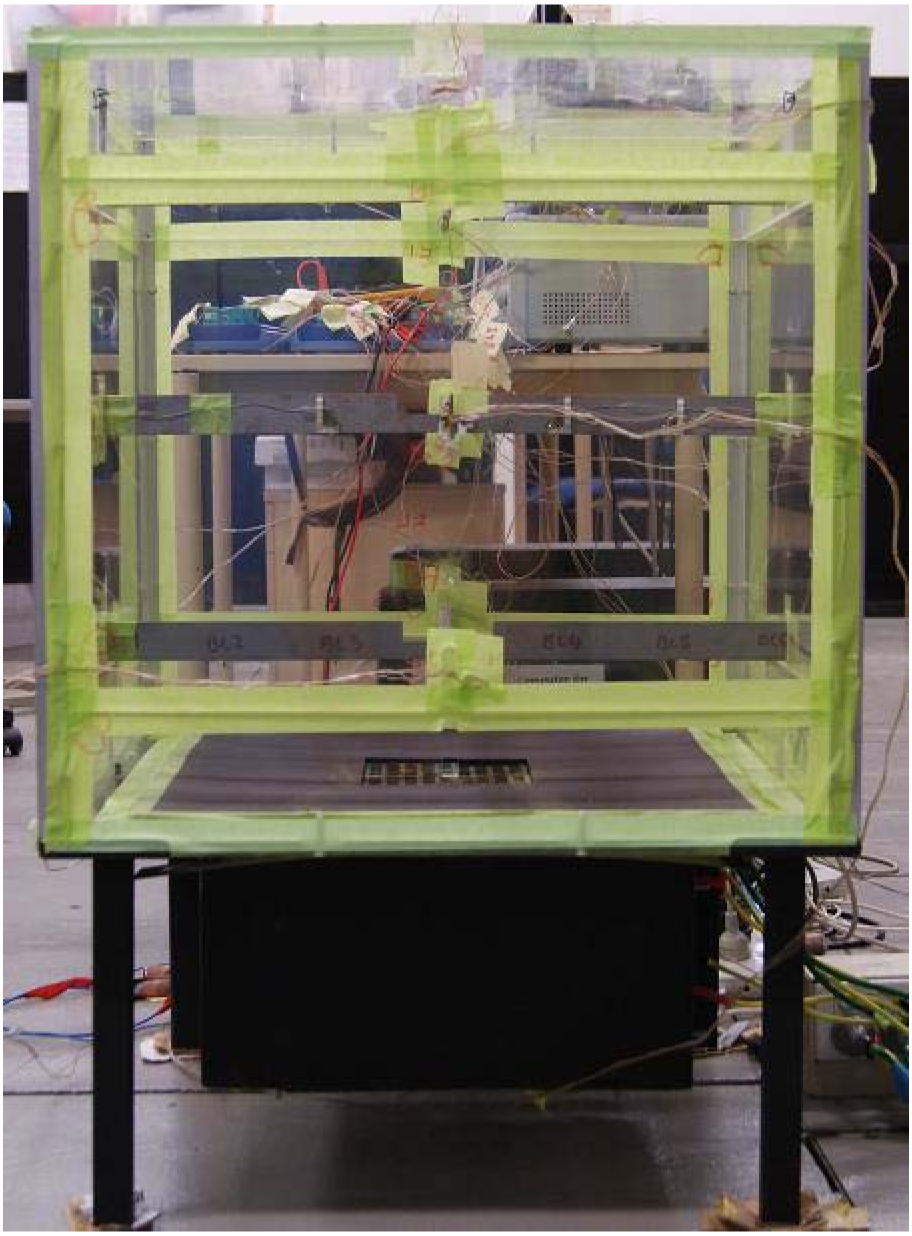


Figure 3.1 Photograph of the short enclosure

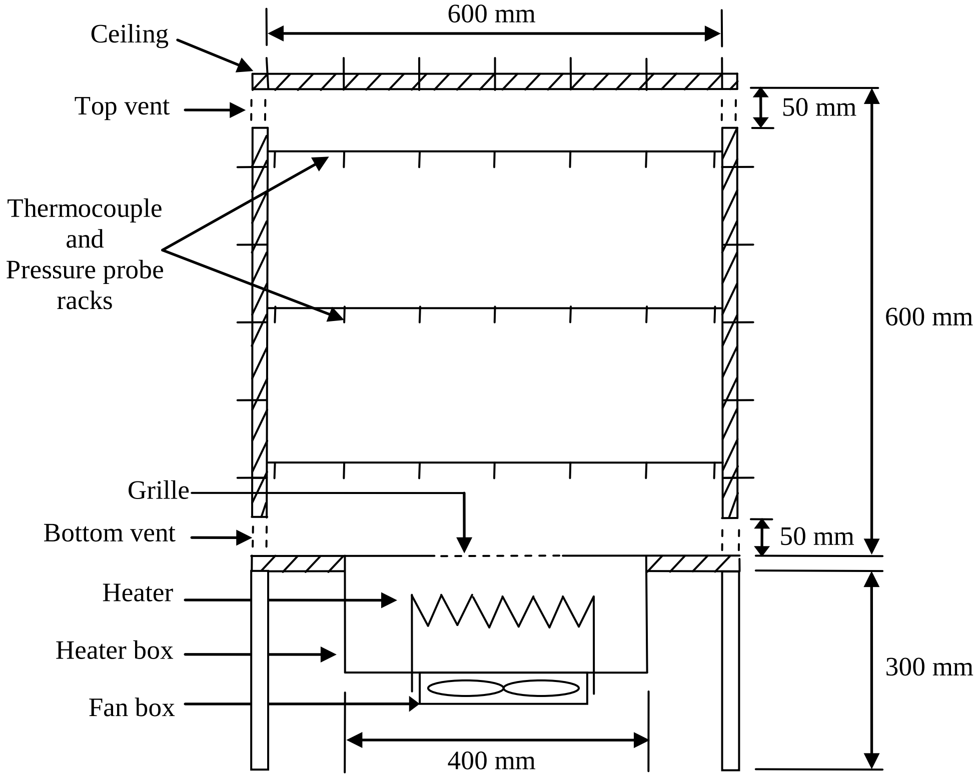


Figure 3.2 Schematic of the short enclosure

The photograph of the tall enclosure is shown in Figure 3.3, and a schematic is shown in Figure 3.4.

Figure 3.3 Photograph of the tall enclosure.

The inner dimensions of the tall enclosure were 0.6 m (length) × 0.6 m (width) × 1.2 m (height). The tall enclosure shown in the above photograph was used for both natural convection and forced convection studies, with suitable changes done to the base floor of the heater box to accommodate the fan for forced convection studies. The walls of the tall enclosure were made of Perspex and had similar vents at the bottom and the top of the vertical walls as the short enclosure.

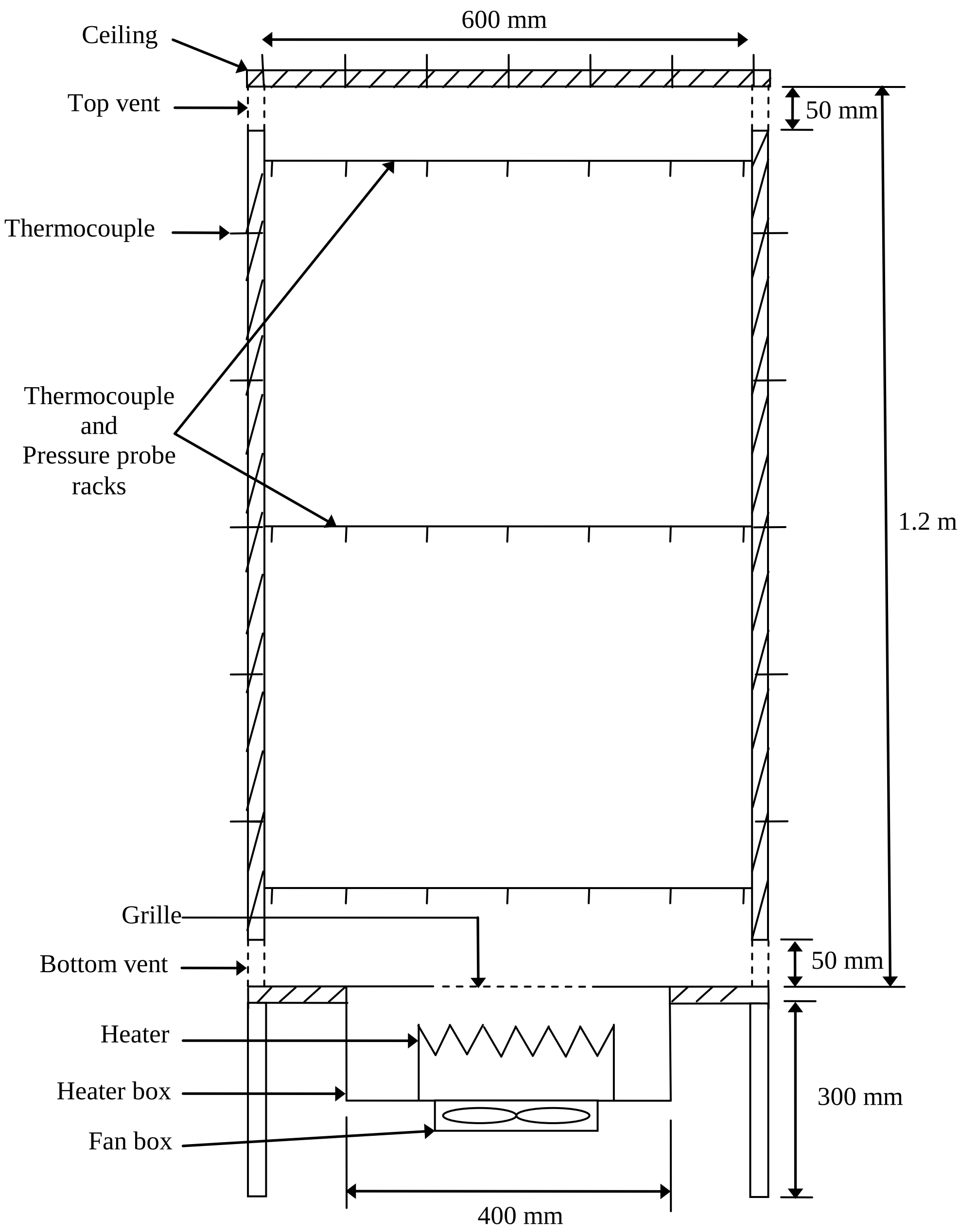


Figure 3.4 Schematic of the tall enclosure

The base of the enclosure was positioned at height of approximately 0.3 m from the ground and was supported by four vertical legs. This space allowed for an adequate flow of ambient air, and also provided the space required to mount a suitable fan for forced convection experiments. A square opening of size 0.4 m × 0.4 m was cut into the centre of the base of the enclosure. A rectangular heater box was attached below this opening. The heater box contained two W-shaped stainless steel finrod tubular electrical heaters (500 W each) that supplied constant heat flux into the enclosure. The heaters had edge-wound stainless steel fins attached to its sheath, and were obtained from Helios Electroheat Pty Ltd. A grille was used as a partition between the heater box and the enclosure such that the heater set-up delivered a uniform heat flux into the enclosure. The photograph of the heater set-up is shown in Figure 3.5.

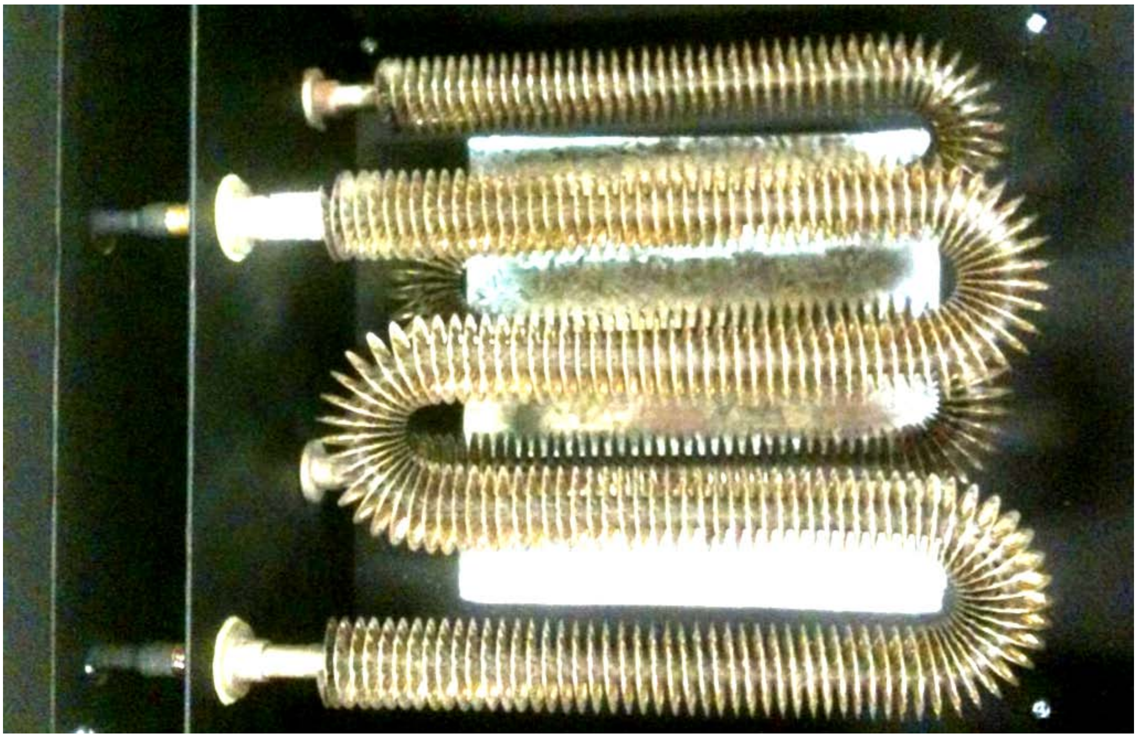


Figure 3.5 Photograph of the W-shaped finrod tubular heater assembly.

Each vertical wall of the enclosure had two vents - one at the bottom, and the other at the top. The top vents were 50 mm × 50 mm in size, and the bottom vents were 12 mm × 50 mm in size. The bottom vents were the inlet vents, and the top vents were the outlet vents for the enclosure. The top and bottom vents were located at the centre of the wall, equidistant from the wall edges. The location of the vents on the short enclosure can be seen in the schematic shown in the side view in Figure 3.6. The bottom vents allowed entry of fresh air into the enclosure, and the top vents provided the outlet for hot air from within the enclosure to the ambient. The top vents were designed in a manner that it formed a part of the wall itself. This provided the flexibility to remove and attach different vents to study a range of outlet flow rates considered in the study.

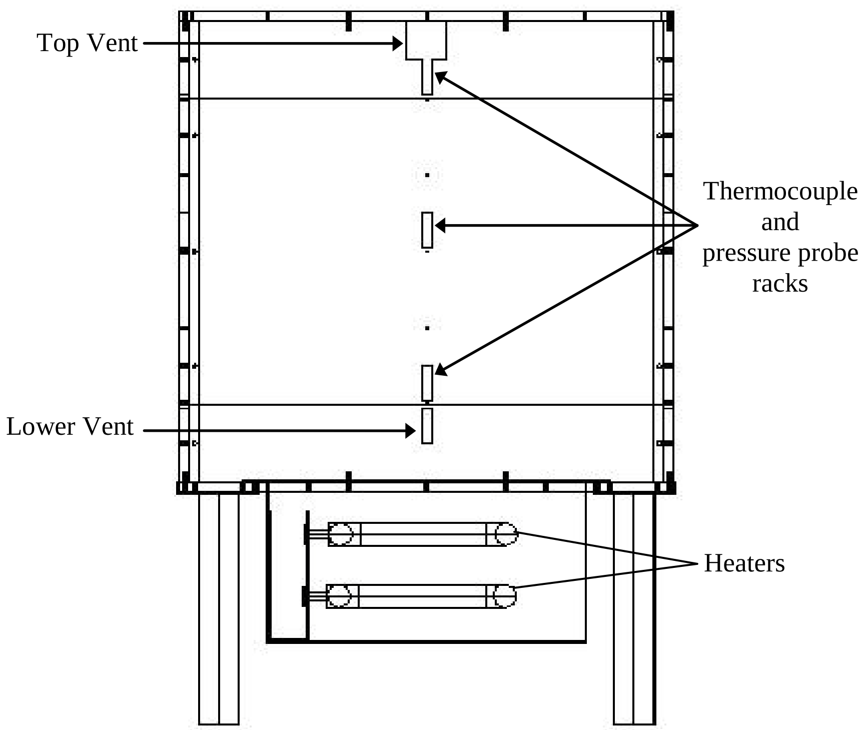


Figure 3.6 Schematic of the short enclosure showing the top and bottom vents

The forced convection heat transfer in a building fire situation is due to a forced flow of air stream caused by either mechanical or electrical means. This is due to appropriate fans that either pull the air out (causing an induced draft), or push the air out of the enclosure (causing a forced draft). In order to study the characteristics of such a forced flow within the enclosure, the enclosures that were used to study the natural convection problem discussed in section 3.2 were used, with some modifications made to the set-up. To create a forced flow within the enclosure, a fan was located at the base of the enclosure to force ambient air through and over the heat source, into the enclosure. For this purpose, a square recess of 300 mm diameter was cut at the centre of the base of the heater box in the set-up. A high-speed automobile radiator fan was mounted beneath the recess. The automobile radiator fan was used as it functioned properly even under the high temperatures encountered in the experiment. The fan operated at 12 V DC, and had a diameter of 305 mm. It was connected to the laboratory DC power supply, GW Instek GPS-2303, to provide a constant power input. Figure 3.7 shows the automotive fan used in conjunction with the heater box.

Figure 3.7 Photograph of the fan used in forced convection experiments.

3.3 Temperature Measurement

For both short and tall enclosures, air and wall temperature measurements were obtained using precision Type-K (Chromel-Alumel) thermocouples from Omega Engineering Inc. The thermocouple had a wire diameter of 0.5 mm. A smaller diameter thermocouple wire was chosen to minimize the effects of thermocouple disturbance to the flow and temperature field during measurement. To consistently achieve a temperature measurement with high accuracy, a thermocouple welder was used to make the measuring beads out of the wires. The thermocouple wire welder TL-Weld from Omega Engineering Inc. was used. To prepare the thermocouple wire for welding, about 12 mm of the insulation around the wires were removed and twisted together. Subsequently, the twisted wires were cut off, leaving sufficient un-insulated material to give approximately 1 mm protrusion for attachment with welding pliers. The wires were positioned in the instrument to the carbon electrode and slowly moved towards it until an arc was created. The thermocouple welder allows a good thermocouple bonding to be formed with a small spherical bead (due to smaller diameter wires). Figure 3.8 shows the close-up photograph of a typical thermocouple bead fabricated in-house for use in the experiments.

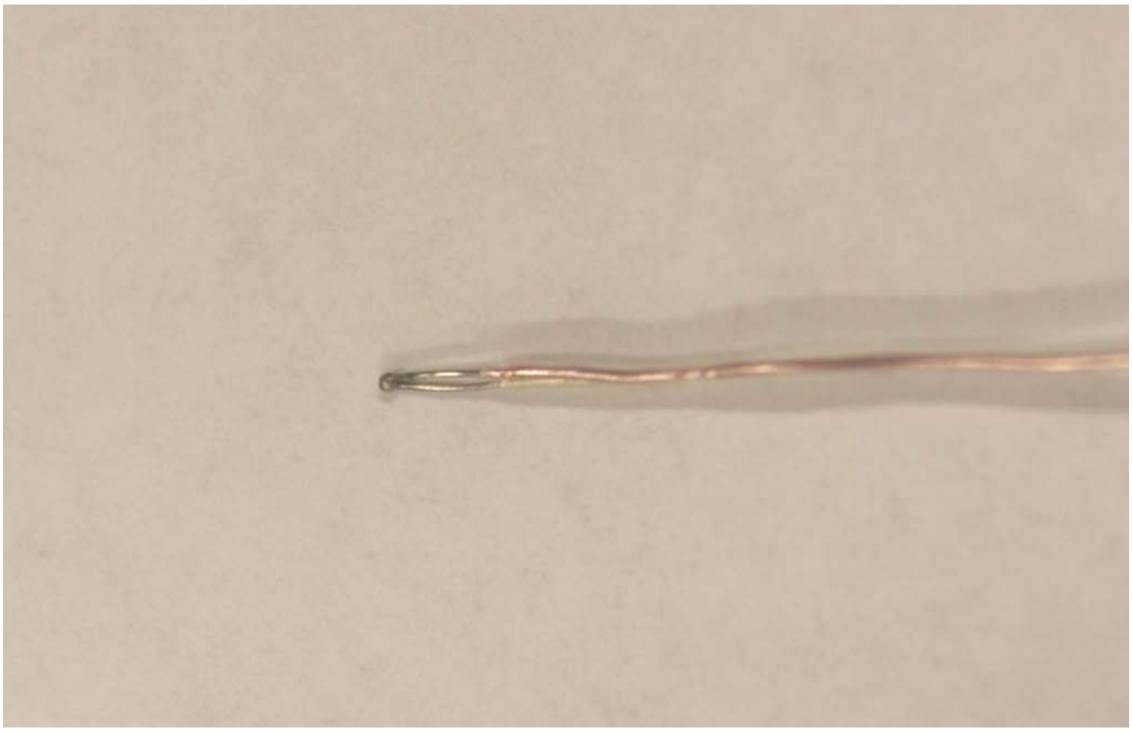


Figure 3.8 Photograph of the thermocouple bead used in the experiments

A total of six thermocouple racks were designed and manufactured for measuring air temperatures. The height of the enclosure was divided into three planes: one close to the base (lower plane), one in the middle, and the other one close to the ceiling (top plane) of the enclosure. Two orthogonal racks of thermocouples were mounted at each plane. For the short enclosure, the horizontal planes were located at distances of 100 mm, 300 mm and 500 mm from the base of the enclosure respectively. The photograph of the thermocouple rack is shown in Figure 3.9.

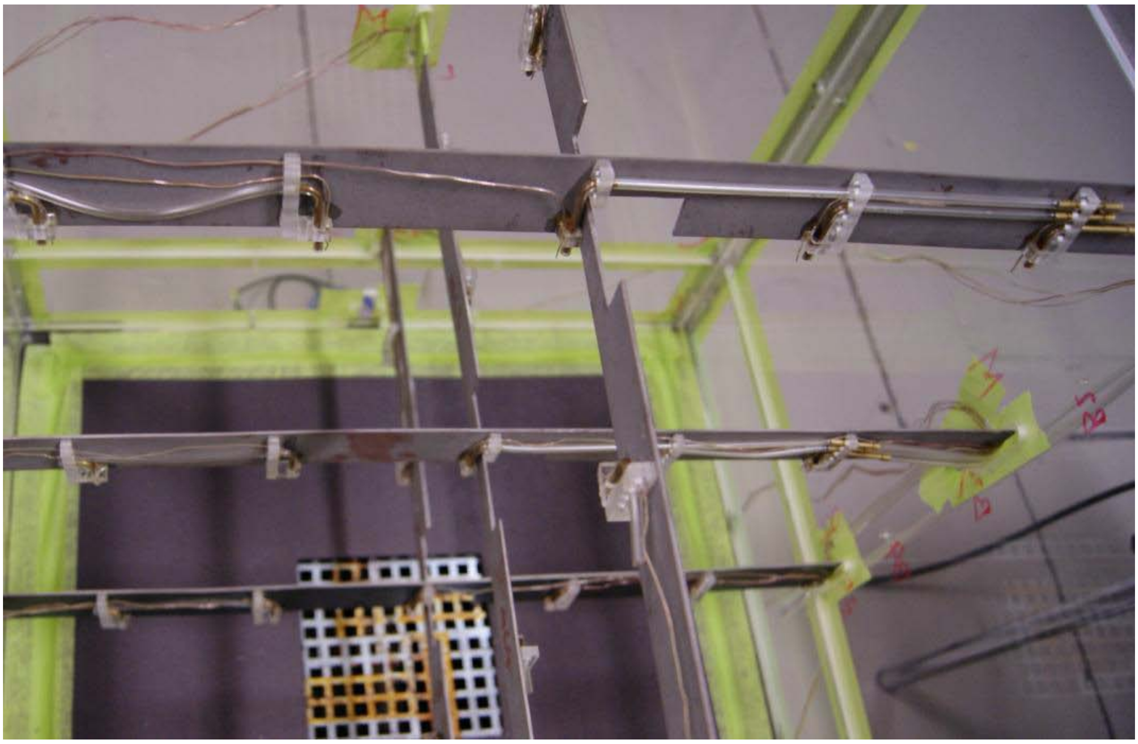


Figure 3.9 Photograph of the temperature/pressure rack.

Each set of thermocouple rack consisted of two aluminum plates crossing each other orthogonally, intersecting at the centre line of the enclosure. The size of aluminum plates were 640 mm (length) × 30 mm (height) × 2 mm (thickness). The 'slim' design allows the plate to minimize the disturbance to the air flow when they flow upward to the ceiling. Seven thermocouples were mounted onto the aluminium plate, 100 mm apart from each other. The thermocouples were positioned such that the beads protruded 5 mm to the hot air to measure the air temperature. These thermocouples were attached to a data logging unit (Pico Technology Limited, UK.) and allowed direct data recording to the computer. The thermocouple locations and the racks on the short enclosure are shown in Figure 3.9. Similarly, for the tall enclosure, three sets of thermocouple racks were mounted within the enclosure at different heights in the enclosure to collect temperature data. They were located at 100 mm, 600 mm and 1100 mm from the base of the enclosure. The thermocouple measuring points on each thermocouple rack were identical to that of the short enclosure. Hence, the thermocouple rack used in short enclosure was able to be used for experiments conducted with the tall enclosure.

The temperatures along the inner surfaces of the walls were also measured using K-type thermocouples. Five thermocouples were mounted along the centre line, at various heights of the enclosure from the base. The thermocouples were embedded in the wall by first drilling a hole through the wall, the placing the thermocouple bead so that it was flush with the inside surface of the wall. A suitable cementing compound made of Araldite™ was then used to firmly attach the thermocouple to the wall. The thermocouple points were separated 100 mm apart from the end of the enclosure. The readings from the thermocouples were recorded using the PICO data logger. The temperature distribution along the ceiling was also measured during the experiments. Seven thermocouples were placed along the centre line of the ceiling, horizontally and vertically with a distance of 100 mm between each thermocouple. These thermocouples were embedded in the holes drilled in the ceiling and cemented with Araldite™.

3.4 Velocity and Flow Rate Measurement

The flow velocity of the heated air at various points along the height of the enclosure was determined by measuring the air pressure at the desired points. In order to measure the pressure, special probes were fabricated out of brass tubes. The tubes had an inner diameter of less than 2 mm, and were fabricated as 90 degree bends. The brass tubes were fixed on the rack in such a way that one end was exposed to the air rising from the base of the enclosure, and the other end was connected to the flexible plastic tubing, which was then connected to the digital manometer. The pressure probes were mounted such that they were 100 mm apart from each other. A photograph of the pressure probe on the rack is shown in Figure 3.10. This photograph also shows the thermocouple.

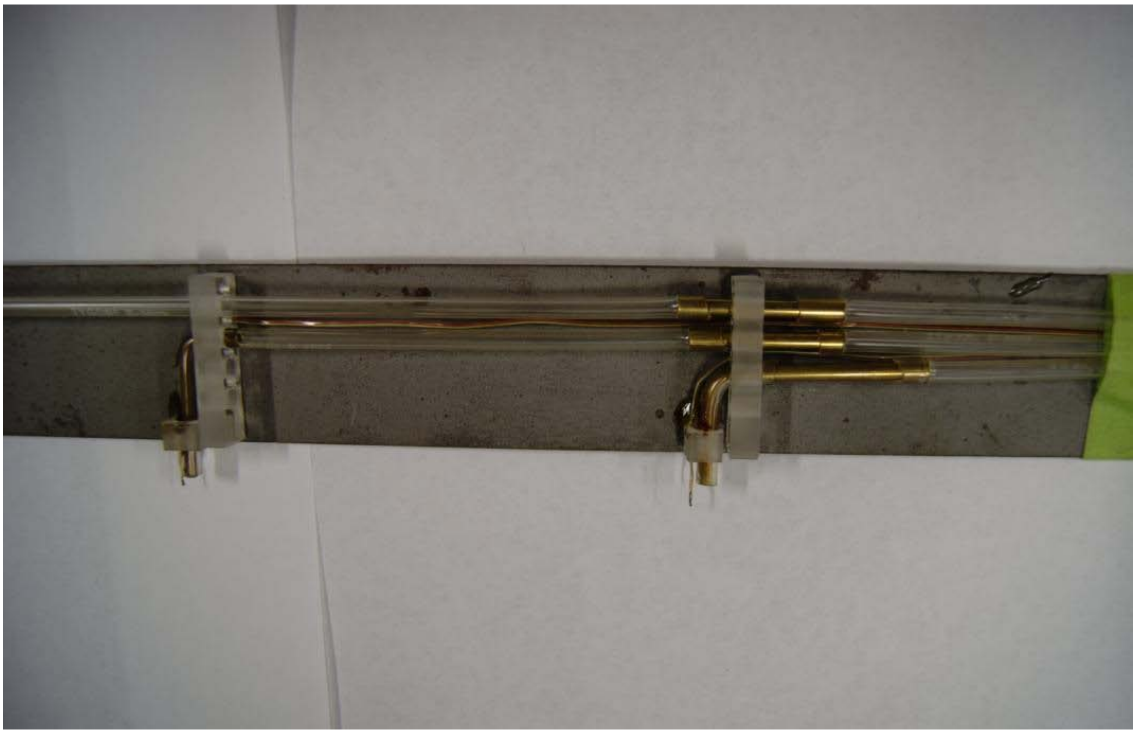


Figure 3.10 Pressure probe and thermocouple on the rack.

The, pressure probes were placed adjacent to the thermocouples on a rack to measure the air pressure at the location where temperatures were measured. The tubes conveying the air pressure were made of TYGON Performance plastic 2.4 mm inner diameter ultra-flexible transparent tubes from Saint-Gobain Inc. The measured pressure differences were used for obtaining the velocity at various points along a plane, along the height of the enclosure.

Each enclosure had two openings, namely the top and bottom vents, which were part of the walls of the enclosure. The top vent allowed the air to flow out of the enclosure while the bottom vent provided an inlet passage for air to enter into the enclosure. When natural convection is present, the flow of hot air flow through the top vent is very small, and hence a very accurate anemometer is required to measure the air flow rate through the vent. The digital micro-manometer PVM620 from TSI Instruments Ltd. was used to obtain the pressure and flow rate measurements.

Figure 3.11 Photograph of the thin film heat flux sensor model HFS - 4.

Within the enclosure and at the center of the ceiling, a thin film heat flux sensor (Model HFS-4) from Omega Engineering Inc. was provided. It was located 5 mm away from the center point of the ceiling wall where the thermocouple is located and towards Wall A. The setup prevents the disturbance of the hot air temperature measured by the thermocouple however, still measuring the overall heat flux impinging from the heat source on the ceiling at the centre. The output from the heat flux gauge was measured using a digital millivolt meter.

3.5 Experimental Methodology

The schematic of the layout of the test set-up of both enclosures are shown in Figure 3.12.

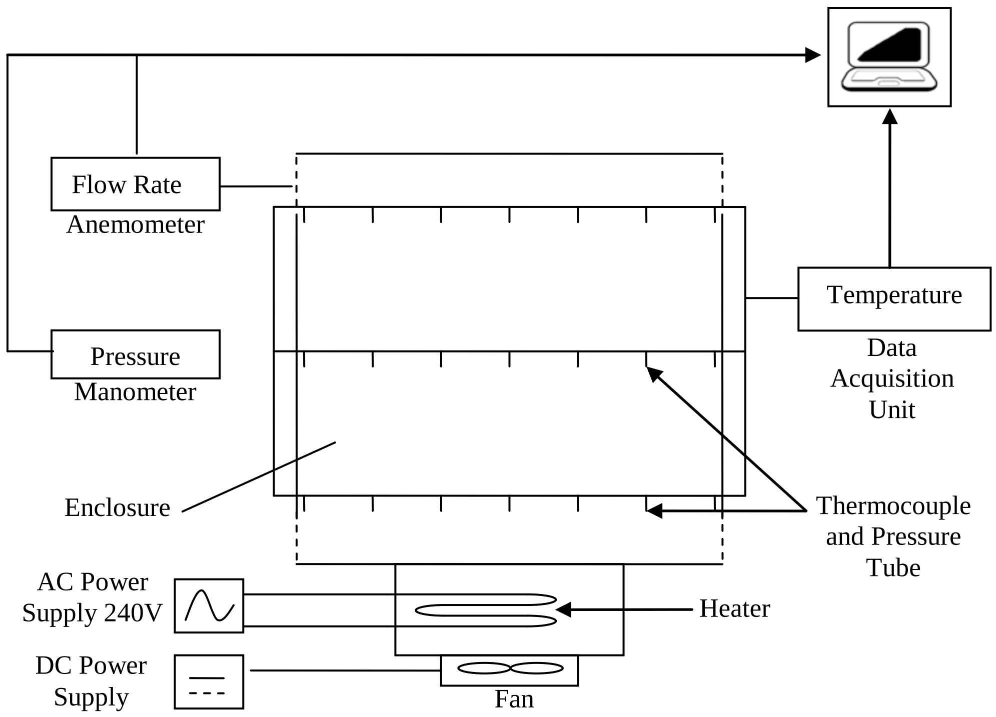


Figure 3.12 Layout of the test set-up.

Before conducting actual experiments within the enclosure, the enclosure was inspected thoroughly, and subjected to several checks and modifications to comply with the safety requirements in the laboratory. The enclosure was positioned horizontally on the floor and the heaters were adjusted so that the hot air moves upward and built-up uniformly under the ceiling, and not to one side. All the edges and joints of the enclosure were sealed with high temperature adhesive tape to prevent air leaks to the ambient. The enclosure was ran without the ceiling during the safety check to obtain the maximum temperature rise as a result of the heater, this was also to check that the enclosure can withstand the temperature without deformation.

The experimental program consisted of running the experiments in the following sequence. The short enclosure was first used to study the natural convection characteristics. This was then followed by forced convection studies using the short enclosure. The tall enclosure was then mounted on the test rig to carry out natural convection experiments. This was then followed by forced convection studies on the tall enclosure. A typical natural convection experiment was conducted as follows. The first experiment was conducted without the ceiling. This was to ensure that the heater was supplying sufficient heat energy into the enclosure, and generating hot air flow within the enclosure. The four bottom vents on the vertical walls were kept open at all times. For a given power input to the heater, the experiment was carried out by changing the top vents at the vertical walls. All the data acquisition units were turned on. Before switching on the heater, temperatures from all thermocouples were recorded. Then, the heaters were turned on and run for 30 minutes. Without changing any parameters, the second set of data from all thermocouples and manometers was recorded. The enclosure was also visually checked to ensure that there were no damages or deformation due to heat. The experiment was then continued for another 3 hours. Temperature and pressure changes were recorded for each 30-minute time interval. After 3 hours, at the conclusion of the experiment, the heaters and data acquisition units were shut down.

During the experiments, the temperature readings of points at identical locations were compared. It was found that an experimental run for approximately 2 hours was sufficient to obtain steady-state conditions. However, in the present study, each experimental run was allowed to continue for 3 hours for additional assurance of obtaining steady-state conditions. The temperatures and pressures were recorded at every 30 minute interval. The experiment was repeated with different combinations of top vents. All the data were recorded and plotted into graph. As mentioned earlier, for the forced convection experiments, the automotive fan located at the bottom of the heater box was energized and experiments were done for a range of flow rates. This was continued for the tall enclosure.

3.6 Establishment of Steady State Conditions

The result of natural convection experiments conducted on the short and tall enclosures is presented next. In both cases, full electrical power was supplied to the heaters, and the experiment was run on natural convection mode continuously for 3 hours. The centre point ceiling temperature of the enclosures was recorded for each

10-minute time interval. Figure 3.13 shows the temperature of the centre point on the ceiling, plotted as a function of time for 3 hours. It can be seen from the graph that the temperature increases rapidly from about 24 °C to about 46 °C for the short enclosure, and from 21°C to 32°C for the tall enclosure during the first 1 hour of heating. The ceiling gets heated due to impingement of the hot air rising upward due to natural convection within the enclosure. The rate of increase is found to be higher for the short enclosure, when compared with the tall enclosure. The air within the enclosure gets heated and moves upward due to density differences, arising out of natural convection.

For the next 30 minutes, the heating of the ceiling wall is found to occur at a slower rate, and is seen to be heading towards attainment of steady state. Thereafter, the temperature rise is very slow, and becomes almost negligible. This is seen from the asymptotic trend of the temperature graph observed beyond about 120 minutes from the start of the heating process. The results of the graph indicate that steady state conditions are attained beyond 120 minutes (about 2 hours) after powering on the heaters. Based on further tests using a few other combinations of vents and heating levels, it was decided to allow a sufficient run time of about 2 hours to enable steady-

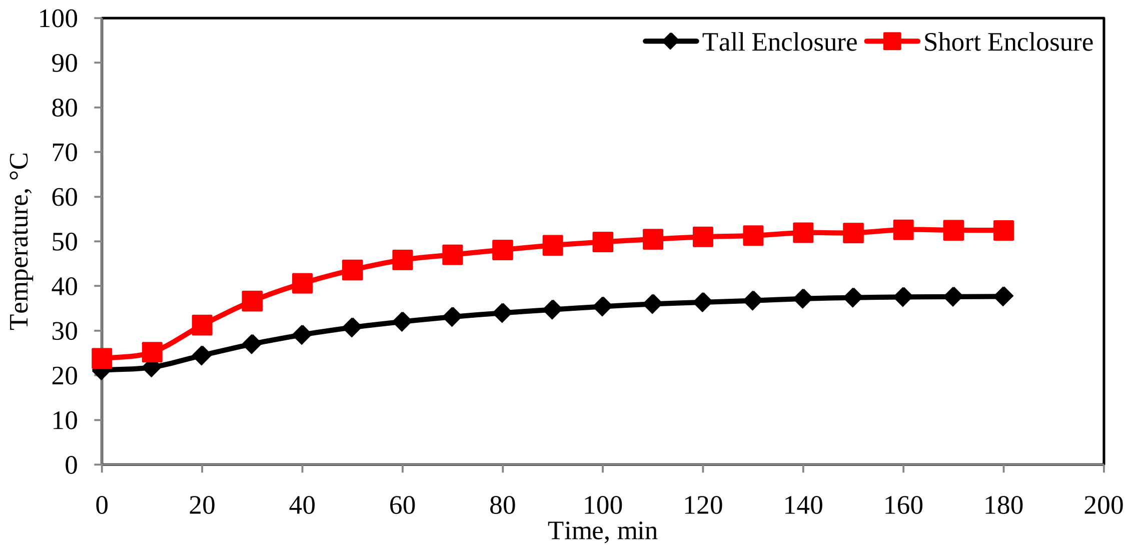


Figure 3.13 Variation of centre point temperature of ceiling with time for short and tall enclosures (natural convection case only).

state conditions to prevail in the enclosure. It was also noted that there was negligible pressure recordings made by the electronic pressure recording from the digital micro-manometer, due to very low flow rates associated with natural convection.

3.7 Flow Visualization

Flow visualization experiments were carried out with the purpose of obtaining qualitative information on flow patterns within the enclosure due to natural convection. In the present research, a smoke generator (PS 27 Dragon Smoke Generator – Pea Soup Ltd. UK) was used to generate smoke for obtaining the flow pattern. For this purpose, the flow cross section was illuminated by spotlights and masking to suitably allow a narrow band of light to illuminate the cross section. Flow visualization photographs were obtained using a Sony Alpha Digital camera with suitable settings. Fine smoke was introduced into the enclosure by means of specially fabricated brass tubes so that the introduced smoke does not disturb the natural convection flow caused by the heater.

A schematic of the flow pattern within the enclosure (short or tall) is shown in Figure 3.14.

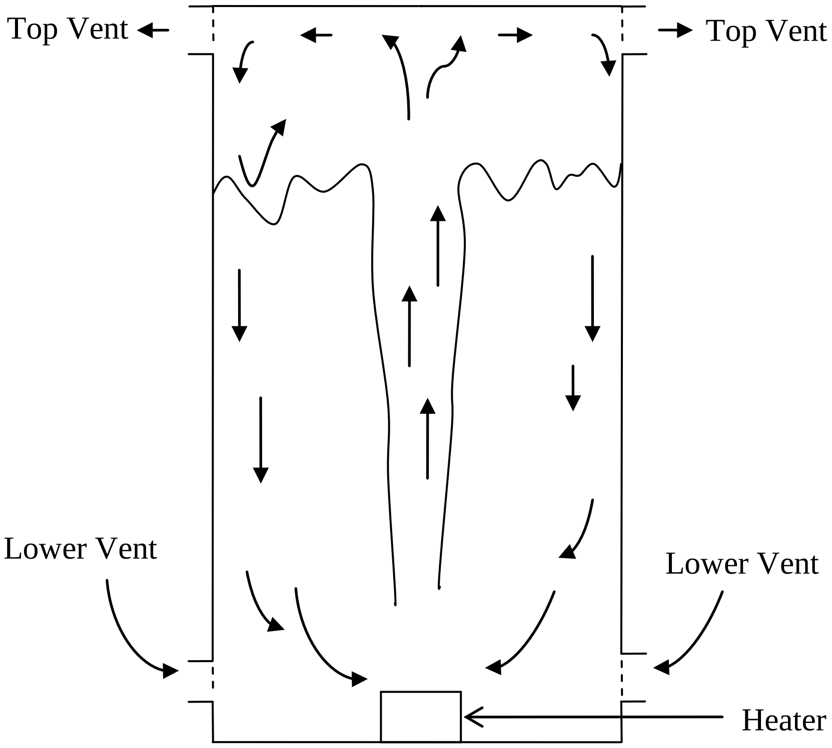
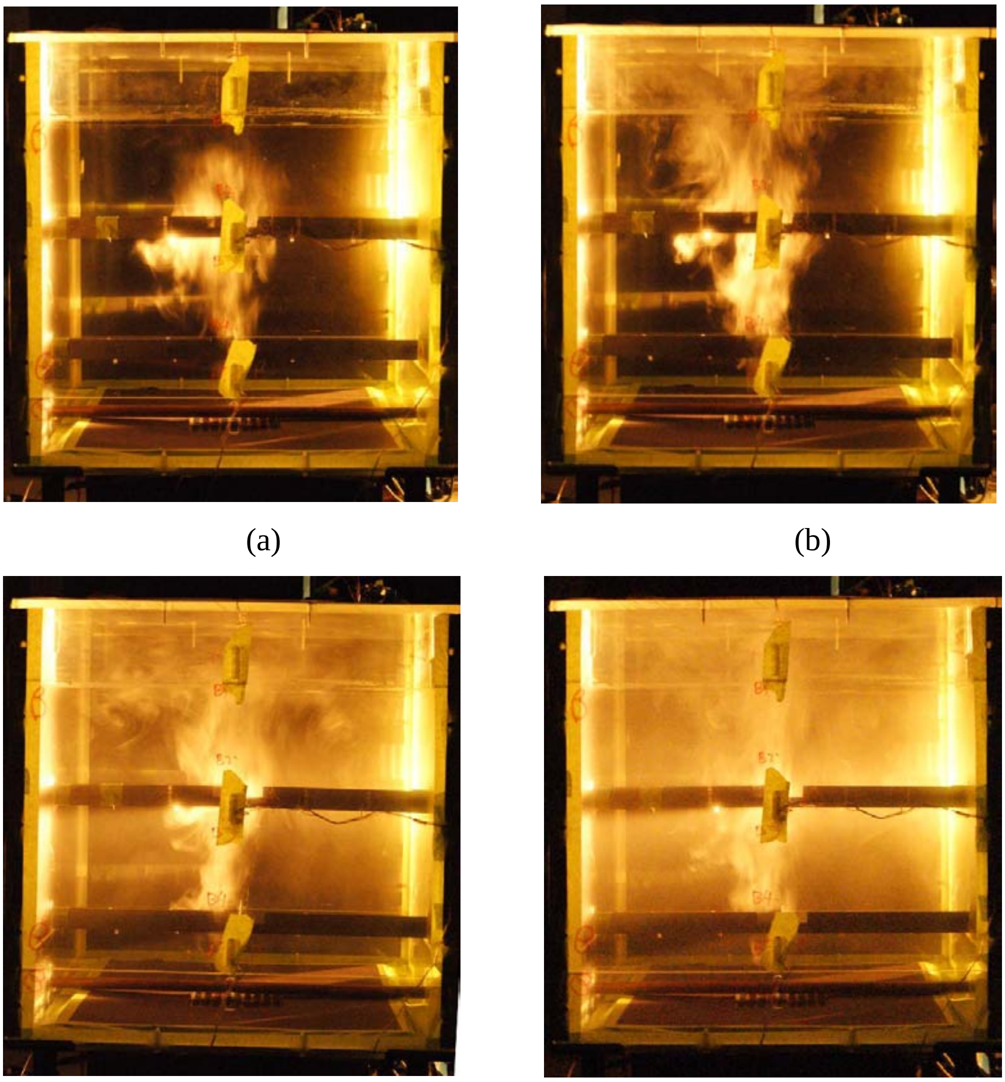


Figure 3.14 Schematic of hot air circulation within the enclosure. The top and bottom vents are also shown.

After powering the heaters, the cool air surrounding the heat source receives a high amount of thermal energy. Due to the density differences with the surrounding air, this heated air impinges on the ceiling. As the heated air rise to the top, it builds-up under the ceiling, and descends as time progresses and hence creating a hot air layer under the ceiling. The hot air near to the vents flows out to the ambient. The cool air surrounding the heat source is entrained into heat source, gets heated and flows to the top.

Figure 3.15 and 3.16 provide the flow visualization for short enclosure with two different vent configurations.

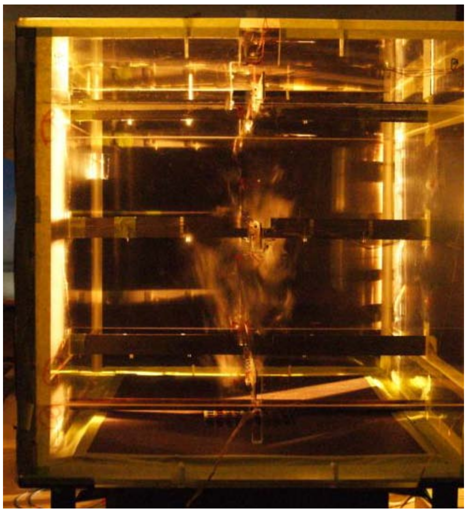


(a) (b)

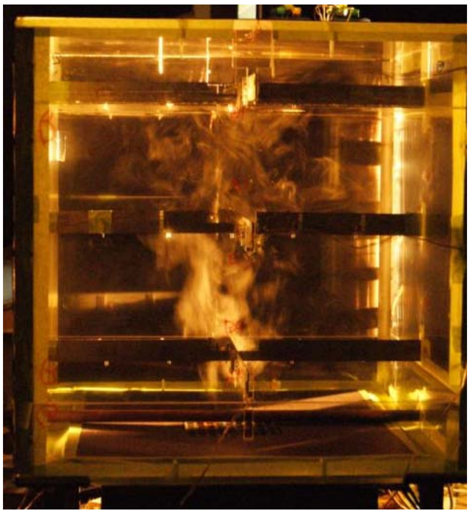
(c) (d)

Figure 3.15 Different stages of smoke growth within the short enclosure with two vents on the wall A and wall C.

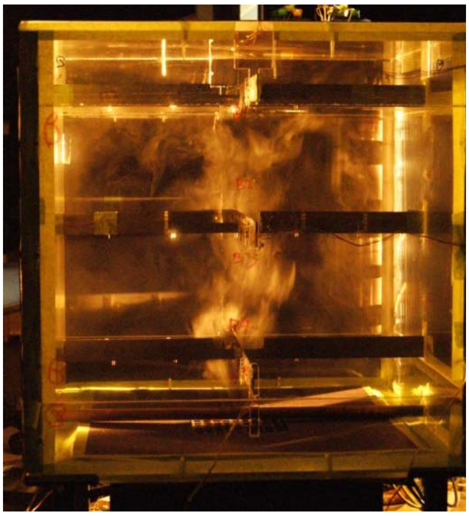
During the initial stage, the smoke gradually rises to the middle of the enclosure (Figure 3.15 (a)). This smoke then impinges on the ceiling and moves along the ceiling (Figure 3.15 (b)). The smoke builds-up under the ceiling (Figure 3.15 (c)), and gradually descends (Figure 3.15 (d)), until it fills the entire enclosure.



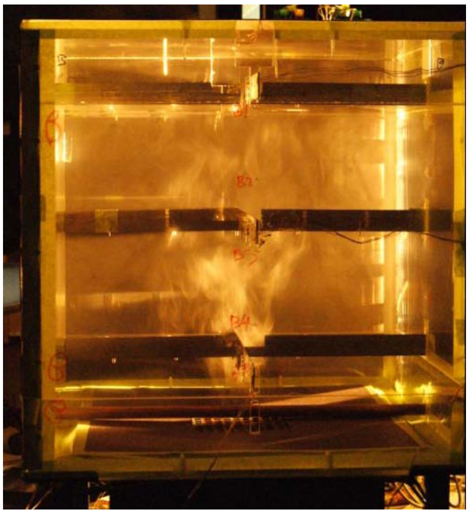
(a)



(b)



(c)

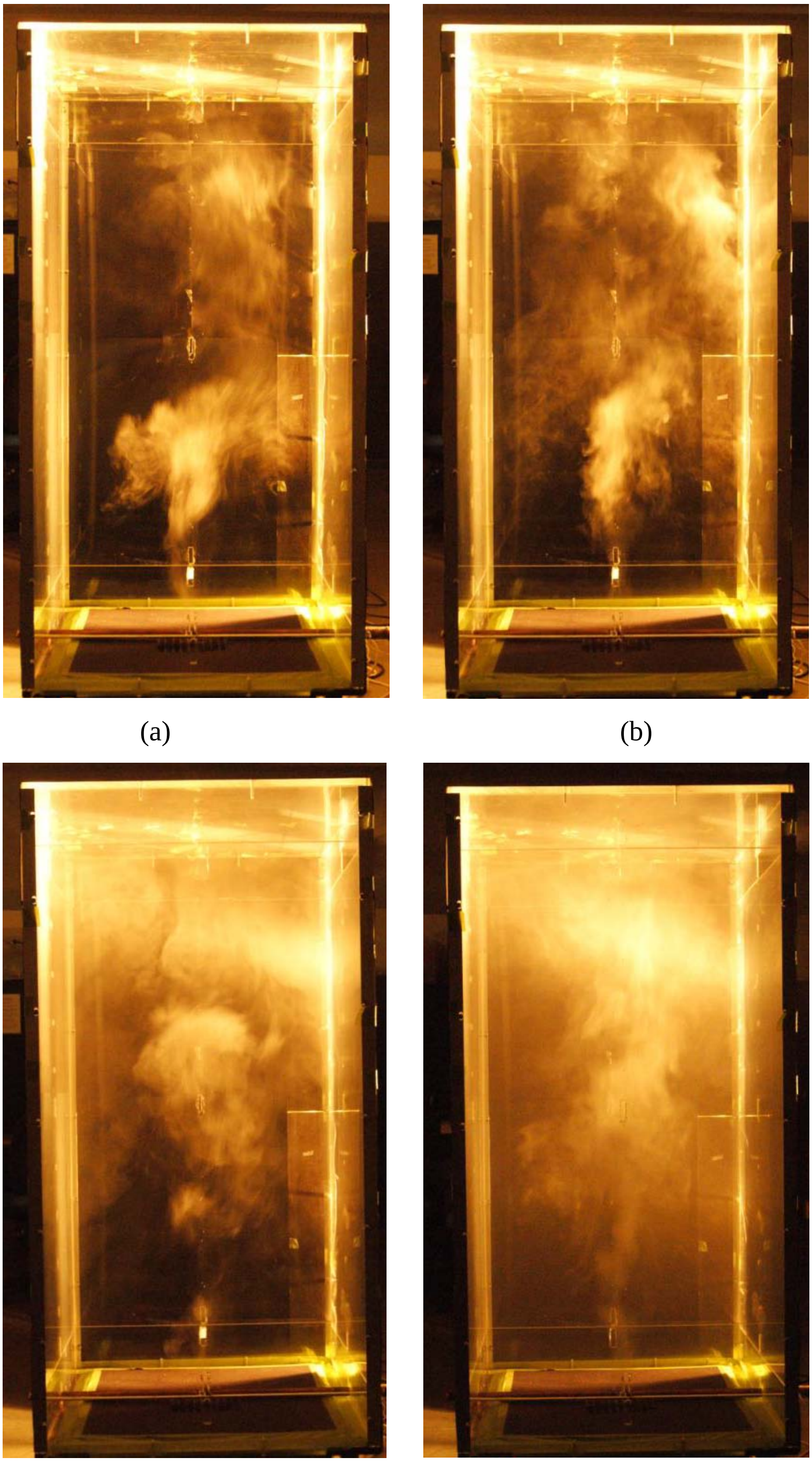


(d)

Figure 3.16 Different stages of the growth of smoke within the short enclosure with vents on all vertical walls.

Figure 3.16 (a) – (d) above shows the smoke flow pattern for the short enclosure with four top vents on all side of the vertical walls. The pattern was found to be very similar to the two-vent case but, the hot smoke was flowing out into the ambient through the top vents in all vertical walls. The time taken for the smoke to build up below the ceiling and to decent was found to be longer and the smoke does not cling to any walls like what happened in the previous case.

Figure 3.17 and Figure 3.18 provide the flow visualization photographs for the tall enclosure with two different ventilation configurations also.



(a) (b)

(c) (d)

Figure 3.17 Different stages of the growth of smoke within the tall enclosure with two vents on wall A and wall C.

(a)

(b)

(c)

(d)

Figure 3.18 Different stages of the growth of smoke within the tall enclosure with vents on all vertical walls.

Figure 3.18 (a) – (d) above showed the smoke flowing pattern for the tall enclosure with four top vents on all side of the vertical walls. The flowing pattern was found to be very similar to the two vents case but, the hot smoke was flowing out into the ambient through the top vents in all walls. The time taken for the smoke to build up below the ceiling and to decent was found to be slightly longer compared to the two-vent case.

3.8 Uncertainty Calculation

In the present study, temperature, pressure and heat flux values are measured and flow rates are calculated using the measured variables. The uncertainty of the temperature measurement is obtained from the uncertainty of the thermocouple and PICO Technology data logging unit, given as ± 0.2 °C for the range of temperatures considered in this study.

The uncertainty of pressure measurement using digital micro-manometer PVM620 from TSI Instruments Ltd. is obtained as ± 1% of the reading for all values considered in this experiment.

The uncertainty of flow rate through the vents consists of the uncertainty associated with the two quantities - flow velocity, V and vent area, A_v. The uncertainty of vent area, A_v is obtained at ± 1mm^2 and the uncertainty of flow-rate is obtained at ± 0.06 m/s. The uncertainty estimates for the derived quantities were obtained using the procedure outlined in Kirkup [20].

3.9 Summary

In this chapter, the descriptions of the experimental models were given. The use of different instruments for data collection, their uncertainties, and the experimental methodology was also described. A section on flow visualization was presented to enable a better understanding of the temperature distribution within the enclosures discussed in the next chapter and beyond. The results and discussion of different cases considered in the study are presented next. The first case (CS1), given in the next chapter that provides the results of experiments using the short enclosure.

CHAPTER 4
RESULTS AND DISCUSSION
CASE STUDY 1: SHORT ENCLOSURE

4.1 Introduction

In the preceding chapter, the experimental set-up and all of its components including the instrumentation was presented. As such, the results from the experimental work on natural convection and forced convection for short enclosure will be presented and discussed in further detail in this chapter. The effect of vents on the hot air layer and ceiling temperature distribution will also be explored.

4.2 Natural Convection Studies on the Short Enclosure

Figure 4.1 shows the schematic of the short enclosure. The vertical walls are named A, B, C, and D respectively as shown in the figure. The enclosure in this figure has four lower vents, and four upper vents. Ambient air is drawn in through the lower vents, and the hot air is expelled through the top vents of the enclosure. The top of the enclosure is closed by the ceiling.

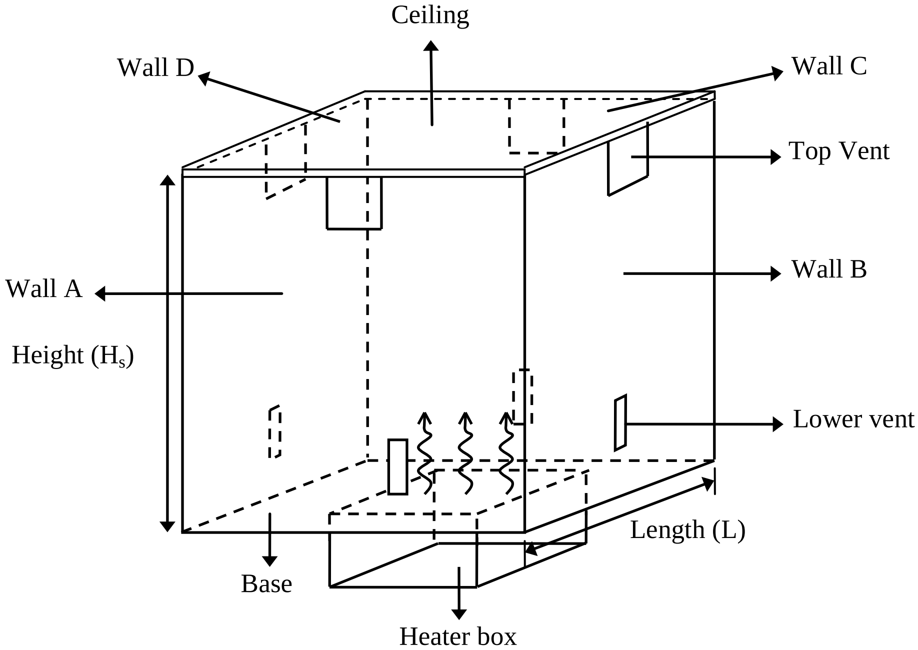


Figure 4.1 Schematic of the short enclosure.

After powering the heater, the heated plume rises from the heat source to the ceiling. It impinges on the ceiling surface, forming a high temperature and high velocity turbulent ceiling jet which flows radially outward along the ceiling. As it transports itself below the ceiling, it heats up the cold ceiling wall. The ceiling heating strongly depends on the radial distance from the point of plume impingement, reducing with the increase of distance from the point of impingement. At the end of the ceiling, the cooled ceiling jet has its lowest temperature, and gains its density. It then turns downward in a complicated flow along the vertical wall surface to the base of the enclosure. Thereafter, it gets entrained into the heat source, and rises upwards.

Overall, not all the ceiling jet gains in density and turns downward to the base of the enclosure. A large portion of the impinged plume retains its high temperature and low density properties. It stays below the ceiling and creates a layer of hot air, named the hot air zone. The hot air zone descends down the ceiling with the increase of time. The cool air below the hot air zone retains its temperature and is termed as the cool air zone. An interface occurs between the two gas layers, within the enclosure.

Figure 4.2 shows the graph of the variation of air temperature across the vertical walls obtained at different planes (low, middle and top) within the enclosure from Wall C to Wall A. For the short enclosure, the lower plane was located at a distance of 100 mm, the middle plane was located at a distance of 300 mm, and the top plane was located at a distance of 500 mm from the base of the enclosure. The three planes had temperature and pressure probes mounted on them (on the aluminium orthogonal racks) at desired locations across the cross section of the enclosure. The heaters were run at full power (500 W), and the temperatures were recorded after 2 hours of powering the heaters. This experiment was conducted with the aim of studying the maximum temperature rise that was possible within the enclosure, in the absence of any top vents.

The interesting pattern of air temperature distribution can be clearly seen from Figure 4.2. The highest temperature is seen to be located at the centre point of the bottom rack, and was found to be about 91 °C. The bottom rack is the one located very close to the heat source, within the enclosure. The centre point of the enclosure was located at a distance of 300 mm from both vertical walls of the enclosure. Air temperatures measured at points farther away from the centre point were found to be similar, and more or less linear and independent of the location, except at the ends (Wall C and Wall A). The end point of the bottom rack which was located at Wall C and Wall A showed 61.5 °C and 62.3 °C respectively. The average air temperature for bottom rack was found to be 70.9 °C.

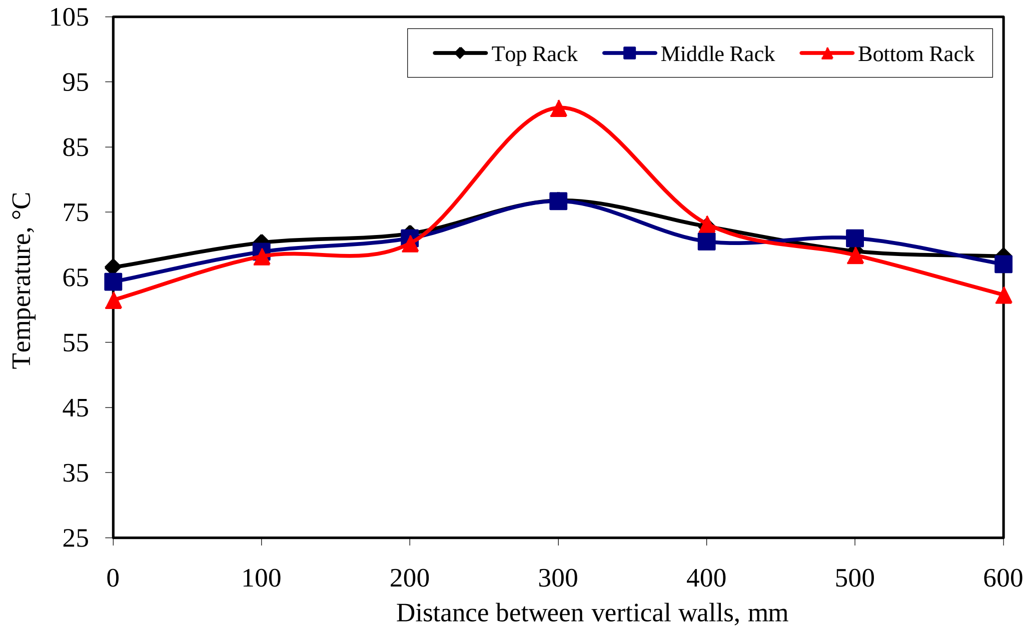


Figure 4.2 Variation of air temperature within the short enclosure across the vertical walls.

Meanwhile, the centre point air temperature for the middle rack was the same as the centre point air temperature for top rack, found to be 76.8 °C. This is a very interesting finding and the reason for the occurrence of same temperature is due to the following reasons: the height of the enclosure is small, and all the top vents were closed, for this experiment. After 2 hours of powering the heaters, it could be inferred from the measured air temperature values that the region between the ceiling and the middle rack was more or less stratified. The average middle and top plane temperature were found to be 69.5 °C and 70.1 °C respectively. It could be seen that the average air temperature for middle rack and air temperature on top rack are more or less the same. However, the region between the middle rack and the ceiling can be considered to be constituted of two layers. One layer of hot gas was present between the ceiling and the top rack, and the other layer of hot gas was present between the middle rack and the top rack. This can be seen from Figure 4.3. The average ceiling temperature was found to be 52.3 °C.

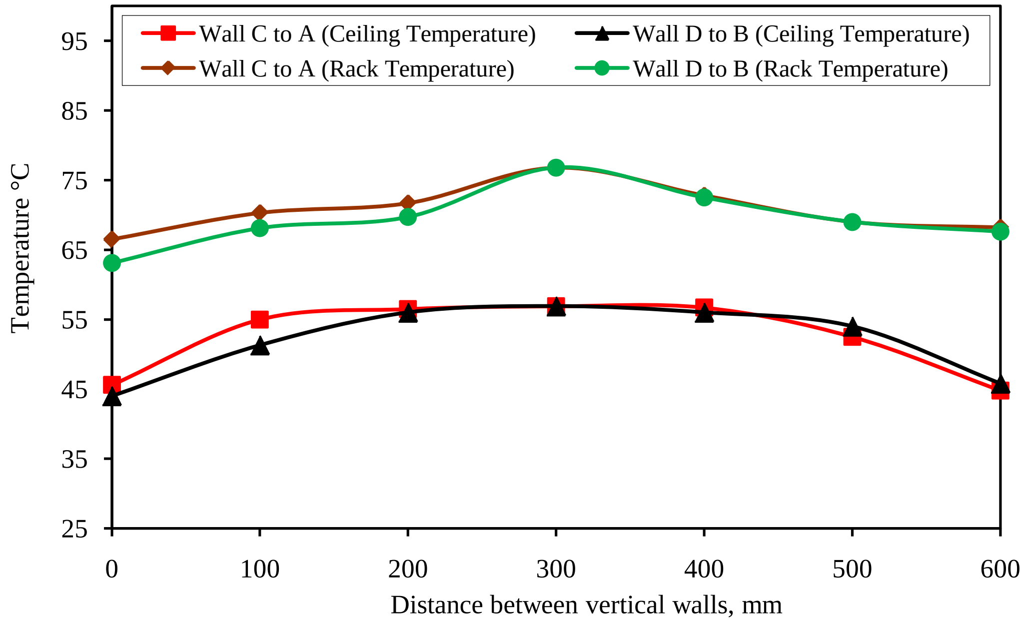


Figure 4.3 Variation of top rack air temperature and ceiling temperature within the short enclosure.

The temperature difference between the top rack average temperatures and the ceiling average temperatures was found to be about 17.8 °C. This can be seen from the graphs shown in Figure 4.3 above.

The build-up of air temperature within the enclosure expressed as a function of time can be explained with the graph shown in Figure 4.4. The air temperatures are plotted along the x-axis, and the height of the enclosure is plotted along the y-axis. The air temperatures are plotted from just before the start of the heating to a period of 120 minutes. The graphs are plotted for each 10 minute interval. An assessment of this figure leads to the following conclusion: along the centre and vertical line of the enclosure, from the base to the ceiling, the short enclosure can be divided into two halves, wherein the bottom half region has a significant temperature gradient, whereas the air temperature is more or less uniform in the top half of the enclosure. These air temperatures are the temperatures measured using the thermocouples located at the centre of the enclosure all along from bottom to top of the enclosure. The air located close to the centre region at the bottom has a higher temperature than the air located at the sides, and has thus resulted in the existing shape of the graphs. The heat sources were entraining cool air from the surrounding, heated and push them from the base to the ceiling by buoyancy force along the centre line.

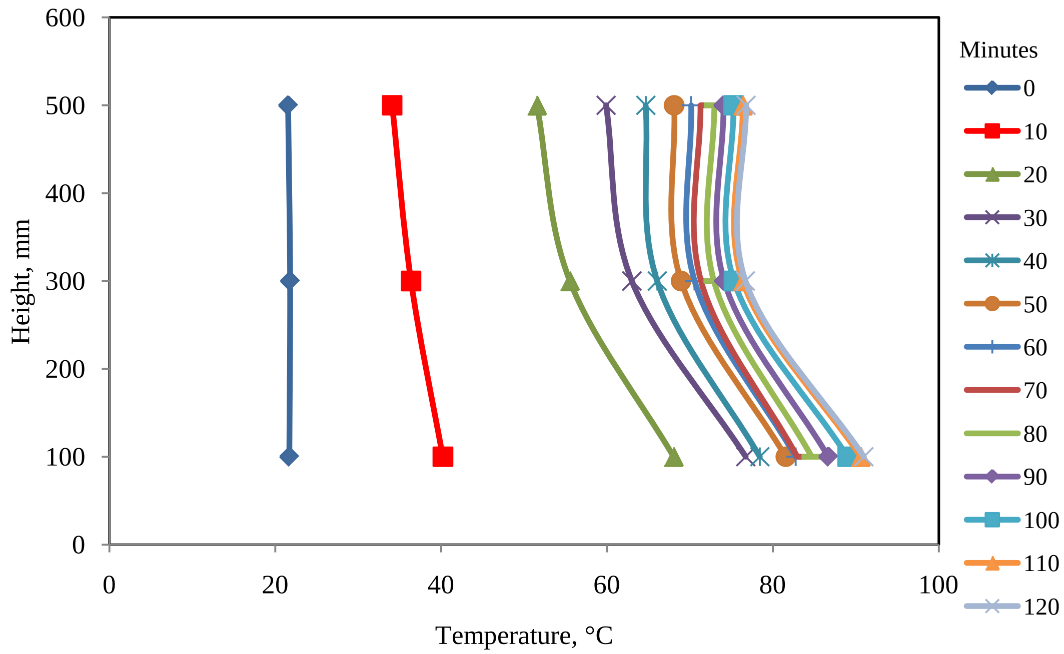


Figure 4.4 Variation of air temperature along the centre line of the enclosure as a function of the height of the enclosure for various times.

Similar air temperature distributions were plotted on Figure 4.5 to show the air temperature within the enclosure, nearer to Wall A as a function of time. The air temperature points were located at distances of 100 mm, 300 mm and 500 mm from the base of the enclosure. During the first 10 minutes of powering the heater, the impingement of the hot air plume rising upward due to natural convection start to heat the ceiling. Subsequently, a layer of hot air starts to build from under the ceiling and downward. This can be noticed from the red curve (refer the 10 min curve on the graph in Figure 4.5). This curve shows that the air temperatures remain constant, at 24.1 °C and 24.4 °C respectively at distances of 100 mm and 300 mm from the base of the enclosure. However, at a point 500 mm height from the base of the enclosure, the air temperature was found to be higher, at 26.7 °C. The hot air building up under the ceiling was found to be building in size, and slowly descending for up to about 40 minutes. Based on the recorded air temperatures, after about 40 minutes the entire enclosure was found to be filled with the hot air layer. Beyond this time, the air within the enclosure was getting heated at a constant rate. This can be found from Figure 4.10 where the air temperatures distributions from time interval of 40 minutes until 120 minutes showed similar trends.

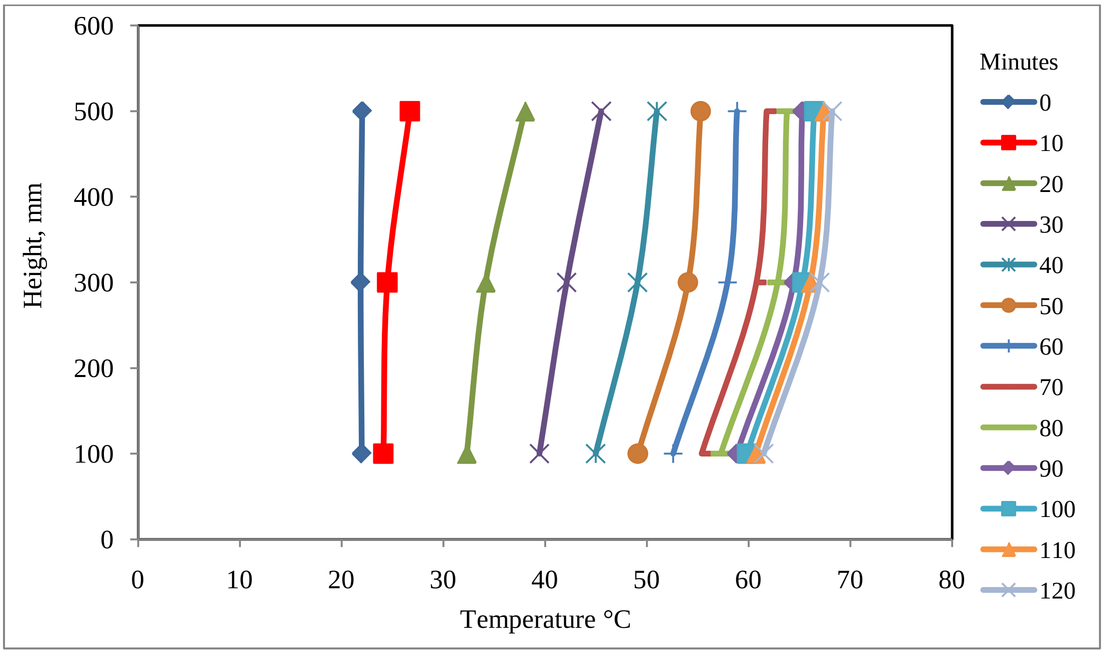


Figure 4.5 Variation of air temperature at a point nearer to Wall A of the enclosure as a function of the height of the enclosure for various times.

In the following section, the air and ceiling temperatures of the short enclosure is discussed in detail with different combination of the top vents. Figure 4.6 (a) – (d) show the comparison of ceiling temperature between the enclosure with no vents and the enclosure having multiple vents. The ceiling temperature distribution is shown between walls A to C, and B to D of the enclosure. As mentioned earlier, the top vents were provided on the top of vertical walls A, B, C, and D of the enclosure.

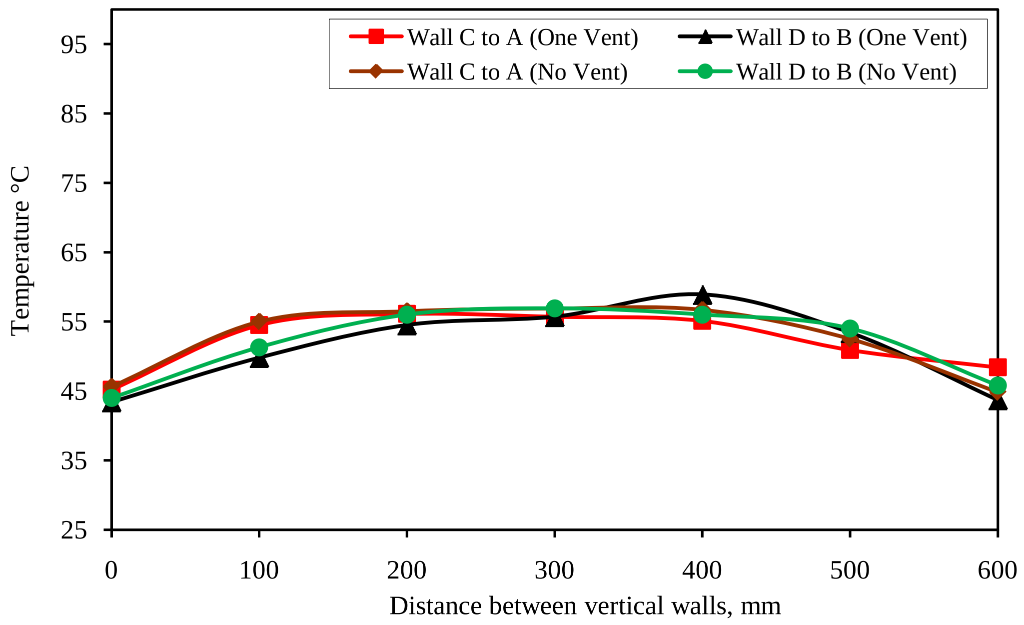


Figure 4.6 (a) Ceiling temperature distributions for short enclosure with one vent. The vent was located on the vertical wall (Wall A), at the top.

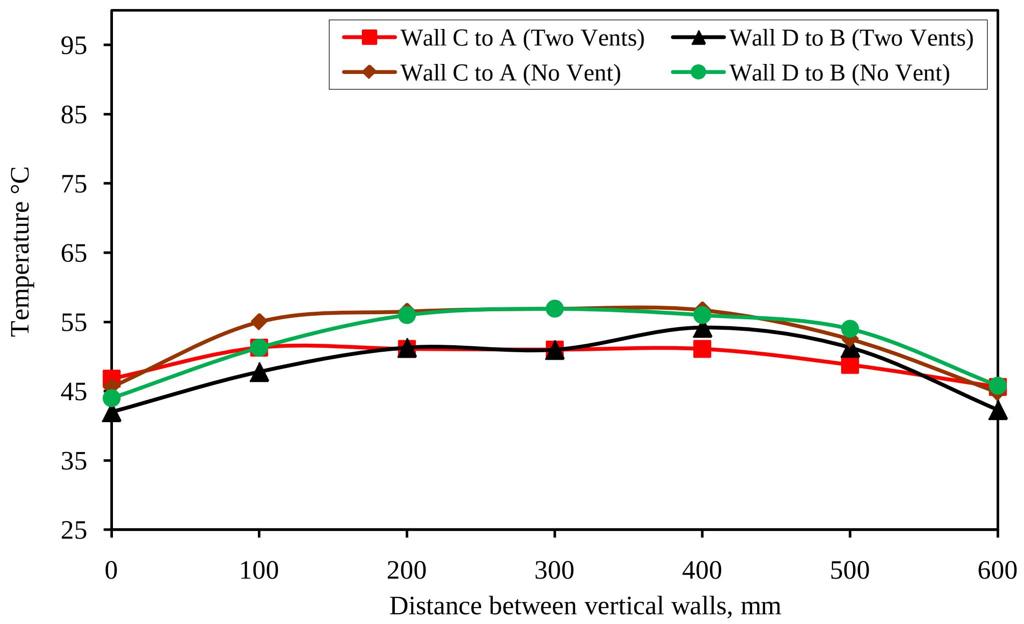


Figure 4.6 (b) Ceiling temperature distributions for short enclosure with two vents. The vents were located on Wall A, and the other was located on Wall C.

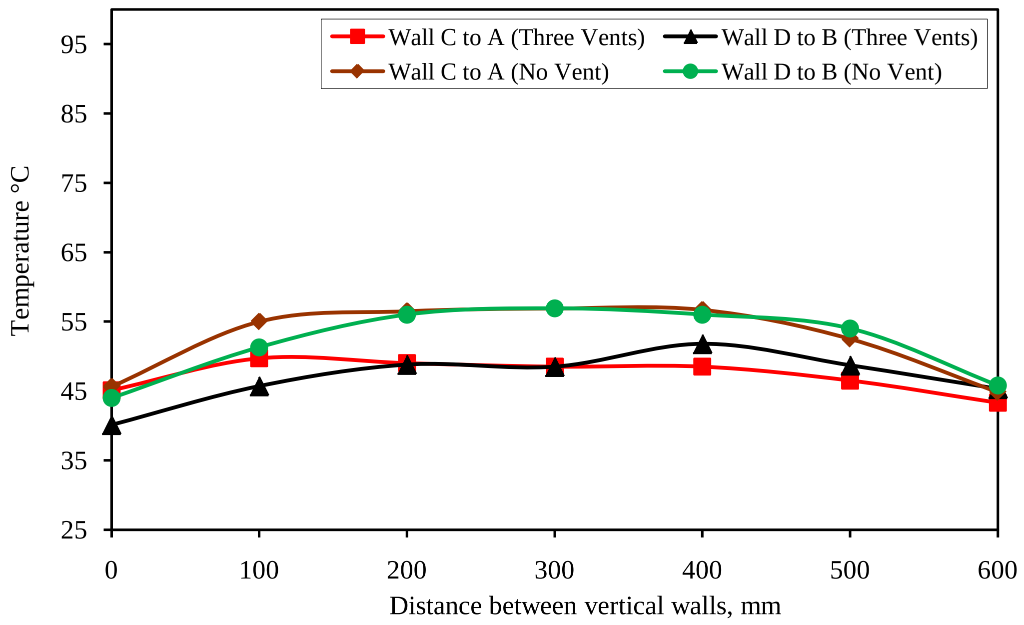


Figure 4.6 (c) Ceiling temperature distributions for short enclosure with three vents. The vents were located on walls A, B, and C

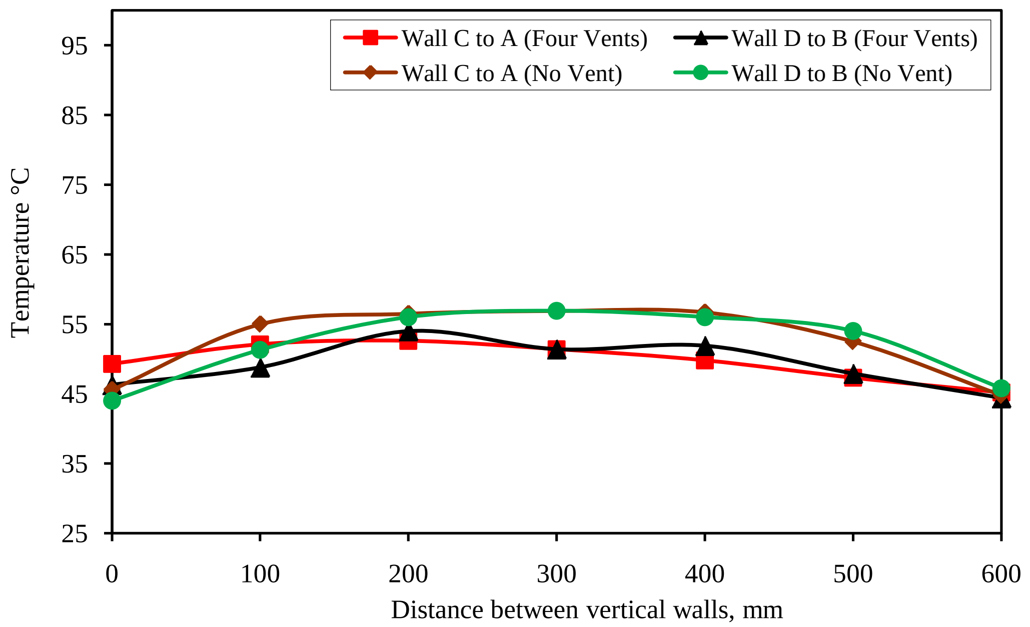


Figure 4.6 (d) Ceiling temperature distributions for an enclosure with four vents. In this case, each wall had one vent located on top of the wall.

Figures 4.6 (a) to (d) shows the air temperatures present when the number of vents was increased from one vent to four vents. Note that in Figure 4.6 (a) the enclosure with a vent on the vertical Wall A, the ceiling temperature showed a limited drop compared to the ceiling temperature without ventilation. The average ceiling temperature for one vent enclosure was found to be 51.8 °C compared to 52.3 °C for the no vent case. However, the ceiling temperature was showed larger drop in average temperature for the case of enclosure with two vents (one vent located on Wall A and other located on Wall C). The average ceiling temperature for the enclosure with two vents was found to be 49 °C. With a further increase in the number of top vents on the enclosure, the ceiling temperature is found to be lower.

It can be seen from all the graphs shown in Figures 4.6 (a) to 4.6 (d) that the ceiling temperature above the vents is always higher than the temperature shown by the measuring point on the ceiling without the vent. From Figure 4.6 (a) to (d), the measurement point at the end of the ceiling nearer to walls A, B, C, and D that have the vents showed a higher ceiling temperature distribution than the ceiling temperature at the measurement point at the end of the ceiling without the vents. This was caused by the movement of the hot air layer within the enclosure, flowing out to the ambient through the top vents. On the vertical wall without ventilations, the hot air layer cools down due to the mixing of the surrounding air and flows down along the vertical wall and is further entrained into the heat source plume.

4.3 Forced Convection Studies on the Short Enclosure

The forced convection experiments on the short enclosure were carried out using the same test rig that was used for natural convection studies. A schematic of the short enclosure used in the forced convection experiments is shown in Figure 4.7. The figure also shows the location of the fan, which was used to force air through the enclosure.

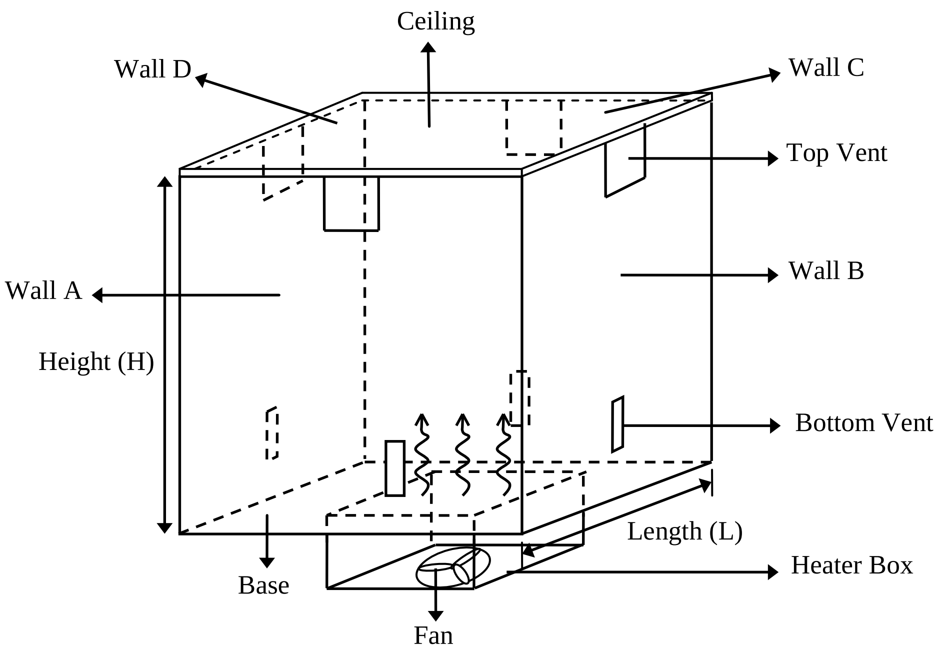


Figure 4.7 Schematic of the short enclosure used for forced convection studies.

The air temperature and pressure measurement points (on the aluminium orthogonal rack) used for natural convection studies were adopted in the present forced convection experiments. As mentioned previously in the Chapter 3, these aluminium racks were located at the distance of 100 mm, 300 mm and 500 mm from the base of the enclosure. The short enclosure remains the four bottom vents. The forced convection experiments were carried out for the short enclosure with one, two, three, and four top vents. The power delivered to the heater was kept constant throughout all the forced convection experiments, and was set equal to that of the natural convection experiments. This was done to enable a proper comparison of heat and flow characteristics at a later stage, between the two cases (natural convection and forced convection). The automotive fan voltage and current was kept the same throughout all the forced convection experiments. It was regulated by means of controlling the input voltage, supplied through a laboratory-level DC power supply unit. In all the experiment, the power input to the fan was set to be 9.6 W such that a comparison between the air temperatures within the enclosure for multiple combinations of vents can be achieved. The results obtained for the forced convection experiments on the short enclosure are presented next.

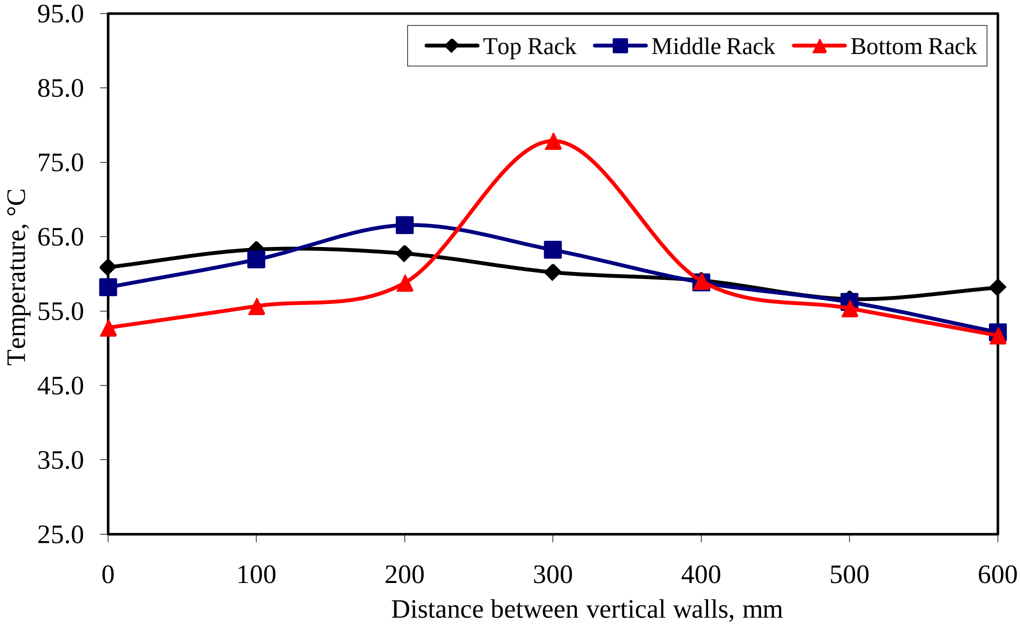


Figure 4.8 (a) Variation of the of air temperature within the short enclosure across the vertical walls, for two vents.

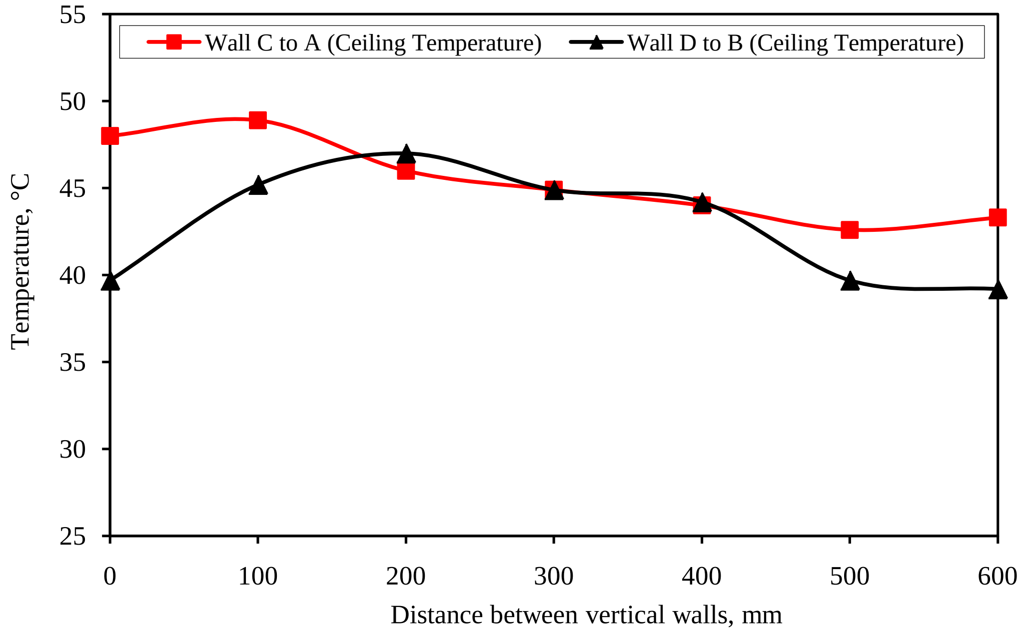


Figure 4.8 (b) Temperature distributions across the ceiling of the short enclosure, for two vents.

Figures 4.8 (a) and (b) show the variation of air temperature between the walls C and A, as shown by the thermocouples installed at the lower, middle, and the upper rack within the enclosure having two top vents. The vents were located on walls (C and A) facing each other. This graph also shows the ceiling temperature between the walls C and A within the enclosure.

The temperature results show a similarity to the results gathered in the previous section for natural convection with two vents located at the same position, on the top of vertical Wall A and vertical Wall C. As shown in Figure 4.8 (a), the highest air temperature was located at the centre point of the bottom plane, and was found to be 77.9 °C. It was found to be about 50.9 °C higher than the room temperature, when measured at the steady-state condition. The steady-state condition was attained after about 2 hours from the powering of the heaters. The centre point on the bottom plane is closest to the heat source, located 100 mm above the heater box. On the same plane, away from the centre point, the temperature distributions were giving fairly similar results. The average air temperature on the bottom plane was found to be 59.1 °C.

At the top rack, the centre point temperature was found to be 60.2 °C. The centre point temperature of the middle rack was found to be 63.2 °C. The temperature readings differed by about 3 °C. It must be taken into consideration that the middle rack was located at a distance of 300 mm and 500 mm above the base of the enclosure. The average of top rack and middle rack air temperatures were 59.9 °C and 59.4 °C respectively. Overall, the average temperatures on different planes for forced convection on the short enclosure were about the same for the short enclosure with two top vents.

The average ceiling temperature in this case was found to be about 44.1 °C. This shows that the ceiling was comparatively cooler than the average air temperature at any of the planes. This could affect, for example the response of any sprinklers or fire alarms mounted on the ceiling.

The end point temperature on the top rack, in the direction of Wall C to Wall A, where the vents were located, that allowed the hot air to exit to the ambient were showing a higher temperature reading of 58.7 °C and 59.7 °C on Wall C and Wall A respectively. The end point temperatures on the top rack in the direction of Wall D to B, were found to be 60.9 °C and 58.1 °C respectively. A similar trend was observed for the middle rack temperatures and bottom rack temperatures that were measured between Wall B and Wall D. This difference in end point temperatures is due to location of the top vents. For example, in the present experiment described in these graphs, the top vents were located on Wall C, and Wall A, and not on Wall D and Wall B.

The automotive fan operates at 9.6 W forces the ambient cold air (room temperature of 22.5 °C) into the heater box, through the grille and into the enclosure. As the cold air moves through the heater box, it receives high thermal energy from the heat source, thus resulting in a higher temperature. Leaving the heater box, it flows through the grille and develops into a hot plume in the enclosure. From there, it flows quickly and ascends along the centreline and impinges onto the ceiling. The hot upper layer therefore grows in thickness and starts to descend towards the floor, or the base of the enclosure. The accumulated hot layer near the ceiling causes an increase in the top rack air temperatures.

Due to the high volume of the cold air being forced into the enclosure, the air pressure inside the enclosure increased, and was found to be 5.9 Pa at the centre point on the top rack. The hot air was found to be flowing out of the enclosure through the top vents located on the top of Wall A and Wall C at an average speed of 2.92 m/s. It is to be noted that for higher fan speeds encountered in this study, it was observed that the build –up of hot air within the tall enclosure, over a period of time led to small air flow through the inlet vents to the ambient as well.

Figure 4.9 shows the variation of bottom, middle, and top rack air temperature distribution between the walls, for forced convection in a short enclosure with four top vents.

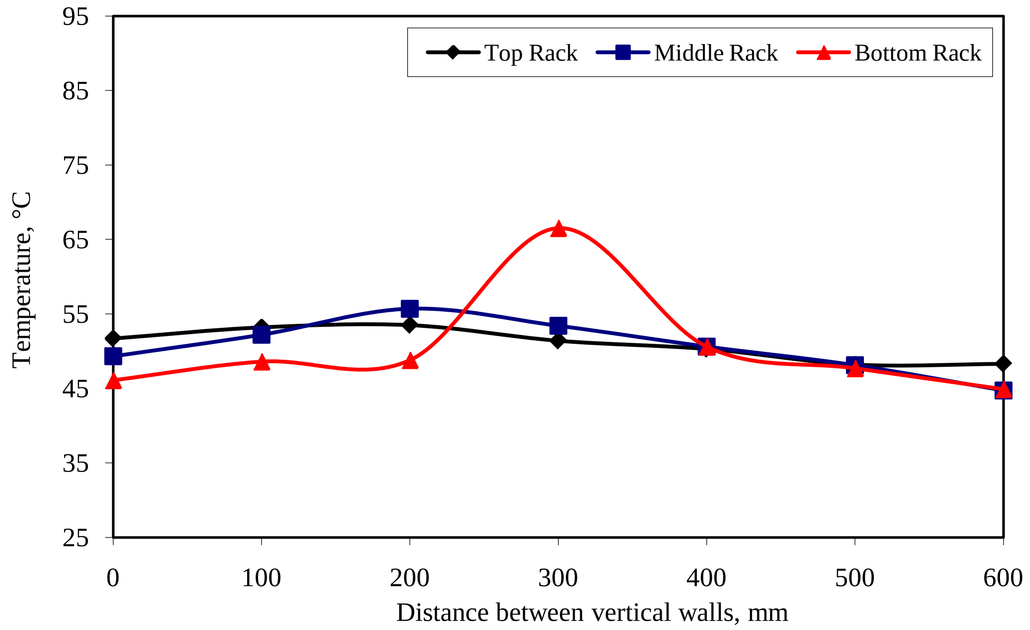


Figure 4.9 Variation of the of air temperature within the short enclosure across the vertical walls, for four top vents.

Based on the observed temperature measurements, the average bottom, middle and the top rack air temperatures were found be almost the same. The bottom rack average air temperature was found to be 50.7 °C, the middle rack average air temperature was found to be 50.6 °C, and the top rack average air temperature was found to be 51 °C. These average temperatures were found to be about 9 °C lower than the corresponding average temperatures encountered for a two-vented short enclosure subjected to forced convection. This indicates that an addition of two top vents has a significant effect in reducing the average air temperatures within the enclosure. It has been observed that there is a significant reduction in the air temperatures when moving from one top vent to two top vents; however further additional vents are not found to contribute to any significant drop in air temperatures. This is shown in Figure 4.10, which is a plot of the variation of ceiling wall temperatures as a function of the flow rate through the vents.

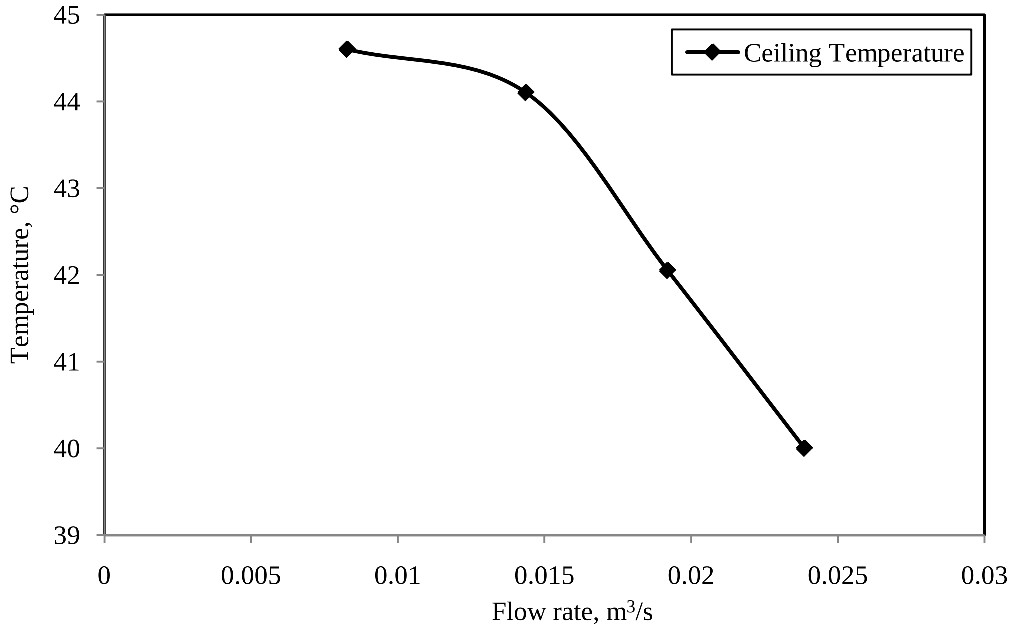


Figure 4.10 Ceiling temperature versus vent flow rate for a short enclosure in forced convection study

From Figure 4.10, it can be seen that there is a significant drop in the average ceiling temperature, as the number of vents are increased. In this case, the average ceiling temperature drops by about 11.5 % for a short enclosure with four vents. Increased vent flowrate has caused a reduction in the average ceiling temperatures.

Figure 4.11 shows the temperature distribution along the ceiling for a short enclosure with four top vents in forced convection. The average ceiling temperature in this case of the enclosure with four top vents was found to be 40 °C. This is the different from the average ceiling wall temperature (44.1 °C) for an enclosure with two top vents in forced convection, for a similar heater power input and fan speed.

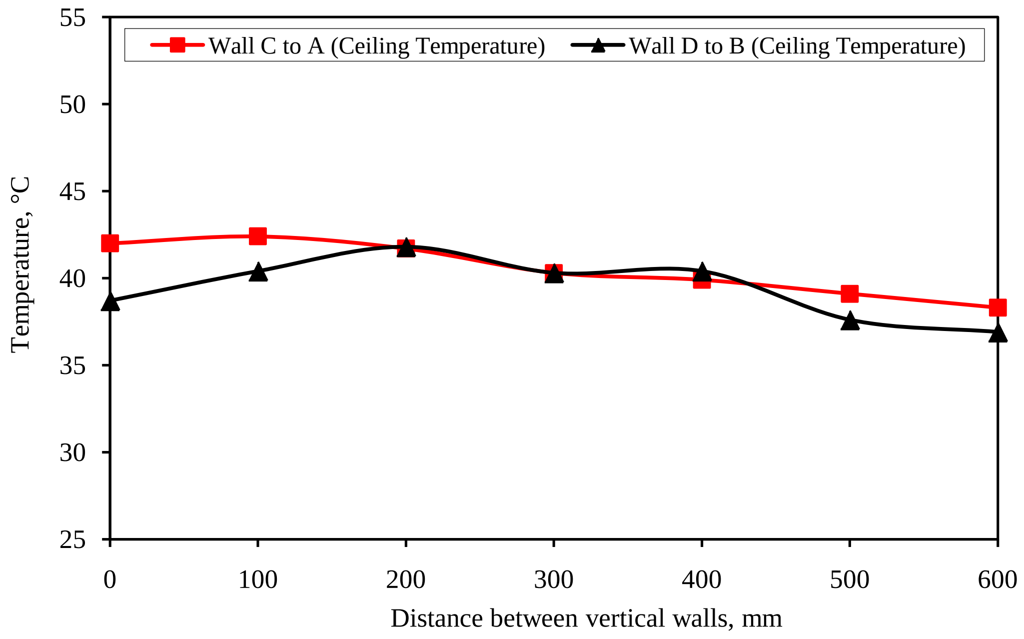


Figure 4.11 Temperature distributions across the ceiling of the short enclosure, for four top vents.

It is of interest to note the variation of ceiling wall temperatures for identical cases of the short enclosure considered for natural and forced convection. This is shown in Figure 4.12.

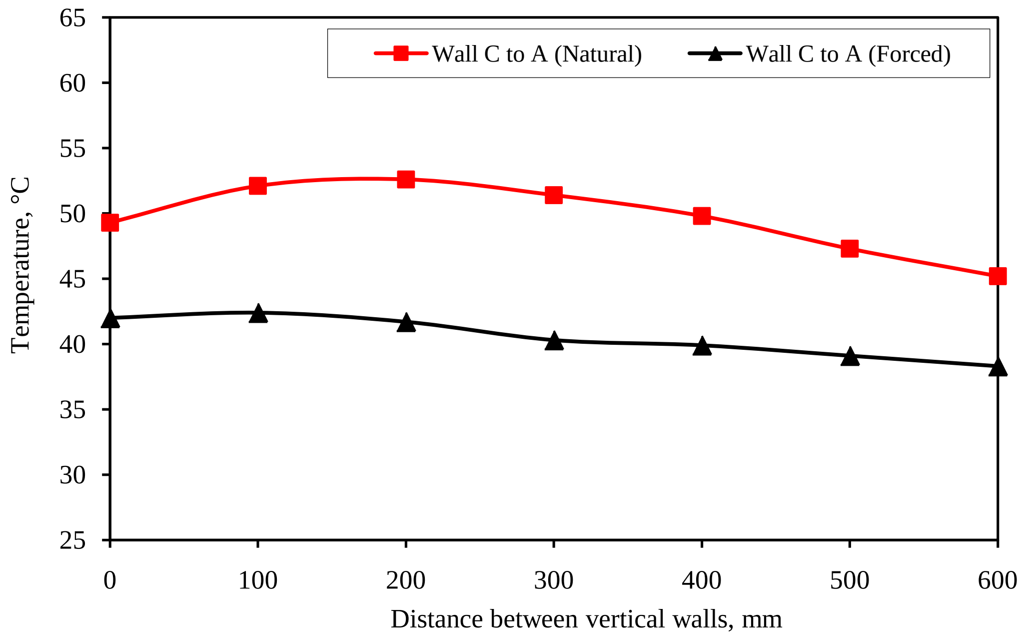


Figure 4.12 Comparison of ceiling temperature from Wall C to Wall A. The comparison is between similar cases for natural and forced convection.

As can be seen from the figure, the ceiling wall temperatures are higher by about 10 °C at every point for natural convection cases for the tall enclosure. Visibly, the effect of forced venting has contributed to the significant reduction of the ceiling wall temperatures.

4.4 Summary

In this chapter, the results of a short enclosure for natural and forced convection experiments were carried out. It was found that with forced convection, the ceiling temperature within the enclosure dropped for about 23.5 % compared to natural convection. The introduction of a fan significantly reduces the ceiling temperature of the enclosure.

CHAPTER 5
RESULTS AND DISCUSSION
CASE STUDY 2: TALL ENCLOSURE

5.1 Introduction

In the previous chapter, the results from the experimental work on natural convection and forced convection for short enclosure was presented and discussed in detail. In this chapter, the results of a similar experimental work carried out for the tall enclosure are presented.

5.2 Natural Convection Studies on the Tall Enclosure

The natural convection experiments on the tall enclosure were carried out using the test rig that was used for the natural convection experiments on short enclosure, except for the enclosure. The tall enclosure had double the height of the short enclosure (1200 mm) in comparison to the height of the short enclosure (600 mm). During the design stage itself, the size of the base for the two enclosures were designed to be the same, in order to compare the characteristics of both the short and tall enclosures for the same mode of heat transfer (natural or forced convection).

Figure 5.1 shows the schematic of the tall enclosure. The four vertical walls were named A, B, C and D respectively. The enclosure had the same design with four lower vents and four upper vents. The lower vents were located 50 mm above the base of the enclosure and the top vents were located right below the ceiling. The lower vents allow the ambient air to be drawn in during the experiments while the top vents allow the expulsion of hot air from the enclosure.

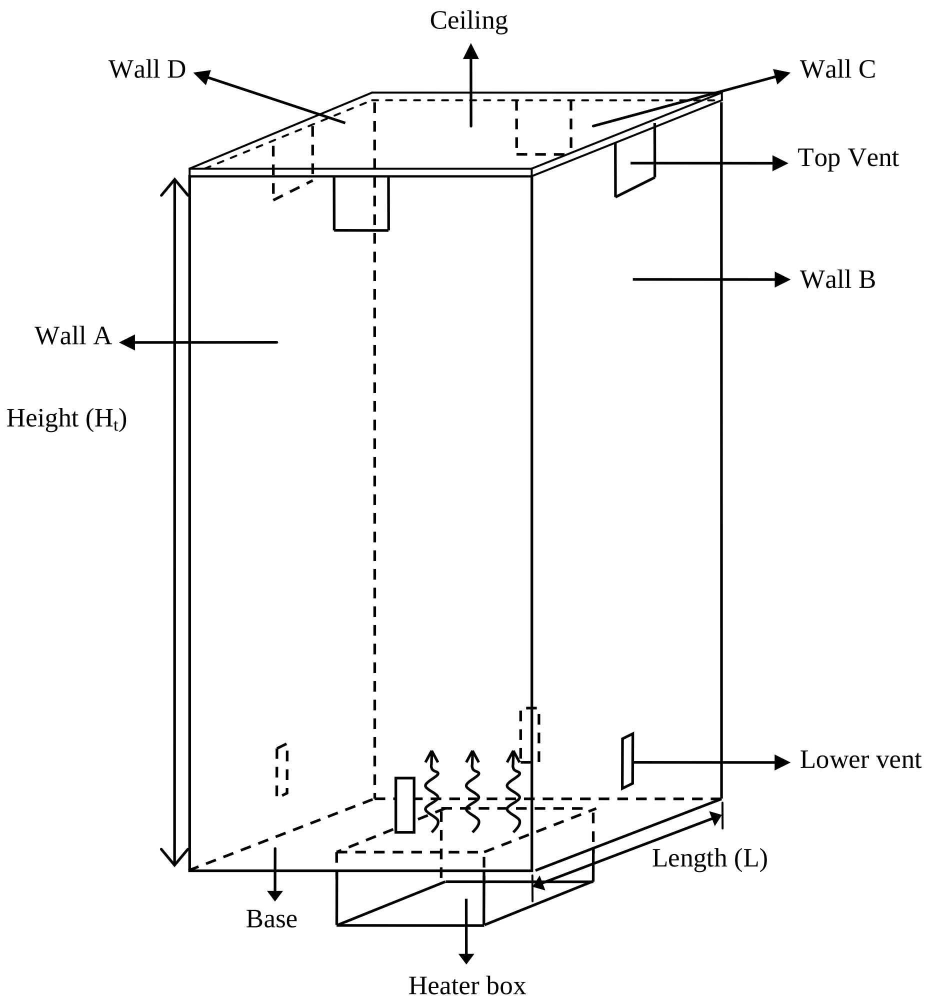


Figure 5.1 Schematic of the tall enclosure.

The temperature and pressure measuring points (on the aluminum rack) used for the short enclosure studies were adopted for the present tall enclosure studies. For the tall enclosure, the region along the vertical height of the enclosure was divided into lower, middle and upper planes. The lower plane was located at a distance of 100 mm, the middle plane was located at a distance of 600 mm, and the top plane was located at a distance of 1200 mm from the base of the enclosure. During the experiment, the heaters were run at the full power (500W) and the temperatures and pressures were recorded after a period of 2 hours.

Figure 5.2 shows the air temperature distribution for tall enclosure along three planes from Wall C to Wall A. This experiment was conducted to study the maximum temperature rise that was possible within the enclosure, in the absence of any top vents. The heated air was emanating from the base of the enclosure as a hot plume, impinged on the ceiling. As there were no vents at the top of the enclosure (for this experiment), the energy released from the heater was accumulated within the enclosure.

From the results, the average temperature on lower plane was found to be the highest, 65.8°C, being nearest to the heat source. The average middle and top plane temperatures were found to be 60.3°C and 62.5°C respectively. These results were found to be lower compared to CS1 (short enclosure), under the same experimental configuration.

The centre point temperature for three planes also showed a reduction in values when moving from the bottom to the top giving 92°C, 73°C and 65.3°C for bottom, middle and top planes respectively. With the increase of the height of the enclosure, where the heated air was entraining as much cooler air as possible when moving from the bottom to the ceiling and thus creating a wide range of temperature difference. A similar trend was observed for the short enclosure case (CS1), however, with smaller temperature changes.

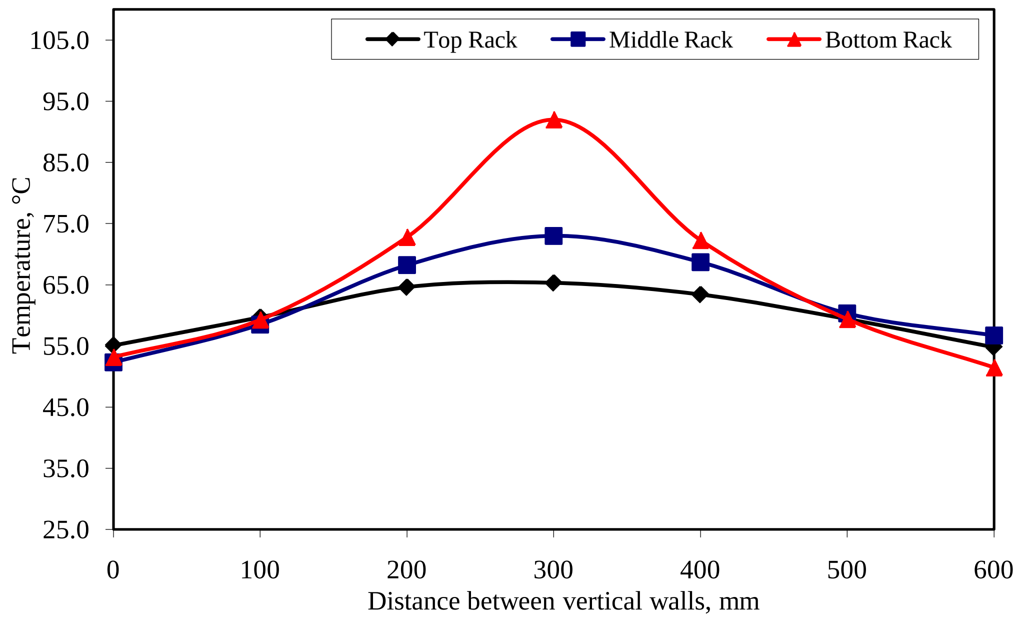


Figure 5.2 Variation of air temperature within the enclosure across the vertical walls.

As can be seen from the Figure 5.2, the hot air temperatures on the upper hot region which represented by the top plane were showing a more uniform temperature distribution compared to middle and bottom planes. The top plane air temperatures had a smaller difference of 10 °C (maximum to minimum) from the centre point to the point close to the wall. However, on the lower cool zone, the temperature distribution had stronger variation of 41.2 °C, from the centre air temperature to the far end air temperature. The higher centre point air temperature was due to the strong hot air rising up from the heat source along the centre line, providing highest temperature point within the enclosure. The air temperature point near to the wall was the cold surrounding air, mixture with the cooled air flowing down from the top.

The air surrounding the region closer to the bottom vents had a lower average temperature, and thus possessing a higher density. This air remained at a lower level, until entrainment into the heat source occurred. Once the cool air got entrained, heats up, increased its density, and is transported into the hot top zone.

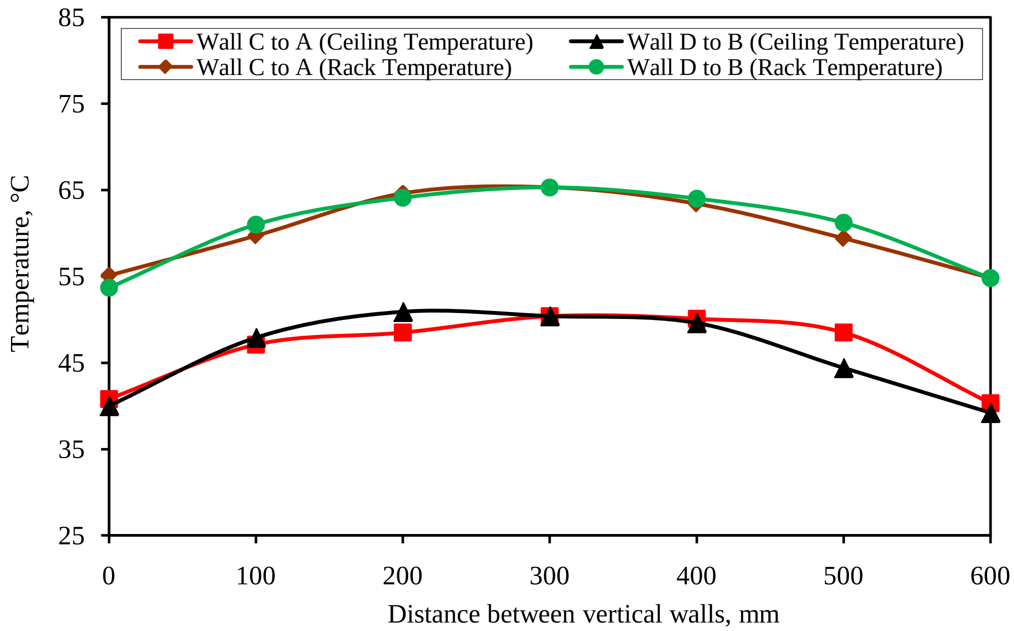


Figure 5.3 Variation of air temperature along the top rack and the ceiling temperature for the tall enclosure.

Figure 5.3 shows a graph of the variation of ceiling temperatures and top plane temperatures across the enclosure for the tall enclosure. The average ceiling temperature for both cases (Wall C to Wall A, and Wall D to Wall B) were found to be the same values equal to 46.2 ± 0.3 °C. The ceiling wall temperatures were found to be lower than the top rack air temperatures and were found to be about 10.3 °C. The average top rack air temperatures was found to be 60.3 °C (from Wall A to Wall C) and 60.6 °C (from Wall B to Wall D) respectively.

The build-up of air temperature within the enclosure as a function of time can be explained with the graph shown in Figure 5.4. The air temperatures were plotted along the x-axis, and the height of the enclosure was plotted along the y-axis. The air temperatures were plotted from just before the powering of the heater to a period of 120 minutes. The graphs were plotted for every 10 minute time interval. It can be seen that the tall enclosure can be divided into two halves, wherein the bottom half region had a significant temperature gradient, whereas the air temperatures was more or less uniform in the top half of the enclosure. These air temperatures were the temperatures measured using the thermocouples located at the centre of the enclosure all along from bottom to top of the enclosure. The air located close to the centre region at the bottom had a higher temperature than the air located at the sides, and has thus resulted in the shape of the graphs.

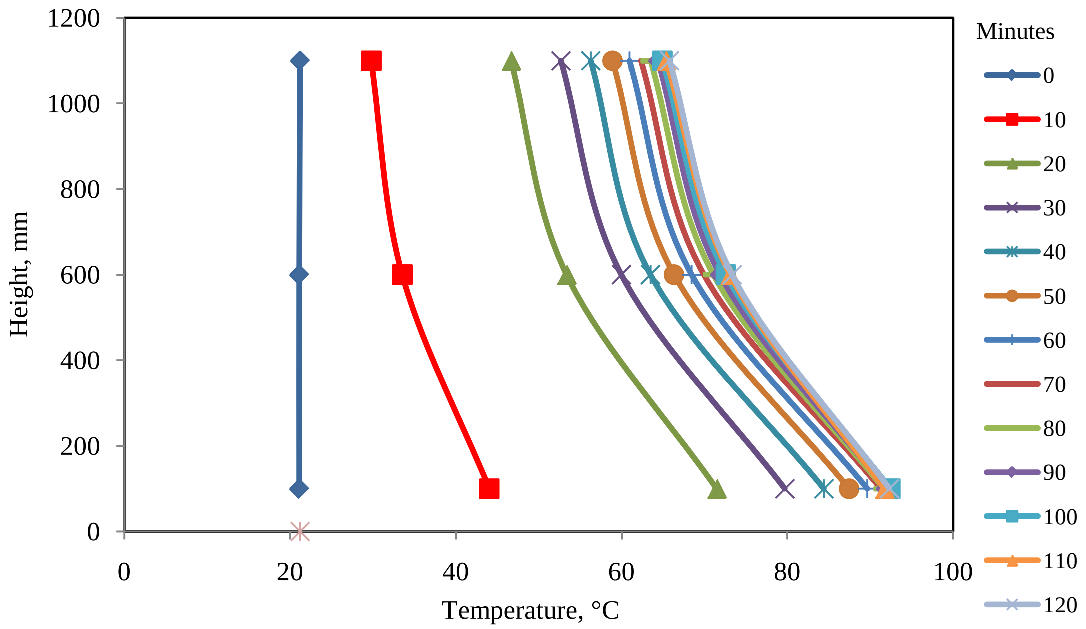


Figure 5.4 Variation of air temperature at the centre of the enclosure as a function of the height of the enclosure for various times.

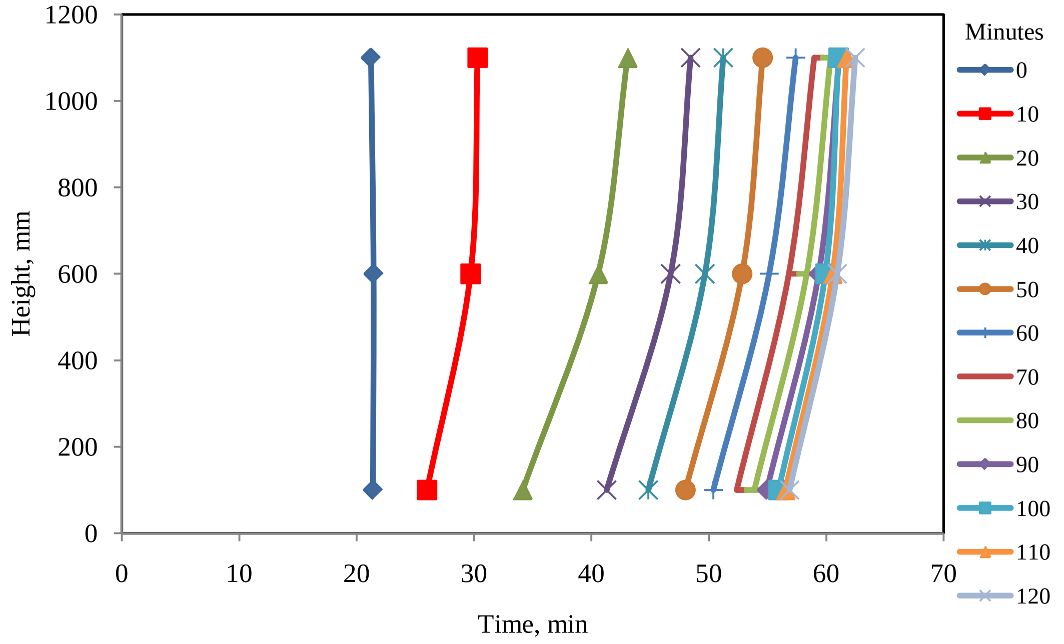


Figure 5.5 Variation of air temperature at a point nearer to Wall A of the enclosure as a function of the height of the enclosure for various times.

Similar air temperature distributions were plotted on Figure 5.5 to show the air temperature within the enclosure, nearer to Wall A as a function of time. The air temperature points were located at distances of 100 mm, 600 mm and 1100 mm from the base of the enclosure. During the first 10 minutes of powering the heater, the impingement of the hot air plume rising upward due to natural convection start to heat the ceiling. Subsequently, a layer of hot air starts to build from under the ceiling and descend. This can be noticed from the red curve (refer the 10 min curve on the graph in Figure 5.5). This curve shows that the air temperatures remain constant, at 24.1 °C and 24.4 °C respectively at distances of 100 mm and 600 mm from the base of the enclosure. However, at a point 1100 mm height from the base of the enclosure, the air temperature was found to be higher, at 26.7 °C. The hot air building up under the ceiling was found to be building in size, and slowly descending for the following 40 minutes. Based on the recorded air temperatures, after about 40 minutes the entire enclosure was found to be filled with the hot air layer. Beyond this time, the air within the enclosure was getting heated at a constant rate. This can be found from Figure 5.5 where the air temperatures distributions from time interval of 40 minutes until 120 minutes showed similar trends.

In what follows, the top rack air temperature and ceiling temperatures of the tall enclosure having multiple vents at the top was discussed in detail. Figures 5.6 (a) – (d) showed the variation of ceiling temperature for an enclosure having multiple vents. The ceiling temperature distribution is shown between walls A and C, and B and D of the enclosure. As mentioned earlier, the top vents were provided on walls A, B, C, and D of the enclosure. The ceiling temperature distribution for an enclosure with two vents (one vent on Wall A and one vent on Wall C) was found to be similar to the ceiling temperature distribution for an enclosure with two vents (one vent on Wall B and one vent on Wall D).

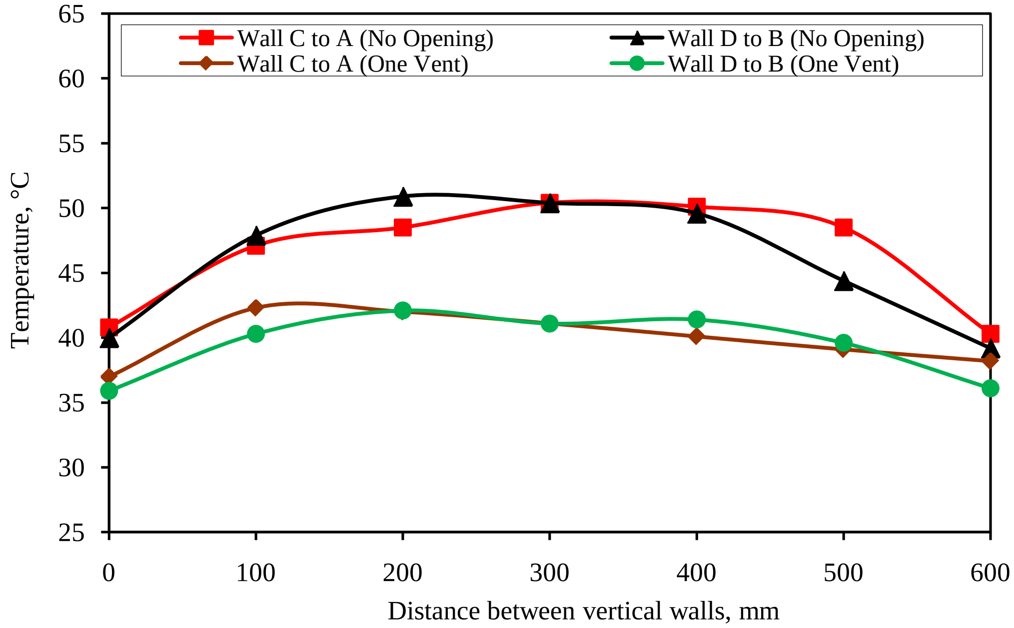


Figure 5.6 (a) Ceiling temperature distribution for an enclosure with one vent. The vent was located on the Wall A at the top.

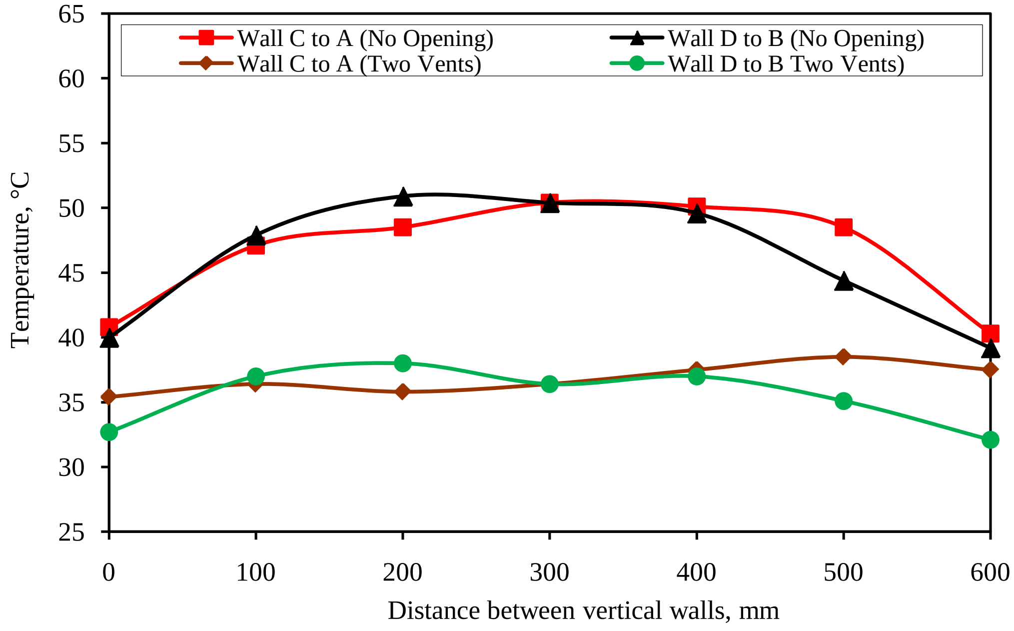


Figure 5.6 (b) Ceiling temperature distributions for an enclosure with two vents. One vent was located on Wall A, and the other was located on Wall C.

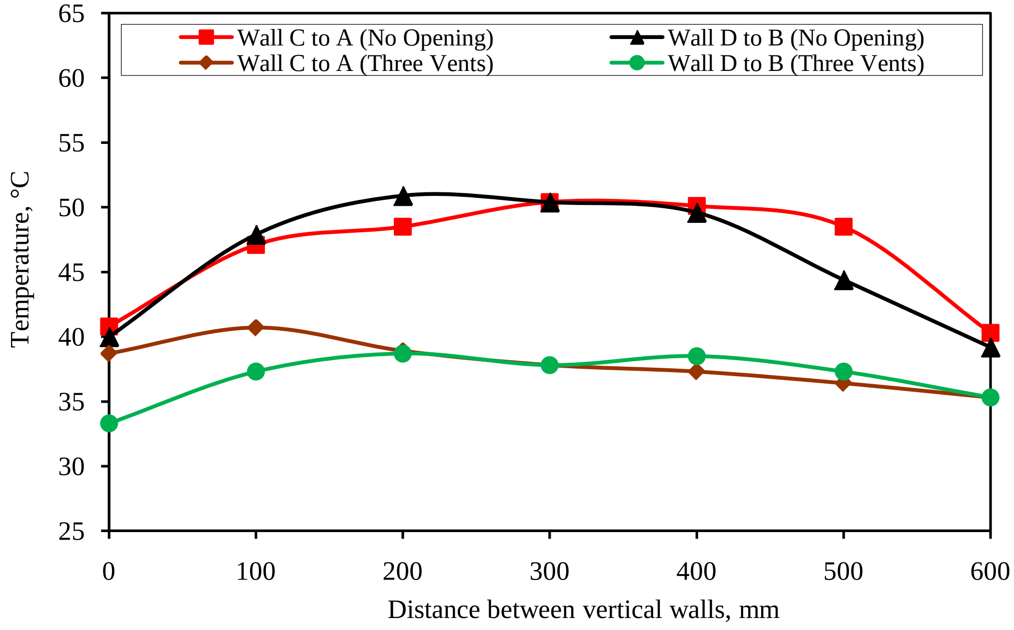


Figure 5.6 (c) Ceiling temperature distributions for an enclosure with three vents. The vents were located on walls A, B, and C.

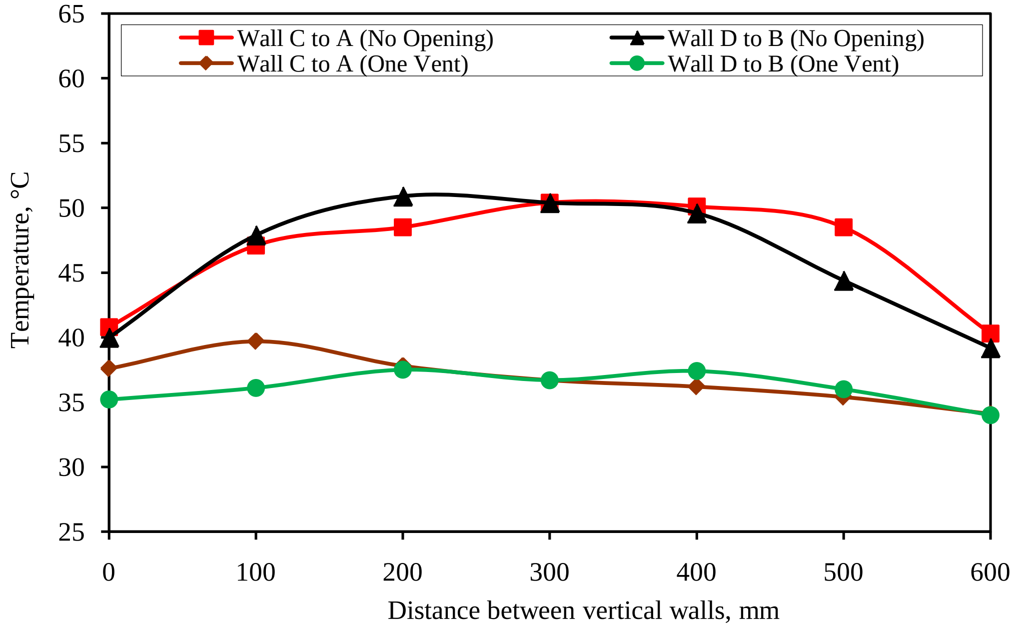


Figure 5.6 (d) Ceiling temperature distributions for an enclosure with four vents. In this case, each wall had one vent located on top of the wall.

It can be seen from Figure 5.6 (a) to (d) that the air temperatures measured by the thermocouples attached to the measurement point on the ceiling (at the edge with the vents) were always higher than the similar measurement point - at the edge without the vents. This was caused by the movement of the heated air within the enclosure, out through the top vents. The air adjacent and below the ceiling were entraining into the exhaust plume, and was carried out through the vent, thereby causing an increase in the ceiling temperature close to the region near the vent. Moreover, it was found that the average ceiling temperature drops by about 6.3 °C for a single-vented enclosure when compared with an enclosure without any vents. In addition, by increasing the number of vents (four, in this case) was found to provide about 9.7 °C drop in temperature when compared with an enclosure having no vents. The increase of the amount of ventilations had significantly reduced the average temperature of the ceiling.

5.3 Forced Convection Studies on the Tall Enclosure

The forced convection experiments on the tall enclosure were carried out using the same tall enclosure that was used for natural convection studies. A schematic of the tall enclosure used in the forced convection experiments is shown in Figure 5.7. The figure also shows the location of the fan, which was used for forcing the air through the enclosure. It was located below the heater box.

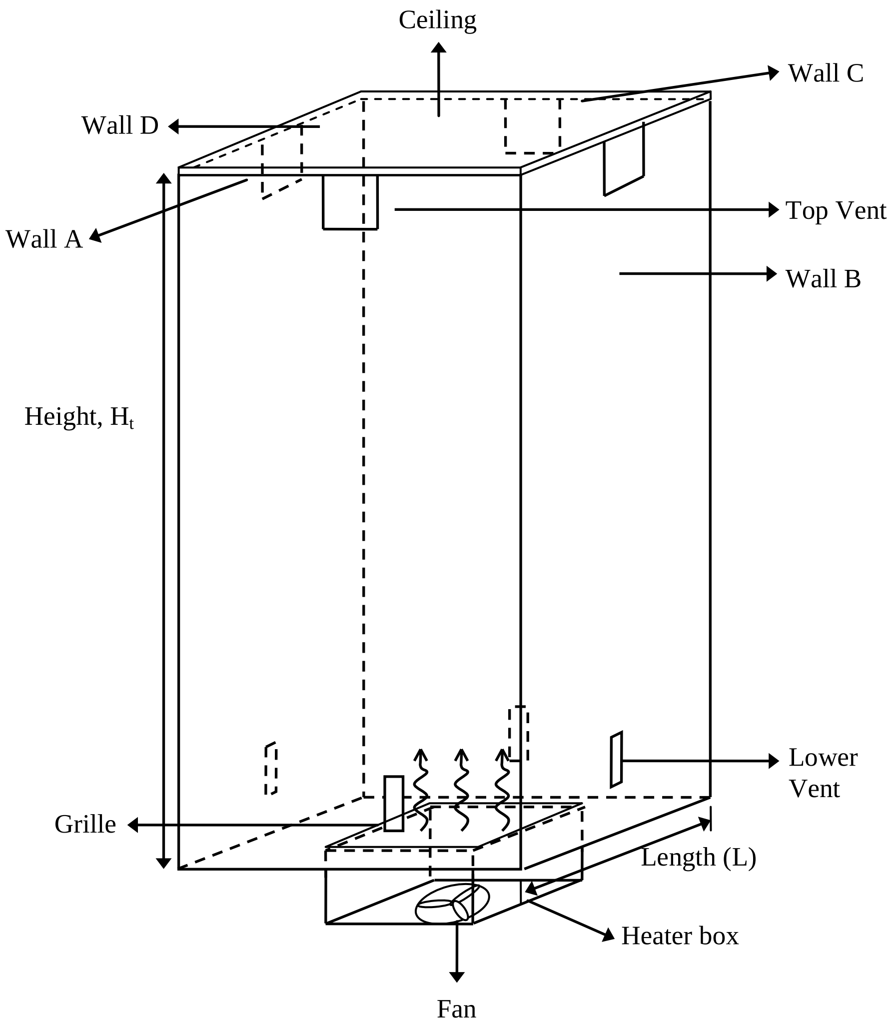


Figure 5.7 Schematic of the tall enclosure used for forced convection studies.

The air temperature and pressure measurement points on the aluminum orthogonal rack used for natural convection studies were adopted for the present forced convection experiments. The tall enclosure retained its four bottom vents. The forced convection experiments were carried out for the tall enclosure with different ventilation configuration and for a range of fan speeds. The results of two and four top vents only will be presented in this section. Different fan speeds were provided for different flow rates within the enclosure. The heater voltage and current however were kept the same throughout all the forced convection experiments, and were set equal to that of the natural convection experiments. This was done to enable a proper comparison of heat and flow characteristics at a later stage, between the two cases (natural convection and forced convection). The fan speed was regulated by means of controlling the input voltage, supplied through a laboratory-level DC power supply unit. Three power inputs: 2.9 W, 7.7 W, and 9.6 W, for the fan provided three flow rates within the enclosure. However, the results were presented for a typical case of 9.6W input power to the fan. The results obtained for the forced convection experiments on the tall enclosure were presented next.

Figures 5.8 (a) and (b) show the variation of the air temperature between the walls C and A for the enclosure having two top vents. The vents were located on walls (C and A) facing each others. Figure 5.8 (a) shows the thermocouple readings at the lower, middle, and the upper rack within the enclosure, while Figure 5.8 (b) shows the ceiling temperature between the walls C and A, B and D within the enclosure.

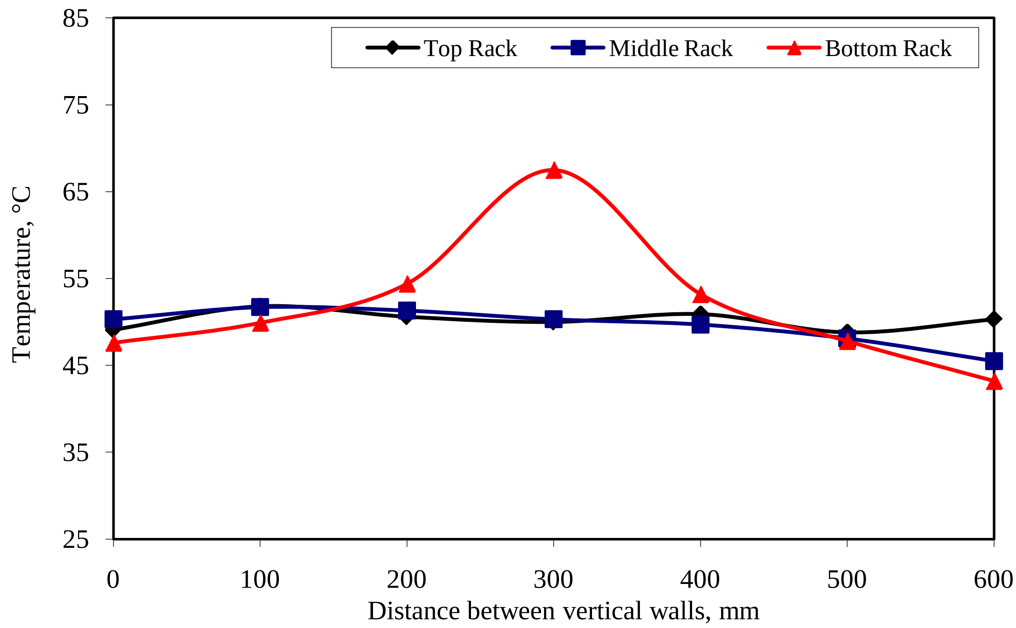


Figure 5.8 (a) Variation of the of air temperature within the enclosure across the vertical walls, for two vents.

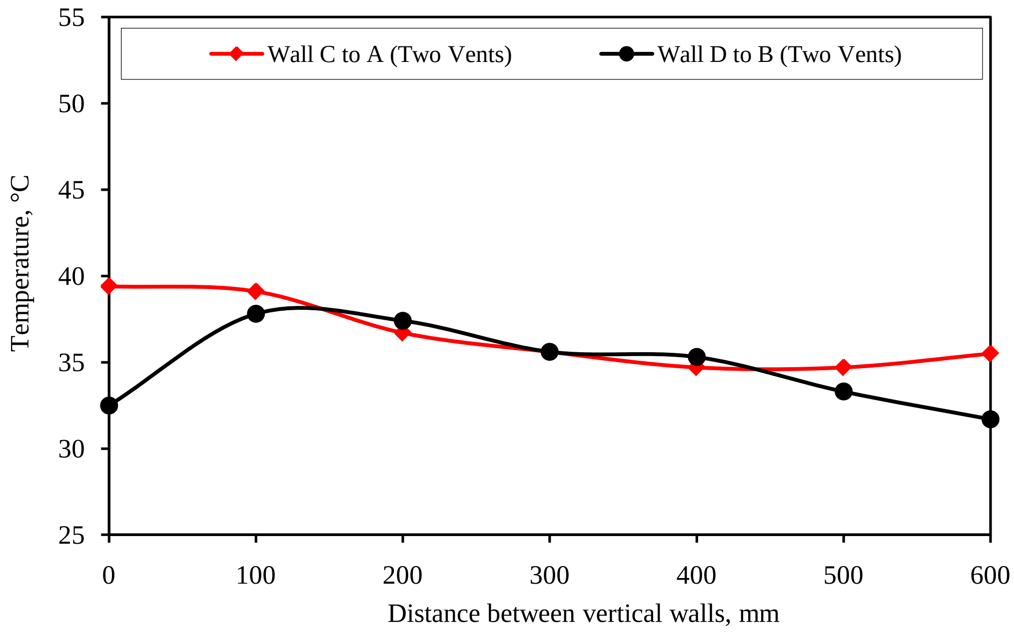


Figure 5.8 (b) Temperature distributions across the ceiling of the tall enclosure, for two vents.

Figure 5.8 (a) shows the highest air temperature was located at the centre point on the bottom plane, and was found to be 67.5 °C. It was found to be about 45 °C higher than the room temperature, when measured at the steady-state condition. The highest temperature point was due to the location closest to the heat source that the strength of the hot air rising up from the heat source was directly heating it. On the same plane, away from the centre point, the temperature distributions were giving fairly average temperatures. The average air temperature on the bottom plane was found to be 50.8 °C.

As noticed from the Figure 5.8 (a), the centre point temperature on the top plane and middle plane were found to be 50 °C and 50.3 °C respectively. Both the temperature readings were merely the same despite the fact that they were located at a distance of 1100 mm and 600 mm above the base of the enclosure. The average of top plane and middle plane air temperatures were 50.3 °C and 49.4 °C respectively.

In addition, the trend line of the air temperature measured on the top plane was merely the same as the trend line of the air temperature on the middle plane. The only noticeable temperature difference was the end point temperature for the top plane where the vents were located on Wall A and Wall C. The movement of the heated air within the enclosure through these vents providing higher temperature reading on the region near to the vents. In addition, the end point temperature on the top rack, in the direction of Wall C to Wall A, where the vents were located, allow the hot air to exit to the ambient were showing a higher temperature reading of 39.4 °C and 35.5 °C on Wall C and Wall A respectively. The end point temperatures on the top rack in the direction of Wall D to B, were found to be 32.5 °C and 31.7 °C respectively. A similar trend was observed for the middle rack temperatures and bottom rack temperatures that were measured between Wall B and Wall D. This difference in end point temperatures is due to location of the top vents. For example, in the present experiment described in these graphs, the top vents were located on Wall C, and Wall A, and not on Wall D and Wall B. These founding was similar to the natural convection case.

The average ceiling temperature in this case was found to be about 35.7 °C. It was comparatively cooler than the average air temperature at any of the planes. The delay in propagation of the higher air temperature to the ceiling occurred due to sufficient top ventilation, and the fact that the enclosure was sufficiently tall for the heat source, and the speed of the fan.

The automotive fan was operated at 9.6 W to force the ambient cold air at a room temperature of 22.5 °C into the heater box. From the pressure measured with digital micrometer PVM 620, the centre point pressure of the top plane was found to be 7.2 Pa. It was found to be relatively higher, at 5.9 Pa, when compared to top plane centre point pressure for short enclosure. When moving away from the centre point to the end, the pressure on the top rack drops to 6.9 Pa at a distance of 100 mm away from the centre. The pressure remains constant until the end of the plane.

The heated air plume impinged to the ceiling spread beneath the ceiling and flowing out of the enclosure through the top vents located on the top wall of Wall A and Wall C at an average speed of 3.09 ms^{-1}. It is to be noted that for higher fan speeds encountered in this study, it was observed that the build up of hot air within the tall enclosure, over a period of time led to small air flow through the inlet vents to the ambient as well. This outflow through the bottom vents was found to be very negligible when compared to the flow rate due to the top vents.

Figure 5.9 shows the variation of bottom, middle, and top rack air temperature distribution between the walls, for forced convection in a tall enclosure with four top vents.

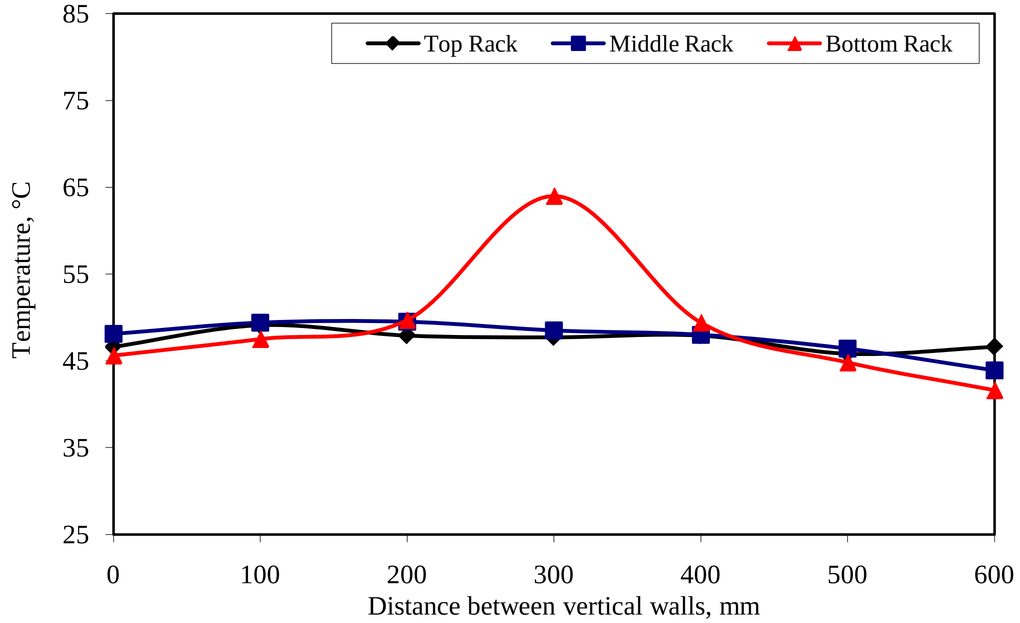


Figure 5.9 Variation of the of air temperature within the enclosure across the vertical walls, for four top vents.

A unique feature of the graph can be seen from Figure 5.9 plotted for the tall enclosure with four vents located on all walls. If the centre point air temperature on the bottom plane was not taken into consideration, the temperature distribution on three planes were showing a similar trend line. The high air temperature at the centre point on the bottom plane is due to the heating of hot air flow directly from the heat source.

Based on the observed temperature measurements, the average bottom, middle and the top rack air temperatures were found be almost the same. The bottom rack average air temperature was found to be 47.8 °C, the middle rack average air temperature was found to be 47.3 °C, and the top rack average air temperature was found to be 47.5 °C. These average temperatures were found to be about 2 °C lower than the corresponding average temperatures encountered for a two-vented tall enclosure subjected to forced convection. This indicates that an addition of two top vents had only a marginal effect in reducing the average air temperatures within the enclosure.

It is observed that there is a significant reduction in the air temperatures when moving from one top vent to two top vents; however further additional vents are not found to contribute to any significant drop in air temperatures. This is shown in Figure 5.10, which is a plot of the variation of ceiling wall temperatures as a function of the flow rate through the vents.

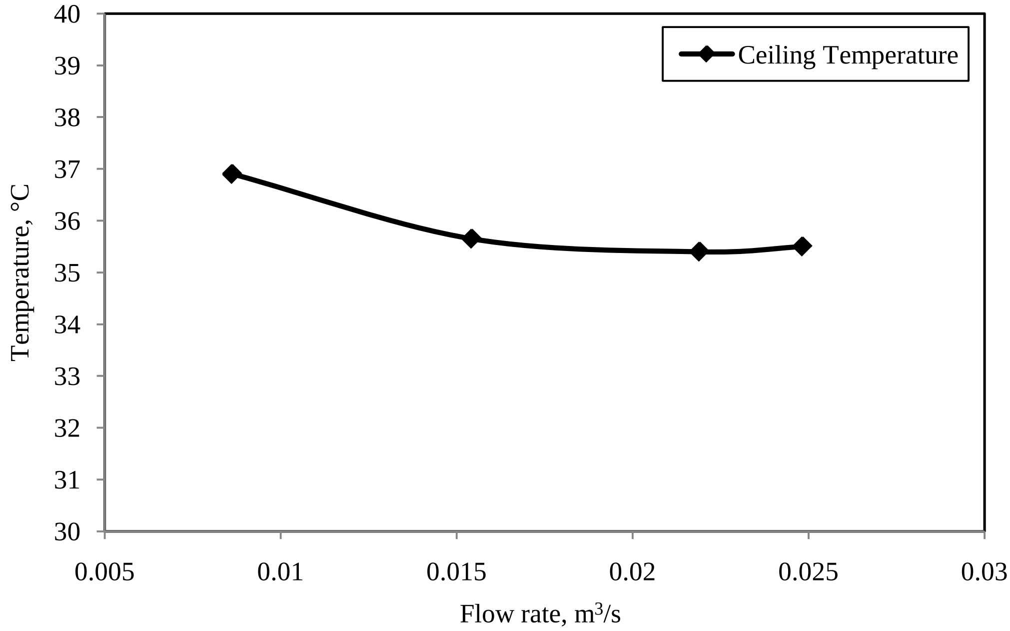


Figure 5.10 Variation of ceiling wall temperatures as a function of the flow rate through the vents.

Figure 5.11 shows the temperature distribution along the ceiling for a tall enclosure with four top vents in forced convection. The average ceiling temperature in this case of the enclosure with four top vents was found to be 35.6 °C. This is the same as the average ceiling wall temperature (35.7 °C) for an enclosure with two top vents in forced convection, for a similar heater power input and fan speed.

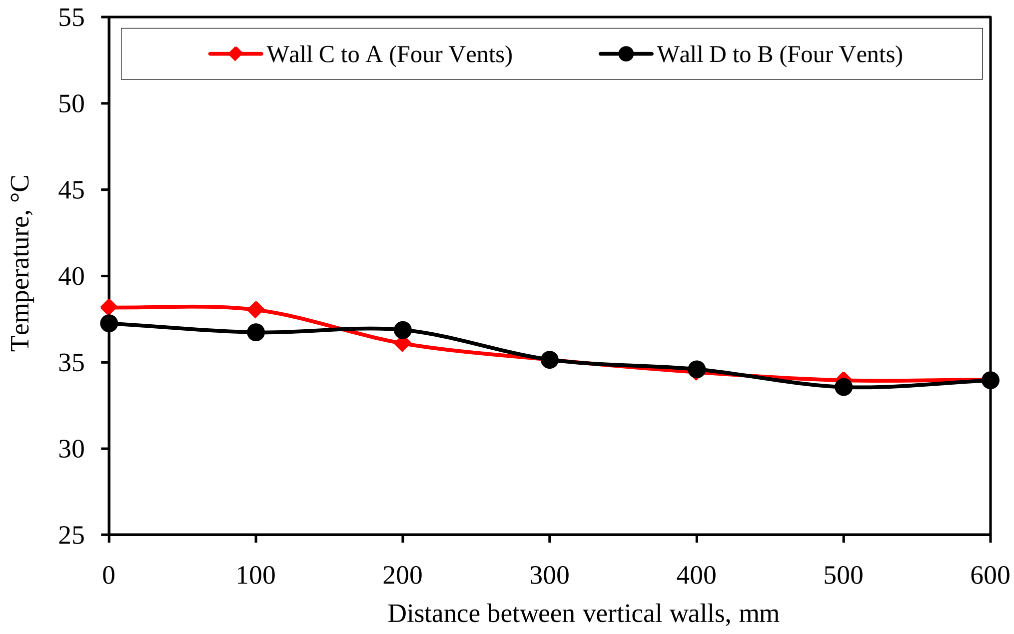


Figure 5.11 Temperature distributions across the ceiling of the tall enclosure, for four top vents.

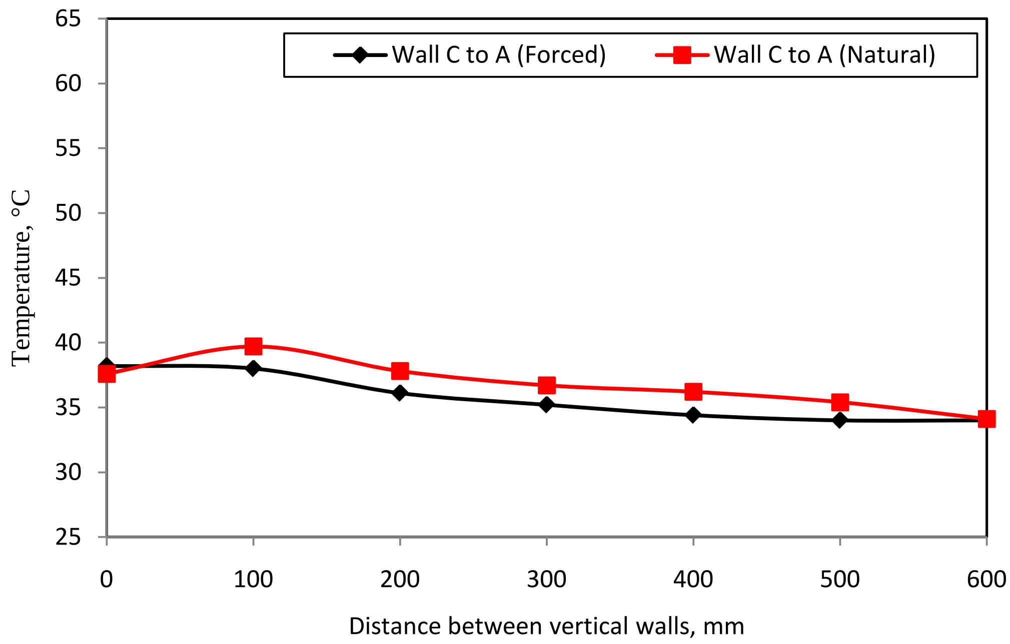


Figure 5.12 Comparison of ceiling temperature from Wall C to Wall A. The comparison is between similar cases for natural and forced convection.

Ceiling wall temperature distribution along Wall C and Wall A for the ‘four vent’ case is plotted on Figure 5.12. From the above figure, it is noted that the ceiling wall temperatures are higher by about 2°C at every point for natural convection cases for the tall enclosure. Meanwhile, the end points on both side of the wall (the vent located with hot air exit out to the ambient) showed a similar temperature reading. The effect of forced venting has contributed to the reduction (though marginal) of the ceiling wall temperatures.

5.4 Summary

The experimental results on the tall enclosure carried out on natural and forced convection was shown and discussed. The change of heated air properties within the enclosure was explained. The results showed that forced convection heating provided lower ceiling temperature compared to natural convection. This outcome is similar to the short enclosure.

CHAPTER 6
RESULTS AND DISCUSSION
COMPARISON OF SHORT AND TALL ENCLOSURES

6.1 Introduction

The experimental results of both the short and tall enclosures were thoroughly discussed in the previous chapters respectively. As a result of this research we found the effects and comparisons due to different combinations of vents, which were located on the top of the vertical wall, for both natural convection and forced convection heat transfer mechanisms.

This chapter will discuss two main points in order to better understand the behavioral patterns of the flow of heated air. Firstly, flow velocity was plotted in order to study the movement of smoke. Lastly, a comparison between the two different case studies: short enclosure (CS1) and tall enclosure (CS2) is brought out.

6.2 Velocity Plots

The pressure measurement points mounted on the middle rack was used to record the air pressure within the plume at various points across the plume. The pressure at these measurement points were obtained using a digital micro-manometer, as was described earlier, in Chapter 3. These recorded air pressures were then used to calculate the velocity at various points. Figure 6.1 shows the heated plume velocity plots for the short enclosure. The graphs were obtained only for forced convection studies. For natural convection studies, the flow velocities encountered were very low, and hence could not be accurately measured.

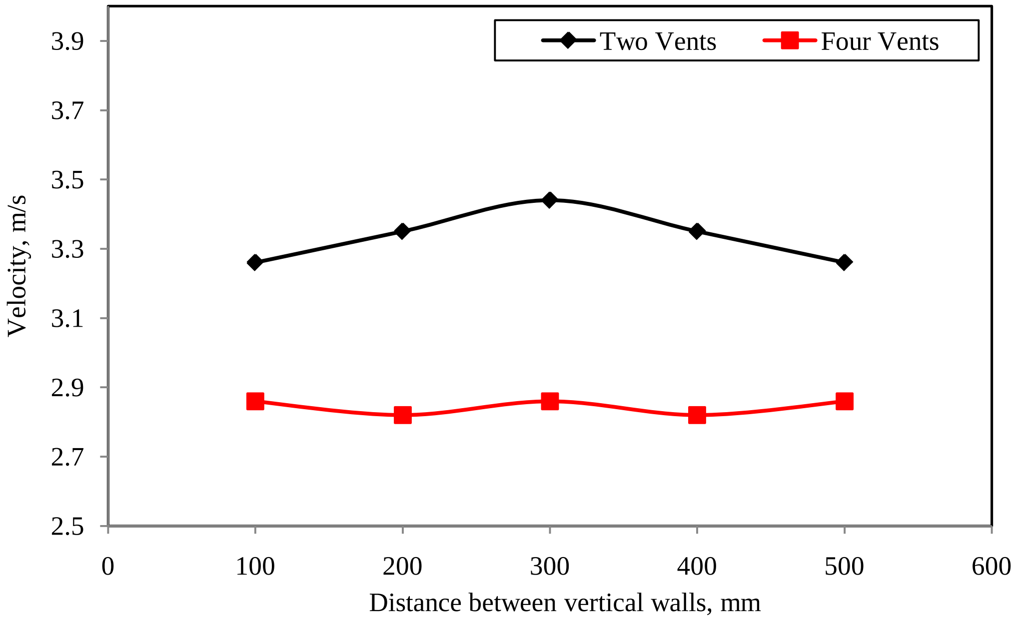


Figure 6.1 Plume velocity measured across the width of the short enclosure.

In this graph, the velocity patterns for a two and four-vented short enclosure is compared for identical test conditions. For both the two-and four vented short enclosures, it can be seen that there is a maximum velocity at the centre line of the plume. The centre line of the plume is located at a distance of 300 mm from the end walls of the enclosure. It can be seen that there is 20 % difference in the maximum velocity observed for the two cases. The velocity profile pattern for a four-vented enclosure is more or less linear when compared with that of the two-vented enclosure. Both profiles appear to be symmetrical with respect to the centre line of the plume as well.

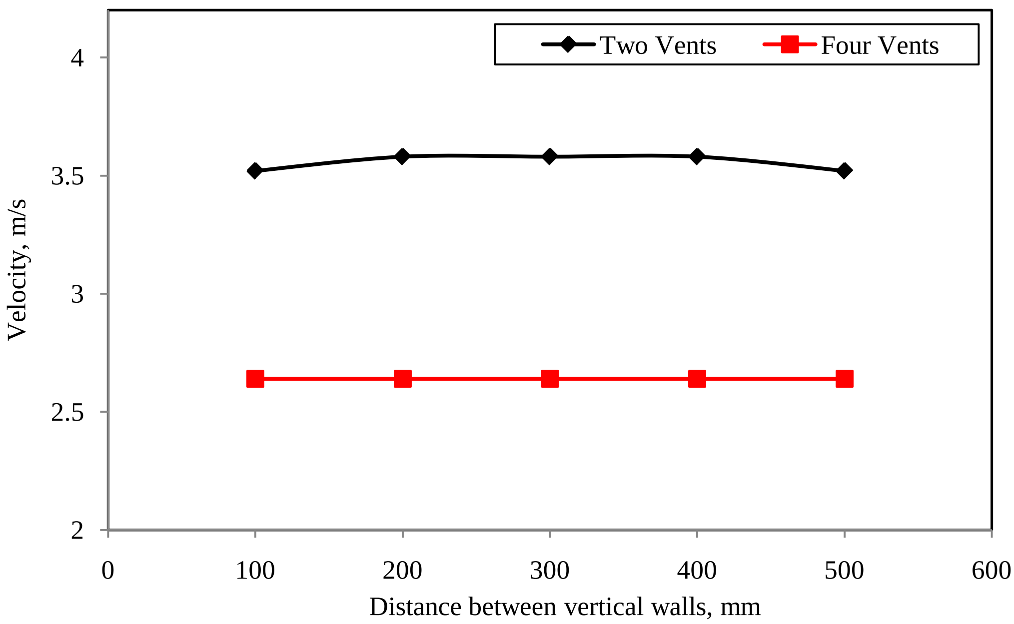


Figure 6.2 Plume velocity measured across the width of the tall enclosure.

Figure 6.2 showed the plot of the plume velocity as a function of the width of the enclosure for a two-and four-vented tall enclosure. Compared to the short enclosure, it can be seen that the plume velocity profiles for the tall enclosure have flat profiles, irrespective of the number of vents. When comparing the maximum centre line velocities, it is found that the velocities for the tall enclosure are slightly lower (by about 4 %) than the corresponding values for a short enclosure for a two-vented enclosure. Similarly, it is found that the velocities for the tall enclosure were slightly lower (by about 8 %) than the corresponding values for a short enclosure for a four-vented enclosure.

6.3 Comparison of Ceiling Temperature Distribution

Figures 6.3 and 6.4 show the ceiling temperature distribution for a short enclosure subjected to natural convection and forced convection studies.

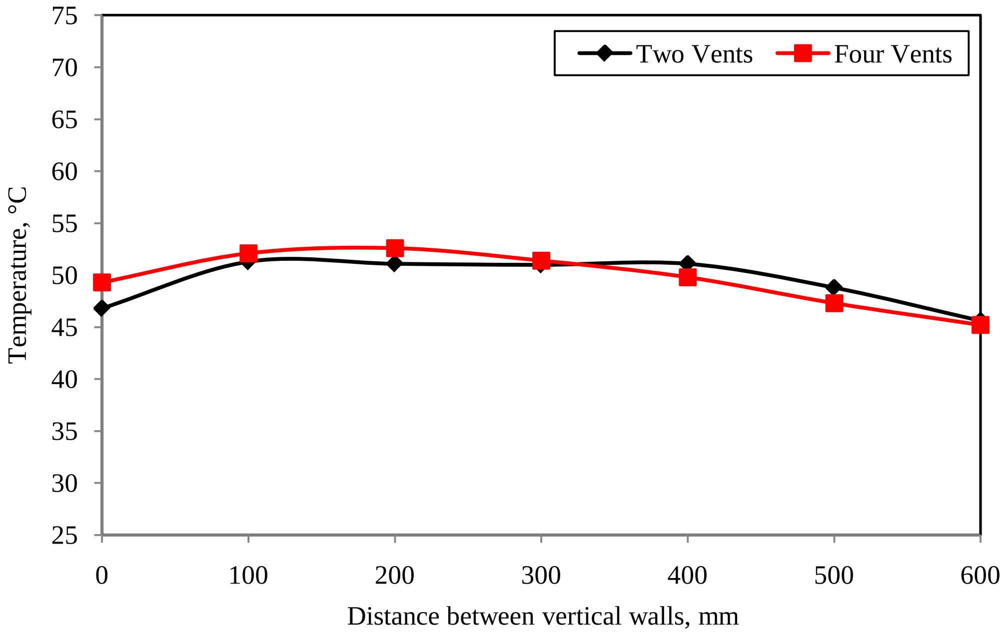


Figure 6.3 Ceiling temperatures for a short enclosure in natural convection

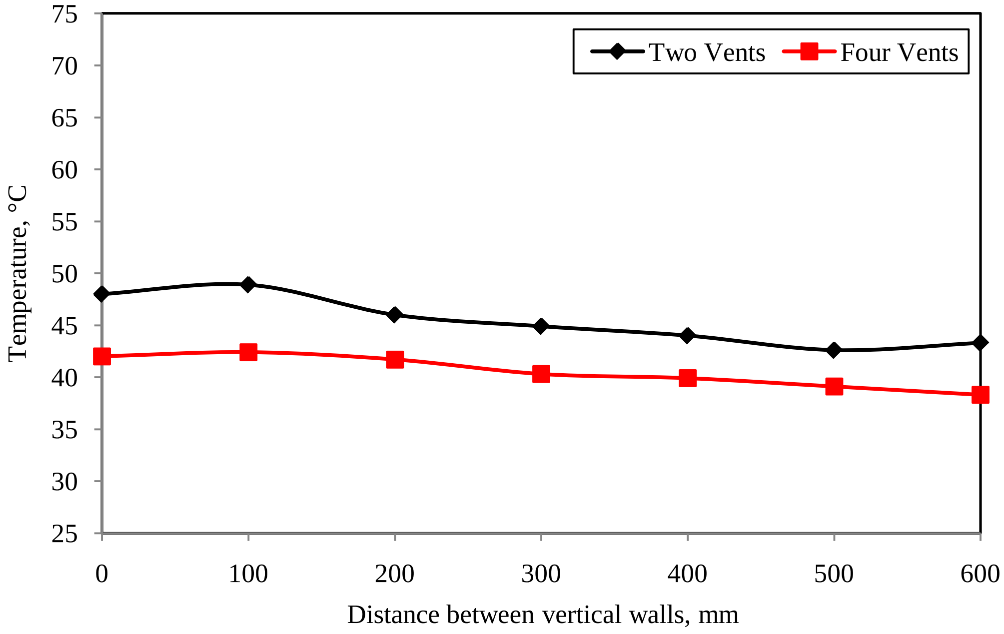


Figure 6.4 Ceiling temperatures for a short enclosure in forced convection

Identical cases are compared in these figures. The average ceiling temperature for a two-vented enclosure (49.4 °C) is found to be the same as the average ceiling temperature for a four-vented enclosure (49.7 °C) when considering natural convection studies for a short enclosure. However, the average ceiling temperature for a short enclosure for forced convection studies depicts a different behavior. In this case, the average ceiling temperature for a two-vented enclosure is found to be higher by about 12% compared to the four-vented enclosure.

Figures 6.5 and 6.6 in turn show the ceiling temperature distribution for a tall enclosure subjected to natural convection and forced convection studies.

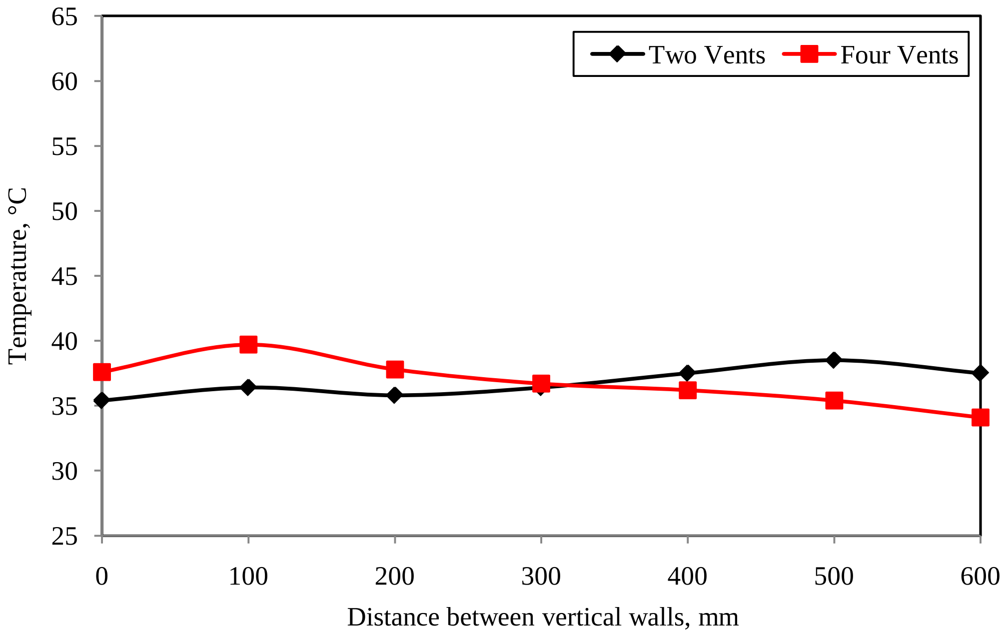


Figure 6.5 Ceiling temperatures for a tall enclosure in natural convection.

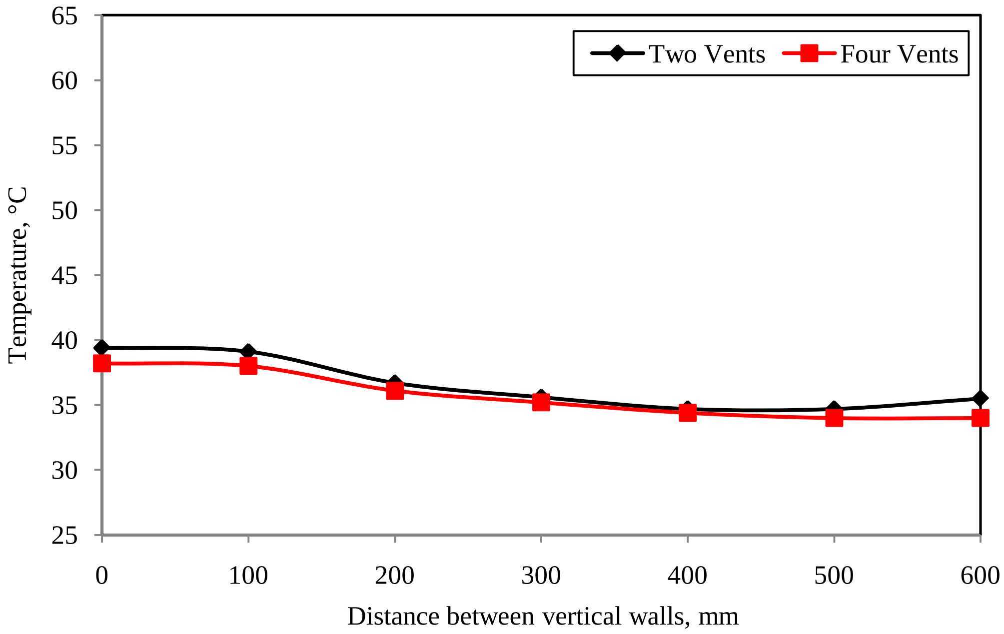


Figure 6.6 Ceiling temperature for a tall enclosure in forced convection.

Again, identical cases are compared in these figures. The average ceiling temperature for a two-vented enclosure (36.8 °C) is found to be the same as the average ceiling temperature for a four-vented enclosure (36.8 °C) when considering natural convection studies for a tall enclosure. The average ceiling temperature for a tall enclosure for forced convection studies is found to be the same for two-vented enclosure and four-vented enclosure. The average ceiling temperature for a two-vented enclosure is found to be higher only by about 2% compared to the four-vented enclosure.

Table 6.1 below shows the percentage difference of ceiling temperature between the centre point and the point near to the end of the ceiling (closer to the vents).

Table 6.1 Percentage differences of ceiling temperature

Number of vents	Short Enclosure		Tall Enclosure	
	Natural Convection	Forced Convection	Natural Convection	Forced Convection
No vent	29.3 %	-	30.5 %	-
1 vent	27.5 %	14.4 %	14.5 %	12.87 %
2 vents	21.4 %	14.5 %	13.4 %	12.3 %
3 vents	20.9 %	11.8 %	13.5 %	9.3 %
4 vents	15.8 %	9.2 %	7.3 %	3.5 %

The ceiling temperature plots for natural convection in Section 4.2 for short enclosure and Section 5.2 for tall enclosure are showing a higher temperature at the centre point in most cases. The ceiling temperature drops when moving from the centre towards the end of the ceiling. These differences between the centre point ceiling temperature and the point near to the end are shown in Table 6.1. The ceiling temperature differences have large variation from 7.3 % to 30.5 %. The ceiling temperature plots for forced convection in Section 4.3 (short enclosure) and Section 5.3 (tall enclosure) show a fairly uniform trend line for most of the cases. The ceiling temperature difference between centre point and end point had a range of differences from 3.5 % to 14.4 %.

As noticed from the Table 6.1, increases in the size and amount of vents on the enclosure will significantly reduce the temperature difference between centre point and end point. This shows that the assumption of uniform ceiling temperature as mentioned in several numerical studies only apply to a large ventilated enclosure and is not suitable for an enclosure with limited ventilation.

In addition, the assumptions used by past researchers such as uniform densities, uniform temperature of the upper and lower gas layers can be applied only for certain cases.

6.4 Heat Flux

A calibrated heat flux gauge was used to obtain the amount of heat flux that transferred from the heat sources to the centre point of the ceiling. In the experiment, thin film heat flux sensor, HFS-4 from Omega Engineering Inc. was used to measure the heat flux from the heat source. The heat flux was mounted at the centre point on the ceiling with transparent double-sided sticky tape which allows it to collect the accurate amount of heat flux transmitted from the heat source to the top. Table 6.2 shows the total heat flux measured by the thin film heat flux sensor for different cases.

Table 6.2 Heat flux measured on the ceiling for different case studies

Number of Vents	Short Enclosure		Tall Enclosure	
	Natural Convection, W/m^2	Forced Convection, W/m^2	Natural Convection, W/m^2	Forced Convection, W/m^2
1 vent	176.5	176.5	117.6	117.6
2 vents	176.5	176.5	117.6	117.6
3 vents	176.5	117.6	117.6	58.8
4 vents	176.5	117.6	117.6	58.8

As noticed from the table above, under the similar heat transfer mechanism, the ceiling of the short enclosure was receiving higher amount of heat flux compared to the tall enclosure. For natural convection, the ceiling of the short enclosure was receiving 176.5 W/m^2 regardless the amounts of ventilation while for tall enclosure, the ceiling was receiving 117.6 W/m^2 of heat flux. Besides, the increase of the number of vents also reduced the heat flux reaching to the ceiling. For the short enclosure, the ceiling was receiving 176.5 W/m^2 of heat flux for single and two vents while for the three and four vents cases, the heat flux reduced to 117.6 W/m^2. Similar results were observed in tall enclosure with forced convection heat transfer mechanism.

6.5 Correlations for Ceiling Temperature

The variation of the ceiling temperature with distance from the centre point of plume impingement is of interest for example, in the design of the layout for locating the fire sprinklers. It is derived from the fact that the response of the sprinklers is dependent upon the temperature prevalent within the enclosure. This is valid for both cases, irrespective of whether natural or forced convection heat transfer is present within the enclosures.

The systematic experiments carried out in the present study has generated enormous data, which is also meaningful, to be presented in the form of some correlations. Hence, using the principle of multiple regression analysis, two correlations for the ceiling temperature distribution as a function of the following quantities: distance from the centre point of plume impingement (r), height of the enclosure (H), and the cross-sectional area of the vents (A_v). These simple correlations are useful in obtaining the ceiling temperature at any location. Both correlations are derived considering short and tall enclosures, and vent areas, for the heating considered in this study. One correlation is applicable for the natural convection situation, and the other is applicable for the forced convection situation, discussed in earlier chapters of this thesis.

(i) Correlation for ceiling temperature (natural convection)

$(T_{ceil} - T_{\infty}) = 44.15 - 25.41\,(r) - 19.55\,(H) - 2.42\,(A_v)$

This correlation is based on 39 data points, and has a correlation coefficient of 0.99, and has an error band within ± 7 %. The parity plot shown in Figure 6.7 shows excellent agreement of the predicted temperature and the experimentally obtained values.

(ii) Correlation for ceiling temperature (forced convection)

$(T_{ceil} - T_{\infty}) = 33.28 - 13.51\,(r) - 13.52\,(H) - 40.7\,(A_v)$

This correlation is based on 42 data points, and has a correlation coefficient of 0.98, and has an error band within ± 7 %. This correlation is applicable for the range of vent flow rates from 0.0086 m^3/s to 0.0248 m^3/s. The parity plot shown in Figure 6.8

shows excellent agreement of the predicted temperature and the experimentally obtained values.

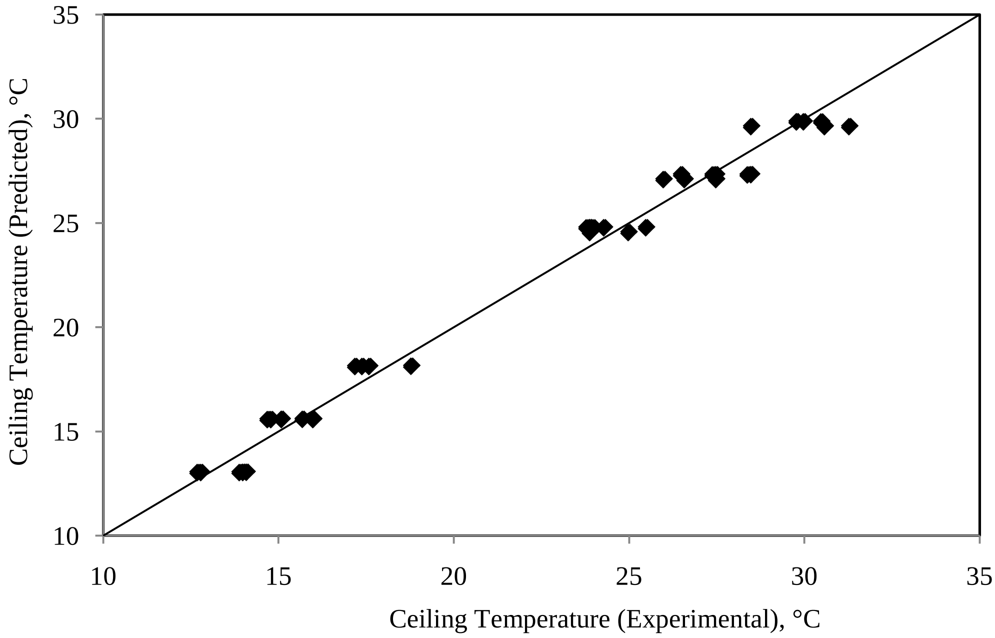


Figure 6.7: Parity plot for ceiling temperature (Natural convection).

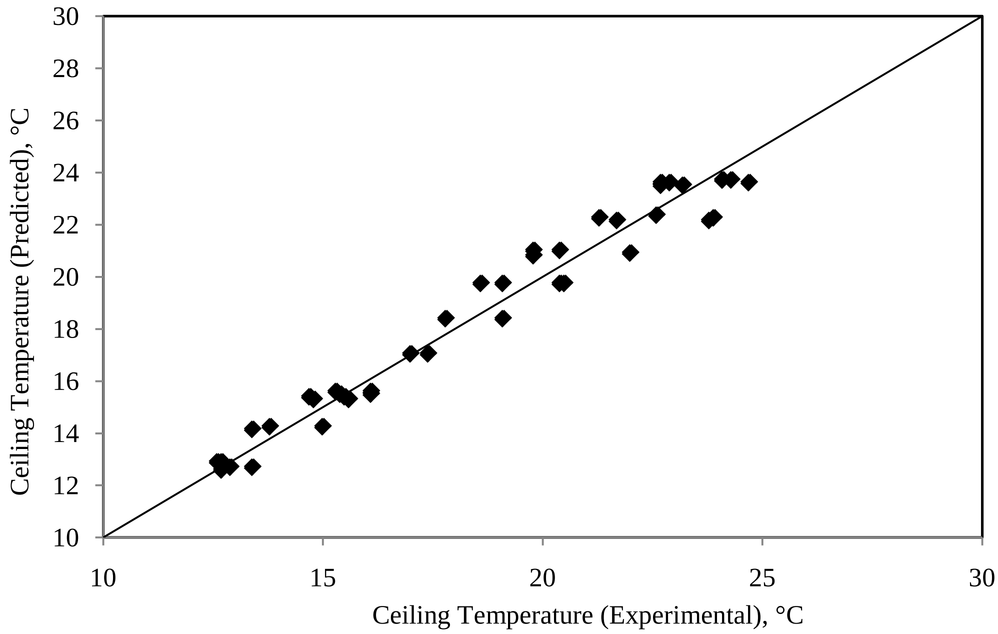


Figure 6.8: Parity plot for ceiling temperature (Forced convection).

6.6 Summary

The results of a comparison of the short enclosure case (CS1) and tall enclosure case (CS2) were presented in this chapter. A comparison of ceiling temperature and heat flux was also provided in this chapter. The next chapter provides the conclusions obtained from experiments conducted on all cases considered in this research.

CHAPTER 7
CONCLUSIONS

7.1 Introduction

In all, this thesis thoroughly presented an experimental study on the convection heat transfer mechanism with the goal of extensively studying the behavior of heated plume within enclosed enclosures.

An elaborate experimental model was developed to evaluate the heated plume properties within the enclosure and the impingement on the ceiling at a steady state. The models were constructed to examine the results from two distinctive heights, with two different heat transfer mechanisms of natural convection and forced convection. The effects of the introduction of vents into the enclosures and its effect on the heated air movement were analyzed. Different ventilation configurations were applied to the models for a complete investigation on the study of their effects.

7.2 Conclusions from the Present Work

The results obtained from the present experimental study have provided a better understanding on the effect of a heated plume within vented enclosures. It can be concluded that from changing the height of the enclosure to a higher value (at an aspect ratio of 1 and 2 in the present study), the hot air temperature within the enclosure (at all planes) will be significantly reduced. The effect of a heated plume impingement on the ceiling is weakened for a taller enclosure, and thus the heating on the ceiling is reduced. In addition, by shifting the heat transfer mechanism from natural to forced convection, the hot air temperature within the enclosure and the ceiling temperature will be reduced. An increase of the flow of air in and out of the enclosure by introducing proper ventilation will also change the hot air temperature and the heat energy stored within the enclosure. Also, by lowering the heat energy in the enclosure this would in turn lower will be the attendant fire risk. In the experiments described in this thesis, the effects of radiation and conduction heat transfer mechanism are not considered.

From the graph on ceiling temperature, it is found that the ceiling temperature is the highest for natural convection cases. The ceiling temperature difference between the centre point and end point varies from 7.9 % to 30.5 %. From the plots on ceiling temperature for forced convection, it shows a fairly uniform trend line for most of the cases. The difference in ceiling temperature between the centre point and end point varies from 3.5 % to 14.4 %. For both cases, the increase of size and number of vents will significantly reduce the temperature difference between centre point and the end point. This indicates that the assumption of uniform ceiling temperature (see for example, Reference [6]) only apply to a large ventilated enclosure and is not suitable for enclosure with limited ventilation. The experimental results of air and ceiling temperature distribution obtained from the present study can be used for validation of numerical modeling results. Based on the experimental results from the present study, two simple correlations for estimating the distribution of ceiling temperature are also provided

7.2.1 Effect of Height

The results obtained showed that the increase of height of the enclosure will reduce the average ceiling temperature and lower the hot air temperature within the enclosure. This increase in enclosure height requires longer travel for the heated plume to reach the ceiling, thus providing an opportunity for the hot air to mix with the existing air. It was found that the average ceiling temperature of the tall enclosure dropped by 4.2% compared to the short enclosure with fully enclosed design. In addition, the average ceiling temperature on the tall enclosure with the two-vent configuration and natural convection showed 26.7 % reduction compared to the short enclosure. In conclusion, by increasing the height of the enclosure (i.e. double in this study), the overall heating rate of the enclosure is reduced.

7.2.2 Effect of Natural Convection and Forced Convection

From the results, the temperatures of the top plane for natural convection consistently have a higher value near to the centre and lower at the end, near to the walls. The hot air plume that rises from the centre provided the high temperature, then cooled and descended along the sidewalls. Meanwhile, the temperatures on the top plane for forced convection show a fairly constant trend line. The forced air flow into the enclosure alters the buoyancy force and creates a mixing of hot and cool air, leading to a more uniform air temperature.

The average ceiling temperature is reduced through the introduction of mechanical ventilation. It was found that the short enclosure with two vents had a 10.4 % reduction with forced convection, when compared with natural convection.

7.2.3 Effect of Ventilation

Ventilation provides an avenue for the heat to be removed from the enclosure. It has a very strong impact on the enclosure's air properties and strongly depends on the size on the stream of flow. This stream of airflow could either be induced through natural convection or mechanical through forced convection.

The results showed that the tall enclosure with a small vent of size 50 mm ×50 mm on one side of the wall, the average ceiling temperature is reduced to 26 % and further reduced to 37.5 % with four vents on each side of the wall.

7.3 Suggestions for Future Work

The aim of this study was to experimentally investigate the effects of a heated plume within an enclosure with changes in geometry, different heat transfer mechanism and ventilation configuration. The present study can be extended through an increase the size of ventilation to find the optimum vent size with respect to the size of the enclosure. Moreover, the experimental set-up can be modified to undertake simple, low-energy fire experiments.

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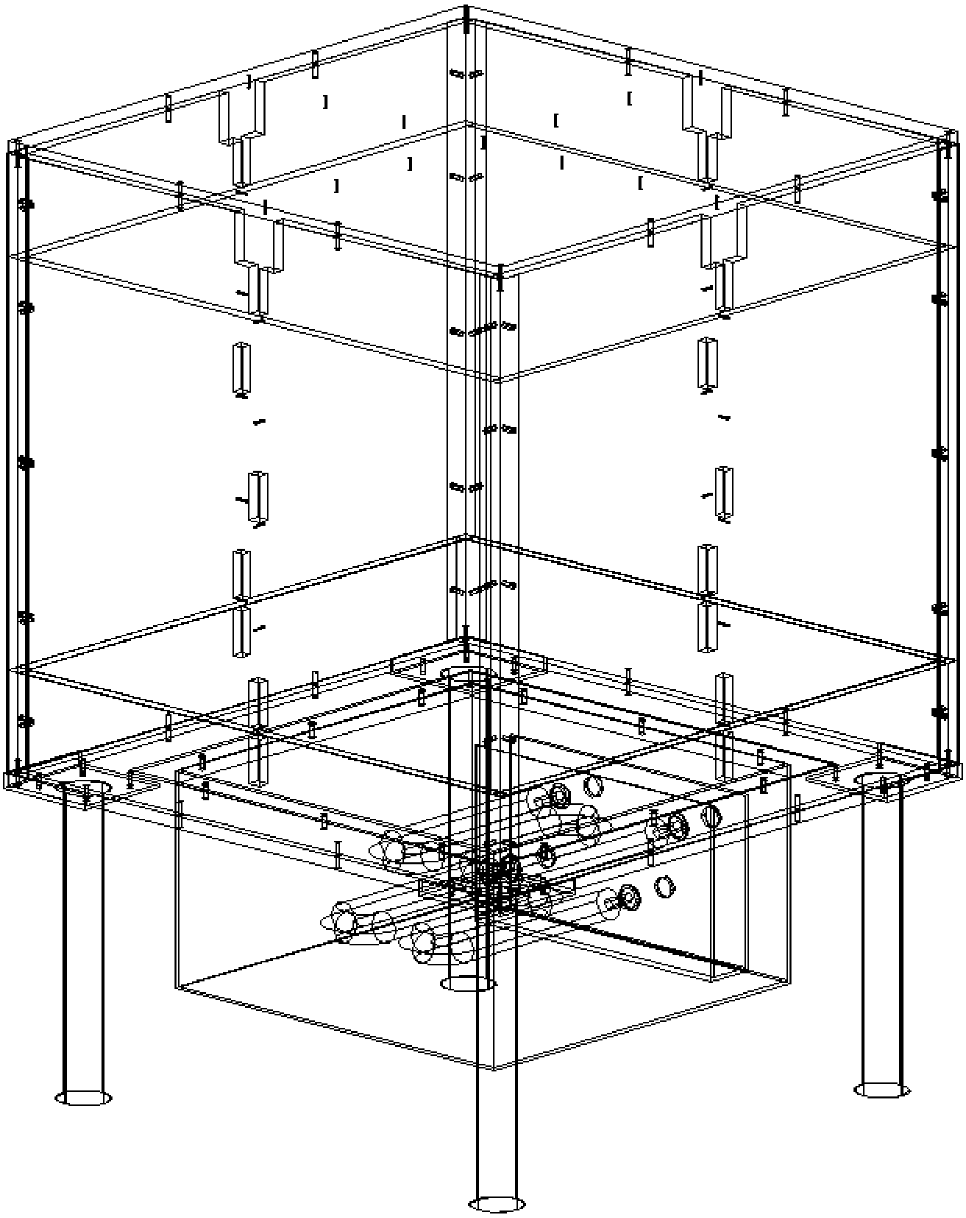
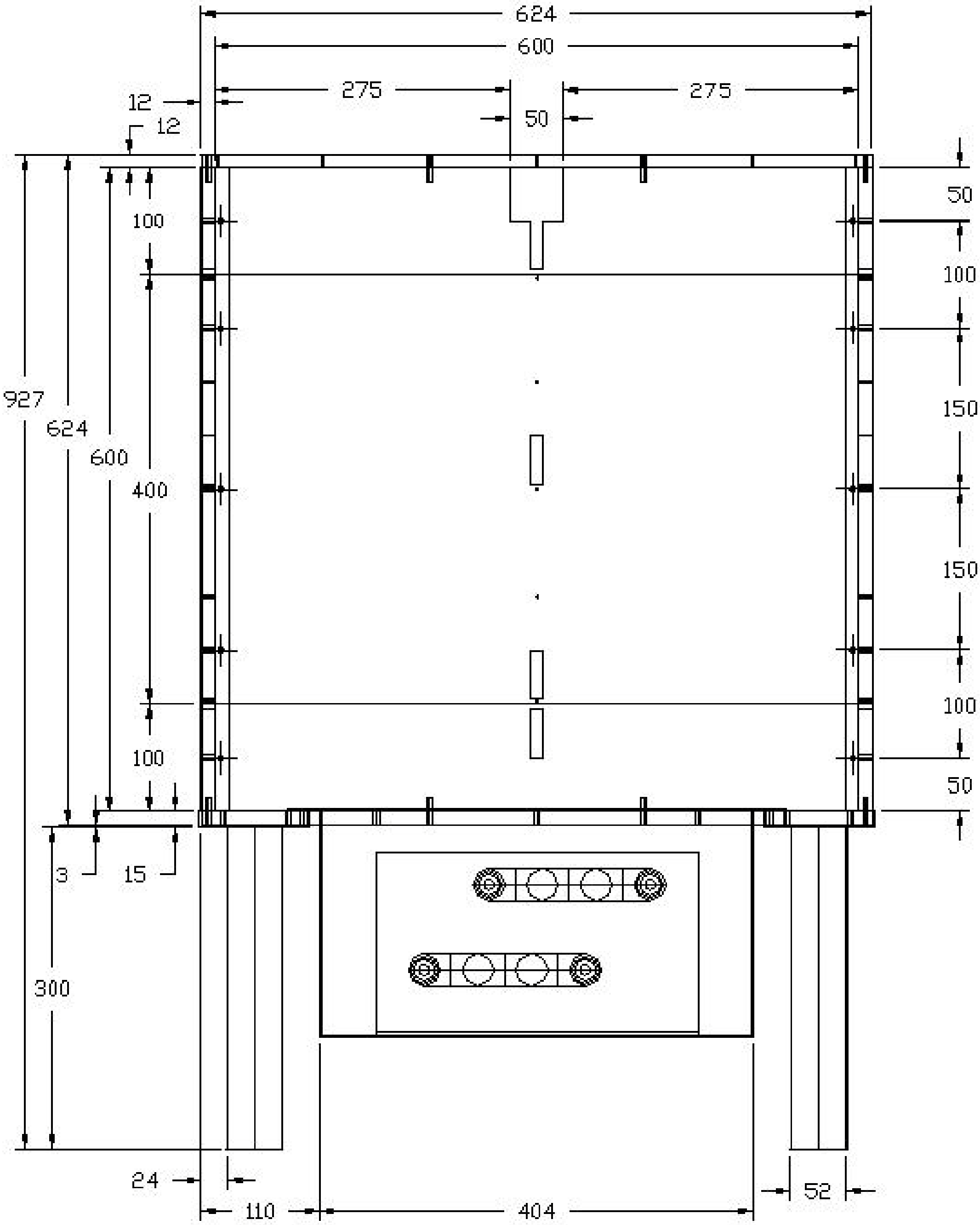
Appendix A

Fabrication Drawings of Enclosures

A1: Short Enclosure

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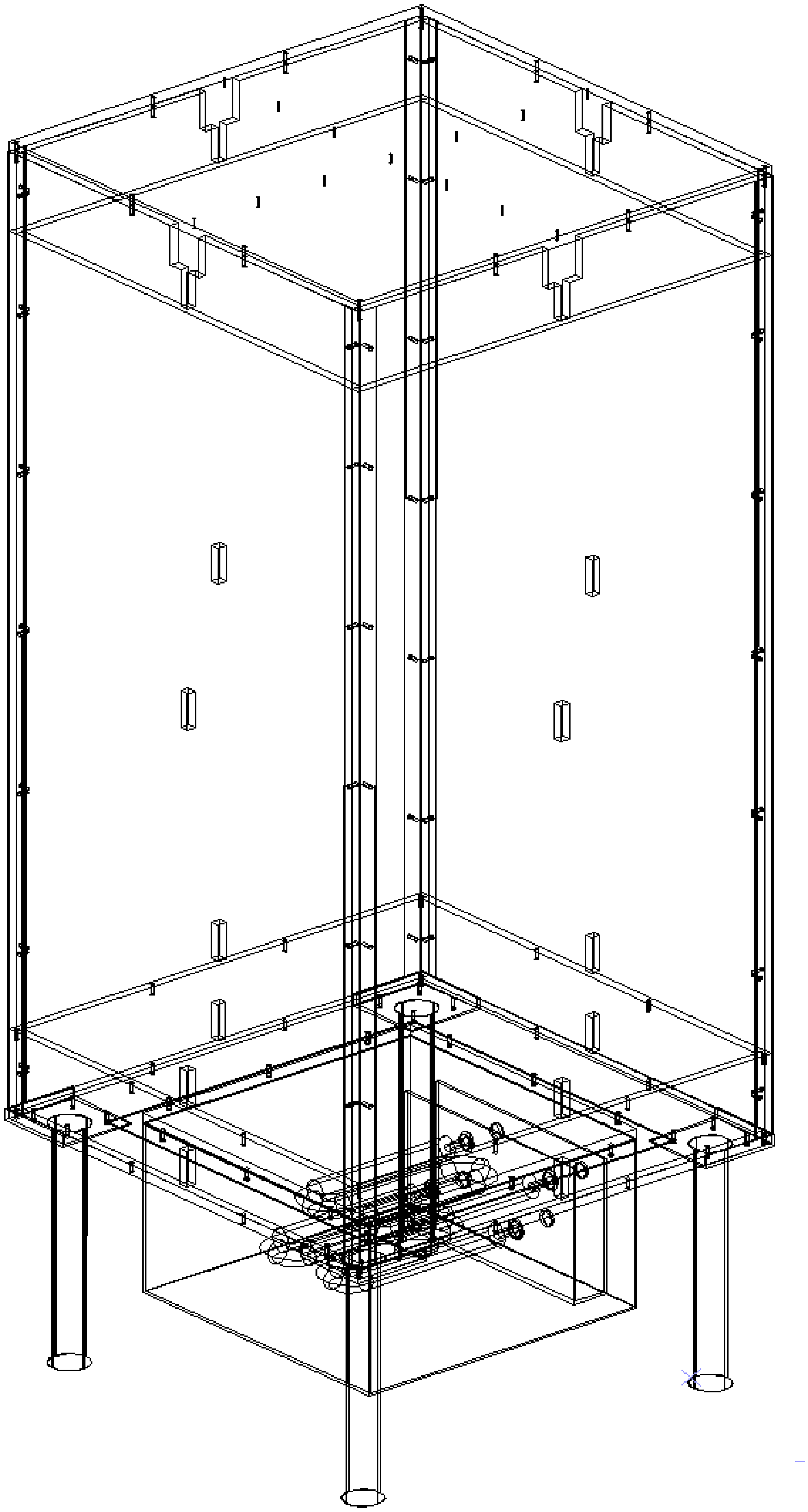
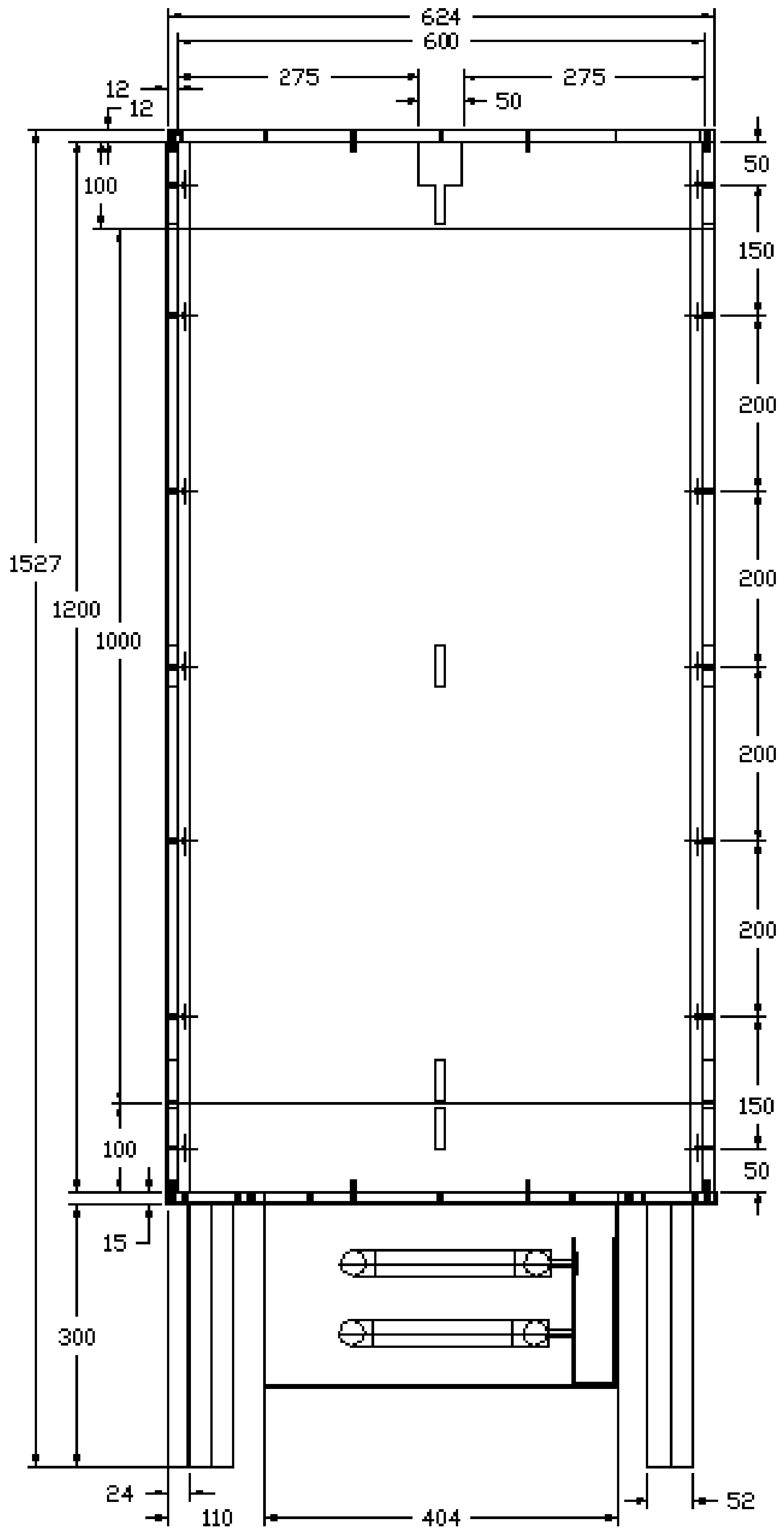
A2: Tall Enclosure





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A3: Heater box