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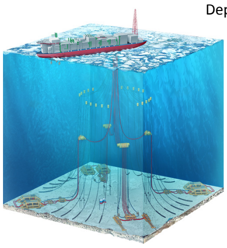
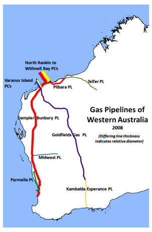
Pressure drop prediction in horizontal natural gas-solid flow based on empirical equations

Corinne Vallet

Department of Chemical Engineering





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Background

- 70% of reserve located in poorly consolidated reservoirs
- Presence of fine sands increases the pressure drop and pipeline erosion.
- Softwares availables such as Flow Manager™, OLGA or CFD: very accurate, in particular CFD, and expensive

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Focus of this study

- predict the overall pressure drop in presence of solids particles:
  - Horizontal natural gas pipelines
  - Dilute solid loadings $\Phi = \frac{\dot{m}_p}{\dot{m}_p} \leq 0.1$
- Pressure drop $\Delta P = \Delta P_f + \Delta P_p$

$$\Delta P = \frac{(\lambda_L \rho_f \, LU_f^2)}{2D} + \frac{4f_p \, U_p^2}{D^2} L$$

Pressure drop

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- Knowns:
  - Operating conditions (P, T, gas composition, flowrate)
  - Sand characteristics (diameter d_p, density ρ_p and solid loading)
  - Pipeline characteristics (D, $\varepsilon_{roughness}$)
- Unknowns:
  - Gas density and viscosity
  - Gas and particles velocities

Pressure drop

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  - Operating conditions (P, T, gas composition, flowrate): ρ_f, μ_f
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  - Gas and particles velocities

Empirical equations used here

- Friction factor from Hinkle (1952):

$$f_p = \frac{3}{8} \frac{\rho_f}{\rho_p} \frac{D}{d} C_D \left(\frac{U_f - U_p}{U_p} \right)^2$$

- Slip velocity (Hinkle's equation modified by the Institut of Gas Technology):

$$\frac{U_p}{U_f} = 1 - 0.068 d^{0.92} \rho_p^{0.5} \rho_f^{(-0.2)} D^{(-0.54)}$$

Michaelides, E.E. and Roy I. Evaluation of several correlations used for the prediction of pressure drop in particulate flows. Int. J. Multiphase flow, 1987, 13, 433-442.

Klinzing, G. E., F. Rizk, R. Marcus and L. S. Leung (2010). Pneumatic Conveying of Solids A theoretical and practical approach, Springer.

Gas and particle velocities

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$$\frac{U_p}{U_f} = 1\text{-}0.068 d^{0.92} \rho_p^{0.5} \ \rho_f^{(-0.2)} \ D^{(-0.54)}$$

- flow rate of the suspension Q_{susp}:

$$Q_{susp} = A[\varepsilon_{vf} \ U_f + (1\text{-}\varepsilon_{vf}) U_p]$$

- Solid loading ratio: $\Phi = \frac{\rho_p Q_p}{\rho_f Q_f} = \frac{\rho_p}{\rho_f} \frac{U_p}{U_f} \frac{1\text{-}\varepsilon_{vf}}{\varepsilon_{vf}}$

Friction factor λ_L due to the gas

- Reynolds number Re
- Darcy friction factor λ_L: Buzzeli approximation of the White-Colebrook equation (0.13%):

$$\sqrt{\frac{1}{\lambda_L}} = \frac{A + 2\log_{10}\left(\frac{B}{Re}\right)}{1 + \frac{2.18}{B}}$$

with $A = \frac{0.774\ln(Re) - 1.41}{1 + 1.32\sqrt{\frac{\varepsilon_{roughness}}{B}}}$ $\quad B = \frac{\varepsilon_{roughness}}{3.7D} Re + 2.51A$

Buzzelli, D. (2008). "Calculating friction in one step." Machine Design 54: 1-2.

Friction factor due to sand particles

- Hinkle's empirical equation: $f_p = \frac{3}{8}\frac{\rho_f}{\rho_p}\frac{D}{d} \ C_D \left(\frac{U_f\text{-}U_p}{U_p}\right)^2$
- Drag coefficient C_D:

$$C_D = \frac{24}{Re_p}(1 + 0.15 Re_p^{0.687}) + \frac{0.42}{1 + 4.25.10^4 \, Re_p^{-1.16}}$$

- Reynolds number for a particle: $Re_p = \frac{\rho_f \ (U_f\text{-}U_p) \ d_p}{\mu_f}$

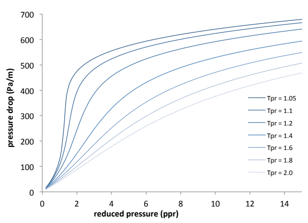
Application to a Nigerian gas field

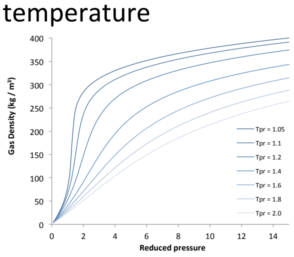
- Operating conditions:
  - Pressure: 0.1 to 25 Mpa
  - Temperature: -20 to + 90°C
  - Gas composition: CH_4: 90.2%, C_2H_6: 6.9%, C_3H_8: 2.1% and C_4H_{10}: 0.8%.
- Critical pressure P_{pc}: 673.249 psia
- Critical temperature T_{pc}: 367.77 °R
- Gas density: maximum at 400 kg/m³ for conditions studied here

Chaczykowski, M. (2009). "Sensitivity of pipeline gas flow model to the selection of the equation of state." Chemical Engineering Research and Design 87(12): 1596-1603.
Ahmed, T. (2006). Reservoir Engineering Handbook, Gulf Professional Publishing, Elsevier.

Overall pressure drop: case of a Nigerian gas field

- Influence of Pressure and temperature



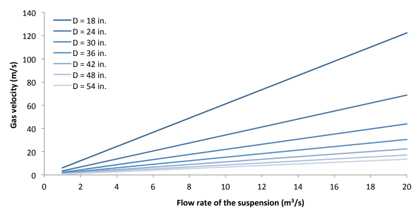


Conditions: d_p=0.1 mm , ρ_g = 300 kg/m³, ρ_p = 2400 kg/m³, Φ = 0.1, P_{pr} = 0.8, T_{pr} =1.5.

- Similar effect of P and T on Pressure drop than on gas density

Application to a Nigerian gas field

- Gas velocity: increase with Q, and decrease with D

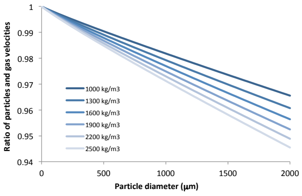


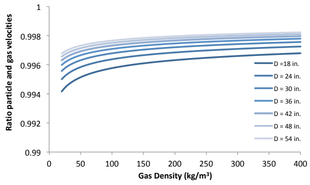
Conditions: d_p=1 mm , ρ_g = 300 kg/m³, ρ_p = 2400 kg/m³, Φ = 0.1

Application to a Nigerian gas field

- Ratio of gas and particle velocities

$$\frac{U_p}{U_f} = 1\text{-}0.068 d^{0.92}\rho_p^{0.5}\ \rho_f^{(-0.2)}\ D^{(-0.54)}$$



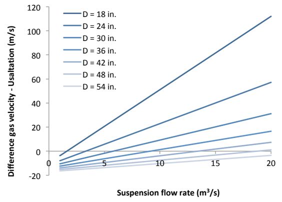


Application to a Nigerian gas field

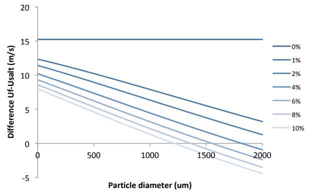
- Saltation velocity

$$U_{salt} = \sqrt{gD}\ \sqrt[(1.1d+2.5)]{\Phi 10^{(1.44d+1.96)}}$$

- Difference gas velocity_saltation velocity



Conditions: d_p=1 mm, ρ_p = 2400 kg/m³, Φ = 0.1

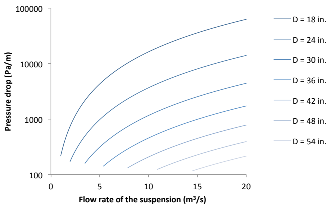


Conditions: ρ_f: 300 kg/m³ , ρ_p: 2400 kg/m³, D 36in., Suspension flow rate: 10m³/s

- With diameter starting from 48 in., flow rate insufficient

Overall pressure drop: case of a Nigerian gas field

- Flow rate

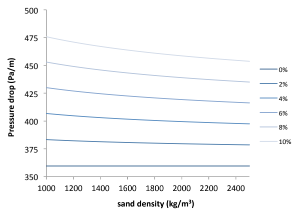


Conditions: d_p=0.1 mm , ρ_g = 300 kg/m³, ρ_p = 2400 kg/m³, Φ = 0.1

Below D=24 in. : very high pressure drop at high flow rate
For a solid loading of 10%.

Overall pressure drop: case of a Nigerian gas field

- Sand loading and sand density



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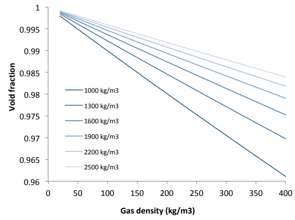
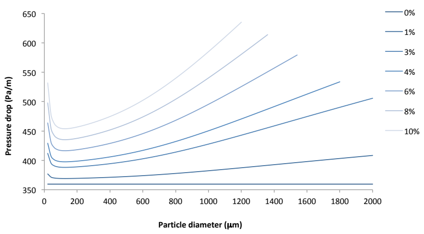


Conditions: d_p=1 mm , ρ_g = 300 kg/m³, Φ = 0.1,, D=36 in.

increase with sand loading,
decrease with sand density

Overall pressure drop: case of a Nigerian gas field

- Sand loading and particle diameter



Conditions Φ = 0.1,, D=36 in, $Q_{suspension}$ = 10m³/s, Pr = 0.8, Tpr =1.5

- Increase of pressure drop at low particle diameter reflects the effect of d on the drag coefficient C_D

Conclusions

- Analytical model based on empirical equations successfully developed here
- Model underlines where mitigation measures have to be taken when different conditions are met such as
  - high particle diameter and high pipeline diameter and high solid loadings
  - High flow rate with a potential presence of sand particles

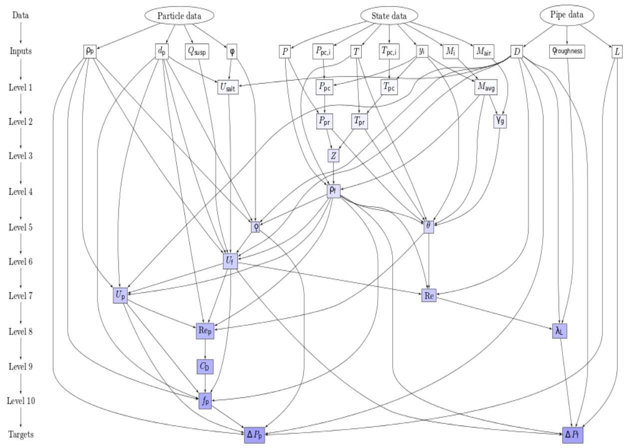
Acknowledgements

- Dr Emmanuel Obanijesu
- Dr Milinkumar Shah
- Prof Moses Tade

Thank you !

Gas properties

- Knowing operating conditions of pressure and temperature, and the natural gas composition, determine:
  - critical pressure (p_c) and temperature (T_c)
  - pseudo reduced pressure (p_{pr}) and temperature (T_{pr})
  - Compressibility factor Z (Heidaryan-Moghasasi-Rahimi for initial value for the iteration method of Dranchuk-Abou-Kassem)
  - Gas density
  - Gas viscosity (Lee-Gonzalez-Eakin)
  - Reynolds number Re: need of gas velocity!



Model Validation

- Use of fortran 90 to build the model

- Validation of each step using appropriate data from the litterature