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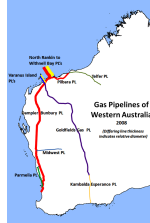
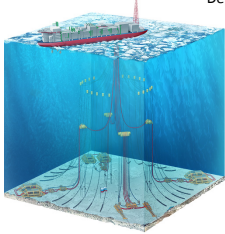


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Pressure drop prediction in horizontal natural gas-solid flow based on empirical equations

Corinne Vallet

Department of Chemical Engineering



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

Focus of this study

- predict the overall pressure drop in presence of solids particles:
 - Horizontal natural gas pipelines
 - Dilute solid loadings $\Phi = \frac{m_p}{m_g} \leq 0.1$

- Pressure drop $\Delta P = \Delta P_f + \Delta P_p$

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

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

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

Pressure drop

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

- **Knowns:**
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Empirical equations used here

- Friction factor from Hinkle (1952):

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

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

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

Gas and particle velocities

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

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

- flow rate of the suspension Q_{susp} :

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

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

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 $A = \frac{0.774 \ln(Re) - 1.41}{1 + 1.32 \sqrt{\frac{\epsilon_{\text{roughness}}}{B}}}$ and $B = \frac{\epsilon_{\text{roughness}}}{3.7D} Re + 2.51A$

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

Friction factor due to sand particles

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

- Drag coefficient C_D :

$$C_D = \frac{24}{Re_p} (1 + 0.15 Re_p^{0.687}) + \frac{0.42}{1 + 4.25 \cdot 10^4 Re_p^{-1.16}}$$

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

Application to a Nigerian gas field

- Operating conditions:

- Pressure: 0.1 to 25 Mpa
- Temperature: -20 to + 90°C
- Gas composition: CH₄: 90.2%, C₂H₆: 6.9%, C₃H₈: 2.1% and C₄H₁₀: 0.8%.

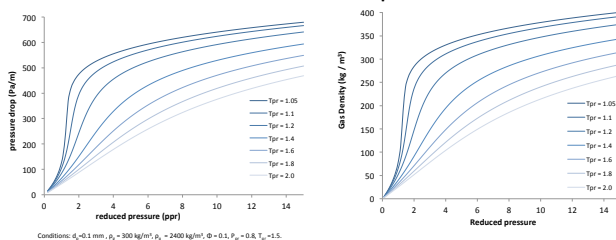
- Critical pressure P_{pc} : 673.249 psia
- Critical temperature T_{pc} : 367.77 °R
- Gas density: maximum at 400 kg/m³ for conditions studied here

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.

Almeid, T. (2006). *Reservoir Engineering Handbook*, Gulf Professional Publishing, Elsevier.

Overall pressure drop: case of a Nigerian gas field

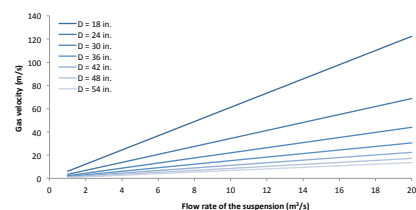
- Influence of Pressure and temperature



- 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

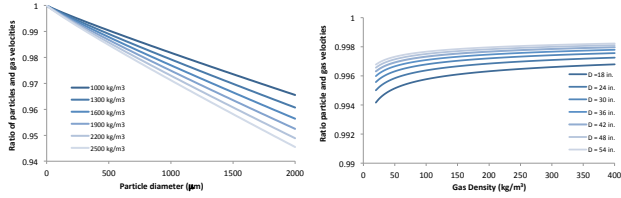


Conditions: $d_p = 1 \text{ mm}$, $\rho_p = 300 \text{ kg/m}^3$, $\rho_g = 2400 \text{ kg/m}^3$, $\Phi = 0.1$

Application to a Nigerian gas field

- Ratio of gas and particle velocities

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

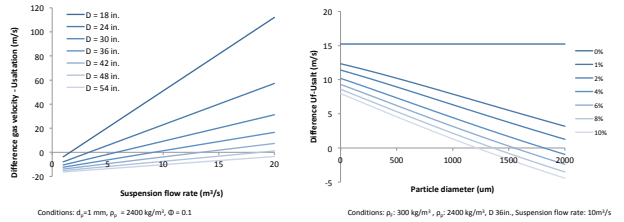


Application to a Nigerian gas field

- Saltation velocity

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

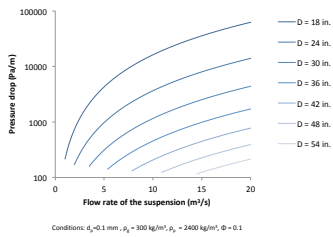
- Difference gas velocity - saltation velocity



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

Overall pressure drop: case of a Nigerian gas field

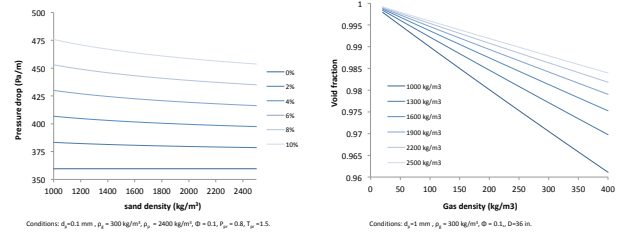
- Flow rate



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

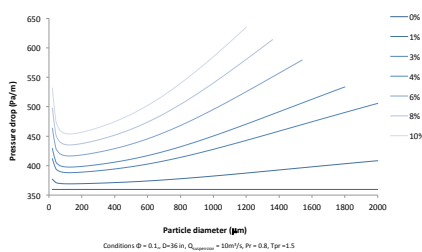
- Sand loading and sand density



increase with sand loading,
decrease with sand density

Overall pressure drop: case of a Nigerian gas field

- Sand loading and particle diameter



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

Conclusions

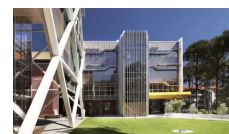
- Analytical model based on empirical equations successfully developed here
- Model underlines where mitigation measures have to be taken when different conditions are met such as
 - high particle diameter and high pipeline diameter and high solid loadings
 - High flow rate with a potential presence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

Acknowledgements

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

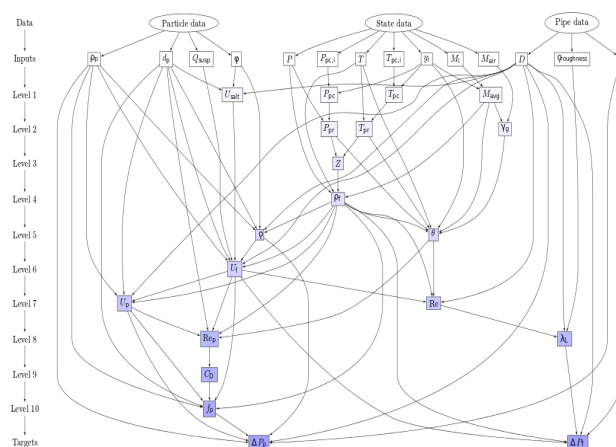


Thank you !



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 literature