Development of Empirical Equations on Pressure Drop as a Result of Dilute Gas–Solid Mixture along Horizontal Natural Gas Pipeline

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Project
Chemical Engineering View project

Project
CFD Simulations and Experimental Investigation of Fluidized Bed Reactor for Biomass Pyrolysis View project
Pressure drop prediction in horizontal natural gas-solid flow based on empirical equations

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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 available 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 \( \phi \frac{m_c}{m_p} \leq 0.1 \)

• Pressure drop
  \[ \Delta P = \Delta P_f + \Delta P_p \]
  \[ \Delta P = \frac{(\lambda _f \rho _f L U_f^2)}{2D} + \frac{4f_p U_p^2}{D^2 L} \]

Pressure drop

\[ \Delta P = \frac{(\lambda _f \rho _f L U_f^2)}{2D} + \frac{4f_p U_p^2}{D^2 L} \]

• Knowns:
  – Operating conditions \((P, T, \text{gas composition, flowrate})\)
  – Sand characteristics (diameter \(d_p\), density \(\rho_p\) and solid loading)
  – Pipeline characteristics \((D, \varepsilon_{\text{roughness}})\)

• Unknowns:
  – Gas density and viscosity
  – Gas and particles velocities

Empirical equations used here

• Friction factor from Hinkle [1952]:
  \[ \eta_f = \frac{3}{8} \rho_f D \frac{C_D}{\rho_p \varepsilon} \left( \frac{U_f - U_p}{U_p} \right)^2 \]

• Slip velocity (Hinkle’s equation modified by the Institut of Gas Technology):
  \[ \frac{U_p}{U_f} = 1 - 0.008 \rho_f D \frac{P_f^{0.3}}{P_p^{0.3}} D^{0.8} \]

In thermodynamic and chemical engineering, the friction factor is typically used for the prediction of drag forces in a pressurized flow. However, the study of Corinne Vallet focuses on empirical equations for pressure drop prediction in horizontal natural gas-solid flow, considering factors such as operating conditions, sand characteristics, and pipeline characteristics. The empirical equations are validated through comparisons with softwares and theoretical approaches, emphasizing the importance of accurate modeling in reservoir engineering.
Gas and particle velocities

• Slip velocity [Hinkle’s equation modified by the institute of Gas Technology]:
  \[ \frac{U_s}{U_f} = 1 - 0.068d_0^{0.5} \rho_f^{0.5} \rho_p^{0.2} D^{0.54} \]

• flow rate of the suspension \( Q_{\text{susp}} \):
  \[ Q_{\text{susp}} = \frac{\epsilon_f \rho_f U_f + (1 - \epsilon_f) \rho_p U_p}{\rho_f} \]

• Solid loading ratio:
  \[ \phi = \frac{\rho_f Q_f + \rho_p U_p \epsilon_f}{\rho_f U_f} \]

Friction factor due to sand particles

• Hinkle’s empirical equation: \( f_r = \frac{3 \rho_f D}{8 \rho_f d} \cdot C_D \left( \frac{U_f - U_p}{U_p} \right)^2 \)

• Drag coefficient \( C_D \):
  \[ C_D = \frac{24}{Re_p (1 + 0.15 Re_p^{0.87})^{+}} \]

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

Friction factor \( \lambda_L \) due to the gas

• Reynolds number Re

• Darcy friction factor \( \lambda_L \): Buzzeli approximation of the White-Colebrook equation (0.13%):
  \[ \frac{1}{\lambda_L} = \frac{A + 2.0 (B / Re)}{1 + 1.5 B} \]
  with \( A = 0.741 \ln (Re) - 1.41 \)
  \( B = \frac{\mu}{3.1 \rho_f} \)

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\(_2\)H\(_6\): 6.9%, C\(_3\)H\(_8\): 2.1% and C\(_4\)H\(_10\): 0.8%.

• Critical pressure \( P_{pc} \): 673.249 psia
• Critical temperature \( T_{pc} \): 367.77 °R

• Gas density: maximum at 400 kg/m\(^3\) for conditions studied here

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 \( D \)
Application to a Nigerian gas field

- Ratio of gas and particle velocities
  \[ \frac{U_p}{U_f} = 1 - 0.068d^{1.02} \rho_f^{0.5} \rho_p^{0.2} D^{0.34} \]

Overall pressure drop: case of a Nigerian gas field

- Flow rate
  \[ \text{Flow rate (m/s)} = \frac{\rho_p}{\rho_f} \cdot \frac{10}{\Phi} \]

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 particle diameter
  \[ \text{Pressure drop (Pa/m)} = \frac{1}{\Phi} \cdot \frac{\rho_p}{\rho_f} \cdot \frac{10}{\Phi} \]

- Increase of pressure drop at low particle diameter
  \[ \text{Drag coefficient} C_D \]

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
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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