Cuttings-liquid frictional pressure loss model for horizontal narrow annular flow with rotating drillpipe

T N Ofei*1, S Irawan1 and W Pao2

1 Petroleum Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Malaysia.
2 Mechanical Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Malaysia.

*Email: titus.ofei@petronas.com.my; titusofei@hotmail.com

Abstract. During oil and gas drilling operations, frictional pressure loss is experienced as the drilling fluid transports the drilled cuttings from the bottom-hole, through the annulus, to the surface. Estimation of these pressure losses is critical when designing the drilling hydraulic program. Two-phase frictional pressure loss in the annulus is very difficult to predict, and even more complex when there is drillpipe rotation. Accurate prediction will ensure that the correct equivalent circulating density (ECD) is applied in the wellbore to prevent formation fracture, especially in formations with narrow window between the pore pressure and fracture gradient. Few researchers have attempted to propose cuttings-liquid frictional pressure loss models, nevertheless, these models fail when they are applied to narrow wellbores such as in casing-while-drilling and slimhole applications. This study proposes improved cuttings-liquid frictional pressure loss models for narrow horizontal annuli with drillpipe rotation using Dimensional Analysis. Both Newtonian and non-Newtonian fluids were considered. The proposed model constants were fitted by generated data from a full-scale simulation study using ANSYS-CFX. The models showed improvement over existing cuttings-liquid pressure loss correlations in literature.

1. Introduction

The prediction of annular frictional pressure losses is an important parameter during drilling operations. This is vital when designing drilling hydraulic program, particularly, the equivalent circulating density (ECD) required for the efficient circulation of drilled cuttings from the bottom of the drill bit, through the annulus, to the surface without any formation damage. Erroneous predictions may result in wellbore catastrophes such as burst, collapse, mud influxes, or induced lost circulation events, especially, in formations where there is a narrow window between the pore pressure and fracture gradient.

Previous field, laboratory and simulation studies [1-15] have been conducted to estimate frictional pressure loss for single-phase Newtonian and non-Newtonian fluids with drillpipe rotation in annular geometries of diameter ratio ranging from 0.37-0.92. Till date however, few experimental studies [16-20] on two-phase cuttings-liquid flow in annulus have been carried out to predict the annular frictional pressure losses. These studies have attempted to propose empirical pressure loss correlations for cuttings-liquid flow in concentric and eccentric annular geometries. These pressure loss correlations are however, only applicable within a diameter ratio of 0.57-0.64, hence, will under-predict for cases where the diameter ratio exceeds 0.70.

Recently, other researchers [21, 22] have implemented computational fluid dynamics (CFD) methods to simulate two-phase cuttings-liquid flow in annuli, where the effects of several drilling parameters such as fluid velocity, drillpipe rotation, diameter ratio, and fluid type were analysed. Validation of CFD model with experimental data showed a very good match. In current drilling
operations, such as, casing-while-drilling and slimhole drilling, the annular geometry is very narrow (i.e. diameter ratio above 0.70). This results in extreme pressure losses as the drilling fluid and cuttings travel in the narrow annular region from the bottom-hole to the surface. Current two-phase cuttings-liquid pressure loss correlations are only limited to annular geometries of diameter ratio of 0.64, hence, may under-predict pressure losses in narrow annular geometries.

The present study proposes an improved frictional pressure loss model for narrow horizontal wellbores with drillpipe rotation and having diameter ratios from 0.64 to 0.90 using dimensional analysis method. The model is compared to CFD simulation pressure loss data generated using ANSYS-CFX 14.0. Furthermore, the accuracy of the proposed model is tested against other existing models in literature.

2. Materials and methods

2.1. Dimensionless analysis

There are several drilling parameters that affect frictional pressure loss estimation of cuttings-liquid flow in annular geometry. These include: annular geometry ($D_i, D_o$), cuttings concentration ($C_c$), drillpipe rotation ($\Omega$), axial fluid velocity ($v_a$), tangential fluid velocity ($v_\Omega$), fluid density ($\rho_f$) and viscosity ($\mu_f$), cuttings density ($\rho_c$) and size ($d_c$), and wellbore inclination ($\theta$). The pressure gradient is mathematically related to these parameters in Eq. (1) as:

$$\frac{\Delta P}{\Delta L} = f(g, \Omega, D_i, D_o, C_c, \rho_f, \rho_c, d_c, \mu_f, \theta, v_a, v_\Omega)$$

(1)

To develop a comprehensive model which is valid for a wide range of drilling parameters, as mentioned above, dimensionless groups of these parameters are defined. Assuming a homogeneous mixture of the cuttings-liquid flow, mixture density and viscosity [23] will be defined respectively as:

$$\rho_m = C_c \rho_c + (1 - C_c) \rho_f$$

(2)

$$\mu_m = (1 + 2.5C_c + 10.05C_c^2 + 0.0273\exp(16.6C_c))\mu_f$$

(3)

where the cuttings feed concentration is given as:

$$C_c = \frac{(ROP)A_{bit}}{R_f \cdot Q}$$

(4)

For a shear-thinning Power Law fluid where the flow behaviour index $n < 1$, the fluid apparent viscosity is defined in SI units as:

$$\mu_f = K \left( \frac{D_o - D_i}{v_a} \right)^{1-n} \left( \frac{2n + 1}{n} \right) \left( \frac{2^{2n}}{12} \right)$$

(5)

Where $K$ is the fluid’s consistency index in Pa s$^n$

The rotation of the drillpipe generates tangential velocity in addition to the axial velocity. With the knowledge of the fluid’s annular flow rate ($Q$), the axial velocity can be defined as:

$$v_a = \frac{4Q}{\pi(D_o - D_i)}$$

(6)
According to Slattery [24], couette flow model is considered in determining the tangential velocity component as a function of radius \( r \), rotational speed \( \Omega \), and diameter ratio \( \kappa = D_i/D_o \). An average tangential velocity in the annulus can be computed as:

\[
v_\Omega = \frac{\frac{D_o}{\kappa^2} \int_{\frac{D_i}{2}}^{\frac{D_o}{2}} \frac{2}{\kappa^2} \frac{D_o}{2 \pi} \int_0^{2\pi} \frac{\sqrt{\kappa^2 D_o \Omega} \left(\frac{2 r}{D_o} - \frac{D_o}{2 \pi} \right)}{\kappa^2 - 1} r d\xi dr}{\int_{\frac{D_i}{2}}^{\frac{D_o}{2}} \int_0^{2\pi} r d\xi dr}
\]

(7)

where \( \frac{D_i}{2} \leq r \leq \frac{D_o}{2} \)

By solving the Eq. (7) analytically, the tangential velocity is expressed as:

\[
v_\Omega = \frac{\kappa^2 D_o \Omega}{(\kappa^2 - 1)(D_o^2 - D_i^2)} \times \left\{ \left(\frac{D_o^3 - D_i^3}{3 D_o}\right) - (D_o^2 - D_o D_i) \right\}
\]

(8)

The pressure gradient equation in Eq. 1 can be summarised by considering the mixture density and viscosity in Eq. 2 and 3 respectively as:

\[
\frac{\Delta P}{\Delta L} = f(g, \Omega, D_i, D_o, C_c, \rho_m, d_c, \mu_m, \theta, v_a, v_\Omega)
\]

(9)

Since there are eleven (11) independent variables in Eq. (9), i.e., gravity \( g \), drillpipe rotation \( \Omega \), outer diameter of drillpipe \( D_i \), diameter of hole \( D_o \), cuttings feed concentration \( C_c \), mixture density \( \rho_m \), cuttings size \( d_c \), mixture viscosity \( \mu_m \), wellbore inclination \( \theta \), axial fluid velocity \( v_a \), and tangential fluid velocity \( v_\Omega \), and three (3) dimensions (M, L, T), thus, eight (8) dimensionless groups will be defined. Applying the Buckingham-\( \pi \) theorem, the dimensionless groups are defined as follows:

\[
\Pi_1 = \frac{D_i}{D_o}
\]

(10)

\[
\Pi_2 = C_c
\]

(11)

\[
\Pi_3 = \frac{\rho_m v_a (D_o - D_i)}{\mu_m}
\]

(12)

\[
\Pi_4 = \frac{\rho_m v_a (D_o - D_i)}{\mu_m}
\]

(13)

\[
\Pi_5 = \frac{v_a^2}{g (D_o - D_i)}
\]

(14)

\[
\Pi_6 = \frac{\Omega (D_o - D_i)}{v_a}
\]

(15)

\[
\Pi_7 = \theta
\]

(16)

\[
\Pi_8 = \frac{\rho_m v_a d_c}{\mu_m}
\]

(17)
The above dimensionless groups represent the following: \( \Pi_1 \) is the diameter ratio (ratio of drillpipe diameter to hole diameter), \( \Pi_2 \) is the amount of cuttings generated by the drill bit, \( \Pi_3 \) is the ratio of inertial to viscous forces in the axial direction, \( \Pi_4 \) is the ratio of inertial to viscous forces in the tangential direction, \( \Pi_5 \) is the ratio of inertial to gravitational forces, \( \Pi_6 \) is a function of drillpipe rotation, \( \Pi_7 \) is the wellbore inclination angle, and \( \Pi_8 \) is a function of cuttings size. The dimensionless groups defined in Eq. (10) to (17) are combined to formulate the frictional pressure loss model for cuttings-liquid flow in narrow horizontal wellbore.

2.1.1. CFD simulation study. Three-dimensional simulations for cuttings-liquid flowing in annular geometries were carried out to generate annular frictional pressure losses data using full-scale experimental setup data. Four annular geometries with diameter ratios \( \kappa = 0.64, 0.70, 0.80, \) and \( 0.90 \) were modelled and meshed using ANSYS Workbench 14.0. The continuity and momentum equations for both fluid and solids were solved using CFX solver [25] which is based on finite volume technique. The Eulerian-Eulerian model in ANSYS CFX, which regards both continuous (fluid) and dispersed (solid) phases as continuous media was adopted due to its ability to account for particle-particle interaction as well as handling high solid volume fractions greater than 20\%. The simulation solution is assumed to be converged when the root mean square (RMS) of the normalised residual error reached \( 10^{-4} \). The boundary conditions applied to the annular geometries are as follows: a mixture mass flow rate was specified at the inlet while a zero gauge pressure was specified at the outlet. No slip condition was also imposed on both inner and outer pipe walls for both fluids and solids. Both Newtonian (water) and Power Law fluid models were used in this study.

2.1.2. Meshing and model validation. The annular meshed geometries are shown in Figure 1. In this study, the geometries were meshed into unstructured tetrahedral elements of approximately \( 0.66 \times 10^6 \) to \( 2.15 \times 10^6 \) depending on the diameter ratio, with about 20\% inflation layers near the wall regions to accurately capture the flow effect. Mesh independence study was carried out to optimise the number of elements until results were independent of the number of elements. The optimum number of elements used for the annular geometries of diameter ratios \( \kappa = 0.64, \kappa = 0.70, \kappa = 0.80, \) and \( \kappa = 0.90 \) are respectively, \( 0.66 \times 10^6, 0.72 \times 10^6, 1.13 \times 10^6 \) and \( 2.15 \times 10^6 \). The operating parameters, fluid and cuttings properties, and wellbore parameters are listed in Table 1. Full-scale experimental frictional pressure loss data from literature [22, 26] are used to validate the simulation model. Excellent agreement is observed between the measured and predicted data for (a) cuttings-water flow and (b) cuttings-power law flow as shown in Figure 2a and 2b respectively.
Figure 1. 3D section of meshed annular geometry.

Figure 2. Experimental and simulation pressure loss data comparison (a) cuttings-water flow (b) cuttings-power law flow.
Table 1. Simulation data for cuttings-fluid flow.

| Rheological and Drilling Parameter | Case 1                     | Case 2                     |
|-----------------------------------|----------------------------|----------------------------|
| Fluid density (kg/m³)             | 998.5                      | 1006.3                     |
| Cuttings density (kg/m³)          | 2761.4                     | 2761.4                     |
| Avg. cuttings size (m)            | 0.00201                    | 0.00201                    |
| Flow behaviour index, n           | 1.00                       | 0.51                       |
| Viscosity consistency, K, (Pa sⁿ) | 0.001                      | 0.289                      |
| Fluid velocity (m/s)              | 1.524-2.7432               | 1.524-2.7432               |
| Inner pipe rotation speed (rpm)   | 0, 80, 120                 | 0, 80, 120                 |
| Hole diameter (mm)                | 50.8                       | 50.8                       |
| Wellbore inclination (degree)     | 90                         | 90                         |
| Diameter ratio (κ=Di/Do)          | 0.64 - 0.90                | 0.64 - 0.90                |
| Eccentricity (e)                  | 0.623                      | 0.623                      |
| ROP (m/s)                         | 0.00508                    | 0.00508                    |

3. Results and discussion

3.1. Frictional pressure loss model
The frictional pressure loss can be expressed as a function of the developed dimensionless groups from Eq. 10 to 17. For cuttings-water flow, with drillpipe rotation ranging from zero (0) to 120 rpm, the frictional pressure loss model can be expressed as:

$$\frac{\Delta P}{\Delta L}_{\text{cut-water}} = \exp[a_1 \Pi_1 + a_2 \Pi_2 + a_3 \Pi_3 + a_4 \Pi_4 + a_5 \Pi_5 + a_6 \Pi_6 + a_7 \Pi_7 + a_8 \Pi_8 + a_9]$$ (18)

For cuttings-power law flow, with drillpipe rotation ranging from 80 to 120 rpm, the frictional pressure loss model can be expressed as:

$$\frac{\Delta P}{\Delta L}_{\text{cut-PL}} = a_1 \Pi_1^{a_2} \cdot \Pi_2^{a_3} \cdot \Pi_3^{a_4} \cdot \Pi_4^{a_5} \cdot \Pi_5^{a_6} \cdot \Pi_6^{a_7} \cdot \Pi_7^{a_8} \cdot \Pi_8^{a_9}$$ (19)

In this study, the wellbore inclination and cuttings size are kept constant, hence, $\Pi_7$ and $\Pi_8$ are excluded from the analysis. Regression analysis is carried out to predict the constants in Eqs. 18 and 19 using the database generated from the simulation study. The final frictional pressure loss model for cuttings-water flow with drillpipe rotation ranging from zero (0) to 120 rpm is:

$$\frac{\Delta P}{\Delta L}_{\text{cut-water}} = \exp \left[23.06 \Pi_1 - 23.47 \Pi_2 + 2.643 \frac{\Pi_3}{10^5} + 8.438 \frac{\Pi_4}{10^5} + 4.417 \frac{\Pi_5}{10^5} - 3.424 \Pi_6 - 9.585\right]$$ (20)

Similarly, for cuttings-power law flow with drillpipe rotation ranging from 80 to 120 rpm, the final frictional pressure loss model gives:

$$\frac{\Delta P}{\Delta L}_{\text{cut-PL}} = 0.255 \left[10^5 \cdot \Pi_1^{-2.021} \cdot \Pi_2^{0.175} \cdot \Pi_3^{-1.51} \cdot \Pi_4^{1.105} \cdot \Pi_5^{0.967} \cdot \Pi_6^{-1.118}\right]$$ (21)
3.2. **Relationship between measured and predicted data**

The frictional pressure loss model for cuttings-water flow in Eq. 20 was developed from a total of 45 data points, while for cuttings-power law flow model in Eq. 21, a total of 40 data points were used. The comparison between the predicted and measured frictional pressure loss for both cuttings-water and cuttings-power law flow are respectively presented in Figures 3a and 3b.

![Graph showing comparison between measured and predicted frictional pressure loss for (a) cuttings-water flow & (b) cuttings-power law flow.](image)

**Figure 3.** Measured and predicted frictional pressure loss for (a) cuttings-water flow & (b) cuttings-power law flow.

In Figures 3a and 3b, the performances of the frictional pressure loss models were measured by a statistical parameter: regression success index, $R^2$. Here, the $R^2$ value for Figure 3a is 0.9985. Similarly, the data in Figure 3b correlated to $R^2$ value of 0.9999, which are reasonably accurate.

3.3. **Comparison of models with existing correlations**

The proposed models in Equations 20 and 21 were compared with existing models in literature. It should be noted that the data range from these existing models [16-17], [26] are similar to that used to develop Equations 20 and 21, with the exception that the diameter ratio $\kappa$, of the annular setup for the existing models ranges from 0.50 to 0.64, whereas for the present study, the diameter ratio ranges from 0.64 to 0.90. Figures 5a and 5b present these comparisons for cuttings-water and cuttings power law flow respectively.

![Graph showing model comparison with existing correlations for (a) cuttings-water flow & (b) cuttings-power law flow.](image)

**Figure 5.** Model comparison with existing correlations for (a) cuttings-water flow & (b) cuttings-power law flow.
Figures 5a and 5b show that the performances of the existing frictional pressure loss models are quite satisfactory, especially, at low diameter ratios of $\kappa = 0.64$ and 0.70. However, as the diameter ratio increases above 0.70, the existing models become unreliable for predicting the frictional pressure loss. It is imperative to note that these existing models were developed for a specific range of diameter ratios, that is, $\kappa = 0.57 – 0.64$ hence, cannot be used for general purposes. Table 2 shows the performances of the proposed models and existing correlations using statistical measurements.

| Models               | $R^2$ for Cuttings-water flow | $R^2$ for Cuttings-power law flow |
|----------------------|-------------------------------|----------------------------------|
| Equation 20          | 0.9985                        | -                                |
| Equation 21          | -                             | 0.9999                           |
| Sorgun et al. (2011) | 0.757                         | 0.337                            |
| Ozbayoglu et al. (2010) | 0.750                        | 0.280                            |
| Reza (2010)          | 0.208                         | -                                |

4. Conclusions
The present study has presented frictional pressure loss models for both cuttings-water and cuttings-power law flow in horizontal narrow annuli with a wide range of diameter ratios from 0.64 to 0.90, and drillpipe rotation from 0 to 120 rpm. A full-scale experimental data were employed in a CFD simulation to predict annular frictional losses for validation purposes. The proposed models were developed based on dimensional analysis and their constants were fitted by regression analysis from the simulated data. The present models performed better than other existing models in literature, particularly, where the diameter ratio exceeds 0.70. The study has shown the deficiencies of existing frictional pressure loss models when they are applied, especially, to narrow horizontal wellbores, such as casing-while-drilling and slimhole applications.

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