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Pressure gradient correlation for oil–water separated flow in horizontal pipes

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ABSTRACT

In this work, a simple pressure gradient correlation for horizontal oil–water separated flow (stratified and dual continuous flows) was developed based on the work of Angeli and Hewitt [3]. Zigrang and Sylvester [28] friction factor equation was modified to work for two phase oil–water flow. The pressure gradient correlation was validated extensively against 11 pressure gradient data sources. To our knowledge, this is the first pressure gradient database that published for oil–water flow which includes wide range of operational conditions, fluid properties, pipe diameters and materials. The predictions agreed reasonable well with the experimental results. The accuracy of the correlation was also tested against the two-fluid model. The percentage errors and standard deviation for the predicted and measured results were presented. The new proposed correlation predicts the pressure gradient with higher accuracy than the two-fluid model.

1. Introduction

Two phase flows of two immiscible fluids (e.g. oil and water) in pipes is a common phenomenon in oil, chemical and petrochemical industries. During the simultaneous concurrent flow of oil and water, several configurations can form which are generally grouped into separated flow where both phases retain their continuity and dispersed flow where one phase is continuous and the other is in the form of dispersed drop.

In separated (segregated) flow, the two phases can either be completely separate, occupying the top and the bottom of the pipe respectively (*stratified flow*), or there may be interdispersion of one phase into the other (*dual continuous flow*) i.e. oil drops are present in the water-continuous layer and water drops are present in the oil-continuous layer. At certain conditions, one phase occupies the core of the pipe with the other is flowing in the annulus around it (*annular flow*).

Quiet large number of studies had reported the occurrence of separated oil–water flow (stratified and dual continuous flows) in horizontal pipes [15,16,19,10,22,5,18,25,24,13,4,20,1]; etc.).

As a result, several attempts have been made to predict the pressure gradient in separated flow. Charles and Lilleleht [9], and Stapelberg and Mewes [23] used the parameters Φ and X, suggested by Lockhart and Martinelli [17] for gas–liquid flow in pipelines to represent pressure drop data in the stratified flow of the immiscible liquids when one was in laminar flow and the other in turbulent flow. The correlation was not able to predict the pressure drop for liquid–liquid flow. Stapelberg and Mewes [23] found out that pipe diameter obviously has effect on pressure drop, and a single model is not sufficient to correlate the data in all the flow regimes of liquid–liquid flow. In recent papers, Angeli and Hewitt [3], Chakrabarti et al. [8], Rodriguez and Oliemans [21], and Yiping et al. [26] employed the two-fluid model to predict the pressure gradient using plane and curve interface. Large discrepancies were obtained between the measured and predicted values especially in dual continuous flow.

As the two fluid model proved to be of limited value in the prediction of liquid–liquid pressure gradient for some systems in horizontal pipe flow, an empirical pressure gradient correlation for separated horizontal oil–water flow is developed in the present work based on the pressure gradient published data of oil–water flow. The accuracy of the correlation is evaluated by comparing its predictions with experimental data and with the two-fluid model.

2. Correlation development

In gas–liquid flow, several empirical correlations have been proposed for the prediction of two-phase frictional pressure loss in horizontal pipe flow. Examples of these are Lockhart and Martinelli [17], Dukler et al. [11], Beggs and Brill [6], and García et al. [14]. These correlations are normally expressed as friction factors where they are usually calculated based on the Reynolds number of the mixture.

In the present study, the Fanning friction factor of gas–liquid mixture is used to develop a pressure gradient correlation in separated horizontal oil–water flow. The equation is expressed as follows:

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$$\frac{dp}{dx} = \frac{f_m \rho_m U_m^2}{2D} \tag{1}$$

where $\frac{dp}{dx}$ is the pressure gradient, f_m is the two-phase friction factor, ρ_m is the mixture density, U_m is the oil–water mixture velocity and D is the pipe diameter.

The mixture density is given as

$$\rho_m = H_w \rho_w + H_o \rho_o \tag{2}$$

where ρ_w and ρ_o are the water and oil density respectively.

H_w and H_o are the water and oil hold-up and they are given by

$$H_w = \frac{Q_w}{Q_w + Q_o} \tag{3}$$

$$H_o = \frac{Q_o}{Q_w + Q_o} \tag{4}$$

where Q_w and Q_o are the water and oil volumetric flow rate respectively.

The friction factor depends on the Reynolds number of the fluid flow and the relative roughness of the pipe wall. Zigrang and Sylvester [28] proposed an explicit equation for the friction factor of single phase in pipe which is a modification of the well known Colebrook equation. Angeli and Hewitt [3] fitted their single oil and water phase experimental data obtained using acrylic and steel pipes to Zigrang and Sylvester [28] equation to estimate the roughness of both pipes. The data were fitted best for a wall roughness of 1×10^{-5} m for the acrylic pipe and for a value of 7×10^{-5} m for the steel pipe. In the present formulation, this equation is applied to calculate the friction factor for two-phase oil–water flow.

The equation can be expressed as

$$\frac{1}{\sqrt{f_m}} = -2\log\left(\frac{\varepsilon/D}{3.7} - \frac{4.518}{Re_m}\log\left(\frac{6.9}{Re_m} + \left(\frac{\varepsilon/D}{3.7}\right)^{1.11}\right)\right) \tag{5}$$

where ε is the wall roughness, Re_m is the Reynolds number of the oil–water mixture that is defined as

$$Re_m = \frac{U_m \rho_m D}{\mu_m} \tag{6}$$

Different models have been proposed for the determination of average mixture viscosity (μ_m) since the viscosity can have anomalous behavior during liquid–liquid flow. For gas–liquid flow, Dukler et al. [11] proposed average viscosity correlation in terms of flow volume fraction. In this work the same principle is applied for oil–water flow, the average viscosity is given as

$$\mu_m = H_w \mu_w + H_o \mu_o \tag{7}$$

where μ_w and μ_o are the viscosity of water and oil respectively.

3. Results and discussion

Superficial oil velocity (U_{so}), superficial water velocity (U_{sw}), and pressure gradient measurements corresponding to 370 experimental points collected from the literature for separated oil–water flow in horizontal pipes were used in this study (see Table A.2). These include the data published by Valle and Kvandal [25], Nädler and Mewes [18], Angeli and Hewitt [3], Elseth [12], Chakrabarti et al. [8], Rodriguez and Oliemans [21], Al-Wahaibi et al. [1], Yiping et al. [26], Al-Yaari et al. [2], and Yousuf [27]. The collected database covers wide range conditions, pipe diameters and oil viscosities. Table 1 summarized the range of the selected data.

The pressure gradient data measured by Angeli and Hewitt [3] for acrylic and steel pipes and those calculated from Eq. (1) are presented in Fig. 1. This step was done to investigate the effect of pipe materials on two-phase frictional pressure gradient. As suggested by Angeli and Hewitt [3], wall roughness of 1×10^{-5} m and 7×10^{-5} m were used to calculate the friction factor for the acrylic and steel pipes respectively. As shown in the figure, the pressure gradients from the steel pipes are still higher than those from the acrylic pipe. Angeli and Hewitt [3] observed that the differences in the values were higher than what would be expected from the differences in tube roughness. They attributed such differences to the large role of the pipe material and especially its wetting properties on pressure gradient. Thus the friction factor equation (Eq. (5)) should be modified to be applicable for two-phase oil–water flow as it is well known that the accurate prediction of the friction factor will lead to accurate prediction of pressure gradient.

As the only difference in the work of Angeli and Hewitt [3] is the pipe material, the relative roughness in Eq. (5) was multiplied by a constant (C) to take into account the effect of pipe materials (wetting effects of pipe materials) on pressure gradient. The new definition of the friction factor is given as

$$\frac{1}{\sqrt{f_{cor}}} = -2\log\left(C\frac{\varepsilon/D}{3.7} - \frac{4.518}{Re_m}\log\left(\frac{6.9}{Re_m} + \left(C\frac{\varepsilon/D}{3.7}\right)^{1.11}\right)\right) \tag{8}$$

Using the new corrected friction factor equation (Eq. (8)), a power law correlation was found to fit the experimental data presented in Fig. 1 for both acrylic and steel pipes (see Fig. 2). The experimental data were fitted best for a constant (C) of 14.8. The correlation for the pressure gradient can then be expressed as

$$\frac{dp}{dx} = 2.4\left(\frac{f_{cor}\rho_m U_m^2}{2D}\right)^{0.8} \tag{9}$$

where 2.4 is a dimensional coefficient fitting parameter in $(\frac{kg}{m^2 s^2})^{0.2}$, ρ_m is the mixture density in kg/m^3, U_m is the mixture velocity in m/s and D is the pipe diameter in m.

While the corrected friction factor (f_{cor}) will be written as

$$\frac{1}{\sqrt{f_{cor}}} = -2\log\left(\frac{\varepsilon/D}{0.25} - \frac{4.518}{Re_m}\log\left(\frac{6.9}{Re_m} + \left(\frac{\varepsilon/D}{0.25}\right)^{1.11}\right)\right) \tag{10}$$

4. Model evaluation

The accuracy of the proposed correlation (Eq. (9)) was validated against the available experimental pressure gradient data collected from the literature of separated horizontal oil–water flow for a wide range of Reynolds number (Re_m = 800–35,000) and against the two-fluid model.

The accuracy of the predictions was measured by calculating the average percent error (APE), average absolute percent error (AAPE) and standard deviation (SD) of each data source (see Table 2).

The average percent error is defined as

$$\text{APE} = \left[\frac{1}{n}\sum_{k=1}^{n}\frac{\left(\frac{dp}{dx}\right)_{pred} - \left(\frac{dp}{dx}\right)_{exp}}{\left(\frac{dp}{dx}\right)_{exp}}\right] \times 100 \tag{11}$$

where subscripts "pred" and "exp" represent the predicted and experimental values, respectively.

The average percent error (Eq. (11)) is used to quantify the degree of overprediction or underprediction of the experimental data. Positive values indicate over prediction while negative values indicate underprediction.

The average absolute percent error (AAPE) is calculated to evaluate the prediction capability of the correlation. Unlike the average percent error (APE), the absolute errors are considered so the positive errors and the negative errors are not canceled. The equation is given by