SPE Brazil Flow Assurance Technology Congress
Rio de Janeiro, Brazil, November 15 – 18 2022

A Drift-Flux Closure Relationship to Estimate the Holdups of Three-Phase Flow in Horizontal and Slightly Inclined Pipes

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Abstract

The study of multiphase flows is of great interest to several industries. In particular, the understanding of three-phase flows, present in the oil industry, allows better predictions to improve new projects and avoid flow assurance problems. This study aims to deepen the knowledge on three-phase air-water-oil flow through the comparison of experimental data with traditional models (homogeneous and drift-flux), in addition to using a new state-of-the-art correlation based on the drift-flux model that considers the slip between the three phases that flow in a pipeline.

Keywords

Drift-flux model; Three-phase flow; Horizontal and slightly inclined pipe.

Introduction

A given flow through a pipe is called multiphase whenever different phases of the same fluid or different fluids (which may or may not be in the same physical state of matter) flow together inside this duct. Particularly, in three-phase flows, three different phases flow together in a pipe. In general, such flows are composed of a gas and two liquid phases.

Three-phase gas-water-oil flows are of common occurrence in the oil and gas industry. It often occurs in subsea wells and pipelines (rigid and flexible - flowlines and risers) before the produced fluid reaches the separation and treatment platform. The gas is present due to the flow decompression along the production system. The presence of water can occur in the form of a film covering the reservoir pores, due to the presence of aquifers or even by the injection of water into the reservoir as a supplementary recovery method. Thus, water is produced together with oil and gas, resulting in the three phases.

Usually, the three-phase flow is modeled by one equation for the momentum of the mixture and two mass conservation equations, one for the liquid phase (homogeneous model without slip between water and oil) and the other for the gas phase. Furthermore, in experimentation sampling, when there are three-phase flows, it is difficult to visually distinguish the oil (liquid phase), water (liquid phase), and gas (gas phase) phases. However, understanding the slip between all phases is interesting for improving prediction models of both the pressure gradient and the volumetric fraction of each phase.

Methodology

Based on the literature review, this study proposes to analyze the accuracy of traditional models to predict the behavior of three-phase flows by calculating the pressure gradient and the holdup in horizontal and slightly inclined pipes (±5°).

During development, the results obtained experimentally will be compared with data calculated from the homogeneous model, which considers the three components totally dispersed forming a pseudo-component with average properties, and from the drift-flux model applied to two (air-liquid) and three (air-oil-water) components.

Experimental Procedure

In this study, experimental data obtained in a test loop at two laboratories will be used: LabPetro (Experimental Laboratory of Petroleum), located at the University of Campinas, and LETeF (Laboratory of Thermal Engineering and Fluids), located at the University of São Paulo.

The gravitational pressure gradient was measured from the hydrostatic column of the mixture contained between the two quick-closing valves at the beginning and end of the test section. The frictional gradient could be calculated by subtracting the gravitational portion from the total pressure drop measured by the differential pressure transducer.

Similarly, the volumetric fractions of oil, α_O, and water, α_A, were measured considering the volumes of liquid phases existing between the two quick-closing valves. The gas volumetric fraction, α_G, was obtained from Eq. (1):

$$\alpha_O + \alpha_A + \alpha_G = 1 \quad (1)$$

To complement, experimental data available in the literature will also be used, if they contain measurements of the volumetric fraction of each phase and the pressure gradient.

Three-Phase Flow

Flow patterns are how the phases are geometrically distributed in the pipeline. They are affected by some factors such as pipe diameter, fluids properties, pipe material, flow rates, pipe orientation, and more.

In the case of three-phase flows, the presence of three fluids makes the measurements of properties, such as in situ velocities, and the definition of the phase arrangement an extremely complex problem.

In the study conducted by Wang et al. [1], three-phase flow patterns were verified as a combination of gas-liquid and water-oil patterns.

According to the Al-Hadhrami et al. [2] study, the flow patterns are strongly dependent on the water fraction and the gas and liquid velocities.

Wang et al. [1], in their research, concluded that, in horizontal flows, the pressure gradient is caused only by the friction between the fluids and the tube wall, considering that the pressure gradient by acceleration can be disregarded.

The experimental data showed that the frictional pressure gradient increases as the gas superficial velocity increases. Furthermore, they observed a clear tendency for the pressure gradient to increase in the region where the oil is the continuous medium, with a peak near the phase inversion point (approximately 20%), and then decreasing as the water fraction increases. At about 40-50% water fraction, the pressure gradient reached its minimum value and then increased again. In general, the value of the fraction of water in which the phase inversion occurs will vary according to the properties of the oil and water. However, a behavior with an aspect like previously described is always expected, considering the higher viscosity of the oil phase.

Similarly, Al-Hadhrami et al. [2] in their study found that the pressure gradient increases as the gas flow increases. Also, for a given gas surface velocity, the pressure gradient increases as the liquid surface velocity increases. Finally, the pressure gradient first increases and then decreases with increasing water fraction. In general, the phase inversion point marks the inflection of the curve.

According to Bannwart et al. [3], in horizontal three-phase flows, the presence of gas considerably increases the friction pressure loss when compared to a two-phase water-oil flow. However, the pressure loss can be reduced by injecting water, which can lubricate the flow in horizontal sections and significantly reduce the friction pressure gradient by preventing the oil from contacting the wall (core flow pattern).

The experimental data obtained by Wang et al. [1] for horizontal flows showed that, with increasing water fraction, the oil holdup decreases while the water holdup increases. Considering the combined effect, the liquid holdup inside the tube is found to be relatively stable.

In comparison with two-phase flows, at the same total liquid surface velocity, the experimental results showed that the liquid holdup in the oil-water-gas horizontal flow is generally lower than that observed in the oil-gas horizontal flow under the same conditions. This result suggests that in three-phase horizontal flows, the liquid phase flows faster due to the lubricating effect of free water (outside the emulsion).

Homogeneous Model

According to Shoham [4], the former models developed for multiphase flows did not consider the flow pattern. These models simply ignored the complexity of multiphase flows and addressed the problem with tools developed for single-phase flows.

In the homogeneous model, for example, the multiphase mixture is treated as a single-phase pseudofluid, with average properties and velocity and there is no slippage between the phases. Mixture properties are determined from gas and liquid properties, based on no-slip holdup.

Drift-Flux Model

The ability to predict the volumetric concentration of a phase, i.e., the holdup or void fraction as a function of design and operation parameters (geometry, pressure, flow rates, and thermodynamic and transport properties of the phases, etc.) is of considerable importance for different industrial sectors.

Zuber-Findlay [5], in their work, criticized predictive methods that disregarded physics in the modeling, when data were obtained only by computational analysis. They also highlighted the fact that, until that moment, there was no study considering the effects of the local relative velocity between the phases and the radial non-uniform distribution of the flow along the cross-section of the pipeline. Therefore, they presented a general method that can be used to predict the volumetric concentration or to analyze and interpret experimental data. This analysis considered both the effects of non-uniform flow and concentration profiles, as well as the effects of local relative velocity between the phases.

The Zuber-Findlay study [5] was developed from two previous studies. Behringer [6] and Bankoff [7] were apparently the first to consider the effect of local relative velocity between phases and the effect of radial non-uniform flow and volumetric concentration in the bubbly two-phase flow, respectively.

Zuber-Findlay [5] formulated the problem three-dimensionally and expressed the velocities as vectors, defining the relative velocity, v_{SLIP}, between the two phases:

$$\vec{v}_{SLIP} = \vec{v}_G - \vec{v}_L \quad (2)$$

the drift velocities, v_{DG} and v_{DL}, in relation to the mixture velocity, v_M:

$$\vec{v}_{DG} = \vec{v}_G - \vec{v}_M \quad (3)$$
$$\vec{v}_{DL} = \vec{v}_L - \vec{v}_M \quad (4)$$
$$\vec{v}_M = \vec{v}_{SL} + \vec{v}_{SG} \quad (5)$$

and obtained Eq. (6):

$$\vec{v}_G = C_0\langle v_M\rangle + \langle \alpha_G v_{DG}\rangle / \langle \alpha_G\rangle \quad (6)$$

Equation (6) can be applied to any two-phase flow pattern.

The effects of radial non-uniform flow and concentration profiles are considered by the distribution parameter, C_0.

The effect of local relative velocity and concentration profile is considered by the weighted mean drift velocity $\langle\alpha_G v_{DG}\rangle/\langle\alpha_G\rangle$.

The value of the distribution parameter can be less than one, i.e., $C_0 < 1$ when $\alpha_W > \alpha_C$, or greater than one, i.e., $C_0 > 1$ when $\alpha_W < \alpha_C$. With α_W and α_C representing the fraction of voids in the near-wall and in the center of the pipe, respectively.

Results and Discussion

As part of the results, the previously mentioned models were extrapolated to a three-phase flow.

The results will be presented in three groups, evaluating the errors from the comparison between experimental data and those estimated by the following models:

- Homogeneous model applied for the three phases;
- Drift-flux model applied for the gas and liquid phases (the homogeneous model will be used for water and oil phases);
- Drift-flux modeling for the three phases, considering slip between the three phases.

Typically, the equations used to describe the flow according to the homogeneous model are two-phase. Equation (7), after extrapolation, calculates the total pressure drop, neglecting the acceleration term:

$$dP/dL = \rho_M\, g \sin\theta + 2f\, \rho_M\, v_M^2/D \quad (7)$$

where g is the gravitational constant, θ is the pipe orientation in degrees formed with the horizontal, D is the pipe internal diameter and f is the friction factor determined as a function of the Reynolds number of the mixture, Re_M, given by Eq. (8):

$$Re_M = \rho_M\, v_M\, D/\mu_M \quad (8)$$

v_M is the average velocity of the mixture calculated by Eq. (9) as a function of the surface velocities, v_{Si}, of each phase, oil, water and gas, indicated by the subscript indices $_O$, $_A$, $_G$, respectively.

$$v_M = v_{SO} + v_{SA} + v_{SG} \quad (9)$$

ρ_M and μ_M are, respectively, the mixture density and viscosity, determined by Eqs. (10) and (11), depending on the fluid properties of each phase:

$$\rho_M = \rho_O\, \alpha_O + \rho_A\, \alpha_A + \rho_G\, \alpha_G \quad (10)$$
$$\mu_M = \mu_O\, \alpha_O + \mu_A\, \alpha_A + \mu_G\, \alpha_G \quad (11)$$

Equation (12), used to determine the volumetric fraction of each phase, is valid only for the homogeneous model:

$$\alpha_i = v_{Si}/v_M,\ \text{where } i = O, A, G \quad (12)$$

According to Karami et al. [8], three-phase flow models can be described as a combination of a two-phase gas-liquid model with a water-oil liquid mixture model. Thus, although the model proposed by Zuber-Findlay [5] was originally conceived for two-phase gas-liquid flows, it is possible to extrapolate its application to three-phase water-oil-gas flows, if the liquid phase flows without slipping between the oil and water components (homogeneous model).

In this study, the correlation developed by Bhagwat-Ghajar [9], Eq. (13), will be used to calculate the gas volumetric fraction, as it is independent from flow pattern.

$$\alpha_G = v_{SG}/(C_0\, v_M + v_{DG}) \quad (13)$$

The distribution parameter, C_0, is calculated by Eqs. (14) and (15):

$$C_0 = \frac{A}{(1+Re^*/1000)^2} + \frac{B+C}{(1+1000/Re^*)^2} \quad (14)$$
$$Re^* = \rho_L\, v_M\, D_H/\mu_L \quad (15)$$

where Re^* is the Reynolds Number in function of liquid density, ρ_L, liquid viscosity, μ_L, and hydraulic pipe diameter, D_H. The A, B and C terms are determined by Eqs. (16) to (18):

$$A = 2 - (\rho_G - \rho_L)^2 \quad (16)$$
$$B = \left[\left(\sqrt{\frac{1+(\rho_G/\rho_L)^2\cos\theta}{1+\cos\theta}}\right)^{(1-\alpha_G)}\right]^{2/5} \quad (17)$$
$$C = C_1\left(1 - \sqrt{\frac{\rho_G}{\rho_L}}\right)\left[(2.6 - \beta_G)^{0.15} - \sqrt{f_F}\right](1 - x)^{1.5} \quad (18)$$

The term C is a function of the constant C_1, which assumes the value 0.2 for circular or annular pipe geometry and 0.4 for rectangular pipe geometry, the two-phase Fanning friction factor, f_F, the two-phase flow quality, x, and the gas volumetric fraction obtained by homogeneous model, β_G, using Eq. (12).

The drift velocity, v_{DG}, is defined by Eq. (19):

$$v_{DG} = K\, C_2\, C_3\, C_4 \sqrt{\frac{g D_H(\rho_L - \rho_G)}{\rho_L}(1-\alpha_G)} \qquad (19)$$

where K, C_2, C_3 and C_4 are defined by Eqs. (20) to (23) and σ is the surface tension:

$$\begin{array}{lll}
K = 0.35 \sin\theta + 0.45 \cos\theta & & (20) \\
C_2 = 1 & \mu_L \leq 0.01 & (21) \\
C_2 = [0.434/\log_{10}(\mu_L/0.001)]^{0.15} & \mu_L > 0.01 & \\
C_3 = 1 & La = \sqrt{\sigma/(g\Delta\rho)}/D_H \geq 0.025 & (22) \\
C_3 = (La/0.025)^{0.9} & La < 0.025 & \\
C_4 = 1 & \theta \geq 0° & (23) \\
C_4 = -1 & \theta < 0° &
\end{array}$$

For the third part of this study, the correlation of Vazzoler Junior (not yet published) was used. Based on the drift-flux model, this new correlation considers the slip between the water-oil phases, applying multiplier factors to correct the homogenous oil volumetric fraction.

Conclusions

Figure 1 shows, respectively, the volumetric fractions for gas, oil and water calculated by the three-phase model compared to LabPetro experimental data.

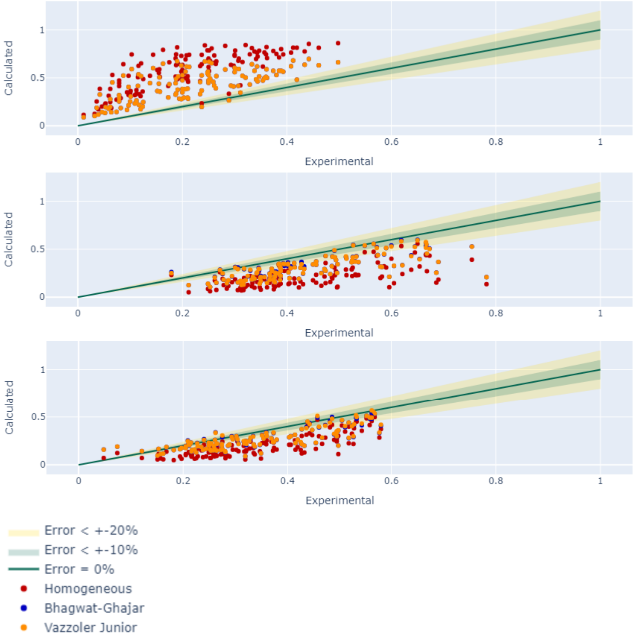

Figure 1. (a) Gas (b) Oil (c) Water volumetric fractions.

In this three-phase model, it was considered that the gas volumetric fraction is equal to the one calculated by Bhagwat-Ghajar model.

Above graphical results show that the three-phase model underpredicts liquid volumetric fraction and overpredicts gas volumetric fraction.

The next steps are:

- Improve this three-phase model, considering that the slip between the water-oil phases changes the volumetric fraction of gas ($\alpha_G = f(x)$), according to Eq. (18).
- Compare calculated results with LETeF and other authors experimental data.
- Propose, if applicable, adjustments to this three-phase model to improve adherence to experimental data.

Acknowledgments

I would like to thank Petrobras for the opportunity to complete my master's degree and improve my knowledge, combining academic knowledge with day-to-day practice.

I also thank CEPETRO/UNICAMP and USP/São Carlos for allowing the use of laboratories to collect experimental data. Acknowledgement are extended to ALFA – Artificial Lift and Flow Assurance Research Group of UNICAMP.

And, above all, I would like to thank my technical advisor and co-author for his unparalleled understanding, didactics and availability.

Responsibility Notice

The authors are the only responsible for the paper content.

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