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Modeling of heavy oil-water core-annular upward flow in vertical pipes using the two-fluid model

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ABSTRACT

In this work, a one-dimensional, isothermal, pseudo-transient two-fluid mathematical model is presented to simulate heavy oil-water core-annular upward flow. The model consists of mass, momentum and energy conservation equations for each phase, whose numerical solution is based on the finite difference technique with a first order implicit scheme. The model allows compute the profiles of pressure, velocity, volume fraction and temperature of the phases. Various water-wall and interfacial friction factors proposed in literature were evaluated. It was found that: (1) the interfacial friction factor has an important influence on pressure drop computation, (2) the interfacial shear stress is larger as the oil flow rate increases, and (3) to take into account the buoyancy effect, into the water-wall stress, improves the pressure computation. A characteristic analysis to determine the model stability was also developed and it was found that the well-posed region grows as the oil superficial velocity (J_o) increases, and the model is stable for $J_o/J_w \geq 0.75$ (J_w is the superficial water velocity). The model is in agreement with experimental data and other models reported in literature. The total pressure drop computations present deviations smaller than 6% from experimental data.

1. Introduction

The importance of heavy oil, in the world oil market, is rapidly increasing, this due to the progressive depletion of light oils reserves in the next decades. This leads to a growing economic interest in the exploitation of heavy oil fields, and research on technologies to increase the recovery factor (Bannwart et al., 2001). However, heavy oil has very adverse rheological properties, then very high pressure drop appear during production and transportation. Different techniques (dilution, heating, upgrading, emulsion, and core-annular flow) have been proposed to decrease high pressure drop when heavy oil flows through pipelines (Saniere et al., 2004). The core-annular flow consists on inject heavy oil and a low flow rate of water in a pipe to create an appropriate heavy oil lubrication and to establish a liquid-liquid annular pattern.

Core-annular flow takes advantage from other techniques because the thermodynamics properties of the crude oil are not modified and it is relatively simple to create it. Such flow configuration allows to get a friction pressure drop comparable to that obtained for a single-phase water flow at the same mixture flow rate. Two industrial examples of this technology are: a) the 38.6 km Shell line, from the North Midway Sunset reservoir to the central facilities at Ten Section (California), this line worked during 12 years; b) the 55000 m pipeline, from San Diego to Budare (Venezuela), which was used for transporting Zuata heavy crude oil of 1002.83 kg/m^3 (Saniere et al.; 2004). However, the main problem of this technology is that heavy oil adheres to the wall pipe, leading to an eventual blockage of the flow system. Then, many theoretical and experimental investigations have been developed to understand the behavior of core-annular flow (Rodríguez and Bannwart, 2006; Rodríguez et al., 2009). For example, Bai et al. (1990) visualized flow patterns and measured pressure drop and volume fraction of heavy oil-water flows. Authors investigated several hydrodynamics features of motor oil-water core-annular flow through a 9.525×10^{-3} m i.d. glass tube, where the oil had a viscosity of 0.601 Pa s and a density of 905 kg/m^3. Fourteen years later, Bannwart et al. (2004) carried out an experimental study on the flow patterns formed by heavy oil (0.488 Pa s, 925.5 kg/m^3) and water in vertical and horizontal pipes of 2.84 in i.d. Authors discussed the occurrence of core-annular flow, and base on their experiments, they proposed criteria for the existence of this flow pattern. These criteria were based mainly on the fluid properties, pipe size, and geometry involved.

Theoretical studies have been also developed for modeling core-annular flow. For example, Bobok and Magyari (1996) proposed a unified model to compute pressure drop and liquid fraction. Authors supposed that the flow is fully developed, steady, and laminar. Their

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computations were compared versus experimental data obtained from the gathering system of Nagylengyel field located in South-western Hungary, with a deviation less than 20%.

Bannwart (2001) presented correlations to compute pressure drop and oil volume fraction. The correlations were based on empirical constants found by means of experiments in vertical pipes. The oil used had 17.6 Pa s and 960 kg/m^3 at room temperature. The computed pressure drop presented deviations smaller than 25% from the experimental data. On the other hand, Rodríguez et al. (2009) based on the Blasius's law friction coefficients proposed a model for compute pressure drop on core-annular flow. The model was in agreement with different experimental data reported in literature.

In this work a one-dimensional, isothermal, pseudo-transient two-fluid model for heavy oil-water core-annular upward flow was formulated. The model consists of mass, momentum and energy equations for each phase. A characteristic analysis was developed in order to determine the model stability. The effect of various relationships, for water-wall and interfacial friction factors, on pressure drop were evaluated. Moreover, the buoyancy effect in the water-wall shear stress was taken into account. The model is able to compute pressure, volume fraction, velocity and temperature and it is in agreement with experimental data of pressure drop and volume fraction reported in literature.

2. Conceptual model

In core-annular flow, the highly viscous oil flows at the center and is surrounded by a water ring close to the pipe wall. Accordingly with the conceptual model shown on Fig. 1, the mathematical model was formulated with the next suppositions: 1) one-dimensional, fully developed and isothermal flow without interfacial mass transfer, 2) incompressible phases, 3) the interfacial pressure gradient was neglected, and 4) concentric heavy oil core. In core-annular flows only water touches the wall pipe, then the water-wall shear stress (τ_{wW}) is present whereas the oil-wall shear stress (τ_{oW}) is missed. Since oil and water velocities are different between them, the interfacial shear stress (τ_i) was included and the buoyancy effect was taken into account.

3. Mathematical model

In this work, a two-fluid model was used, where the mass, momentum and energy equations are written for each phase. In order to obtain a numerically stable model, only the temporal terms for water volume fraction (α_w), oil velocity (U_o) and water temperature (T_w) were taken into account. This was based on a stability study (see Section 4) applied on different models that included temporal terms for the other dependent variables (e.i. water velocity, U_w, pressure, p and oil temperature, T_o). Keeping in mind the suppositions from Section 2, the balance equations for core-annular flow are given by:

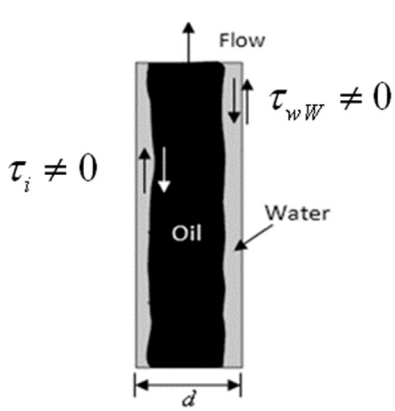

Fig. 1. Schematic description of heavy oil-water core-annular upward flow.

- Mass balance equations

$$\frac{\partial \alpha_w}{\partial t} + U_o \frac{\partial \alpha_w}{\partial z} - (1 - \alpha_w)\frac{\partial U_o}{\partial z} = 0 \tag{1}$$

$$\frac{\partial \alpha_w}{\partial t} + U_w \frac{\partial \alpha_w}{\partial z} + \alpha_w \frac{\partial U_w}{\partial z} = 0 \tag{2}$$

In order to obtain Eq. (1), the relationship $\alpha_w + \alpha_o = 1$ was used into the oil mass balance.

- Momentum balance equations

$$\rho_o \frac{\partial U_o}{\partial t} + \rho_o U_o \frac{\partial U_o}{\partial z} + \frac{\partial p}{\partial z} = \rho_o g \, sin\theta - \frac{\tau_i S_i}{A_o} \tag{3}$$

$$\rho_w U_w \frac{\partial U_w}{\partial z} + \frac{\partial p}{\partial z} = \rho_w g \, sin\theta + \frac{4\tau_{wW}}{D_H \alpha_w} + \frac{\tau_i S_i}{A_w} \tag{4}$$

- Energy balance equations

$$C_{po} U_o \frac{\partial T_o}{\partial z} + U_o \frac{\partial U_o}{\partial t} + U_o^2 \frac{\partial U_o}{\partial z} + \frac{U_o}{\rho_o}\frac{\partial p}{\partial z} = g U_o \cos\phi \tag{5}$$

$$C_{pw} \frac{\partial T_w}{\partial t} + C_{pw} U_w \frac{\partial T_w}{\partial z} + U_w^2 \frac{\partial U_w}{\partial z} + \frac{U_w}{\rho_w}\frac{\partial p}{\partial z} = g U_w \cos\phi \tag{6}$$

In Eqs. (1)–(6)α[adim] is volume fraction, p[Pa] is pressure, T[K] is temperature, U [m/s] is velocity, ρ [kg/m^3] is density and C_p [J/kg-K] is heat capacity at constant pressure. Subscripts o and w represents oil and water respectively; θ is inclination angle, $\phi = \theta + 90°$, g[m/s^2] is acceleration due to gravity, τ_{wW} [Pa] is water-wall friction shear stress, τ_i [Pa] is interfacial friction shear stress, A[m^2] is cross-section of pipe, S_i [m] is interfacial perimeter, D_H[m] is hydraulic diameter, t [s] is time, and z [m] is the axial coordinate. In Eq. (4), into the water-wall stress, the buoyancy effect is involved (see Eq. (A-1) in Appendix A) and appears for inclined or vertical flow only.

The closure relationships used to evaluate shear stresses were taken from the works of Bannwart (2001) and Taitel et al. (1995). Such relationships are described in Appendix A.

4. Characteristic analysis

The two-fluid model equations, to simulate two-phase flow, are conditionally hyperbolic and therefore can be well-posed as initial-value problem (Banerjee and Chan, 1980). It is important to establish the hyperbolic domain of the mathematical model proposed in Section 3, and to establish that the model is still conditionally well-posed. Then, in this work, a characteristic analysis was carried out for the mathematical model (Eqs. 1–6).

If Eqs. (1)–(6) are rewritten in matrix form, the next one-dimensional system of partial differential equations is obtained:

$$\boldsymbol{C}\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{D}\frac{\partial \boldsymbol{v}}{\partial z} = \boldsymbol{E} \tag{7}$$

where $\boldsymbol{v}$ is the solution vector given by:

$$\boldsymbol{v} = [p, \alpha_w, U_o, U_w, T_o, T_w]^T \tag{8}$$

where T is used to express transpose.

In Eq. (7), $\boldsymbol{C}$ and $\boldsymbol{D}$ are coefficient matrices and $\boldsymbol{E}$ is a vector column containing all the algebraic terms given by:

$$\boldsymbol{C} = \begin{bmatrix} 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_o & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & U_o & 0 & 0 & 0 \\ 0 & 0 & 0 & U_w & 0 & C_{pw} \end{bmatrix} \tag{9}$$