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DEVELOPMENT AND VALIDATION OF AN ALGEBRAIC SLIP MODEL FOR WATER-IN-OIL DISPERSED FLOW

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Abstract. *The objective of this work was to develop a model to calculate the slip velocity between the phases in an isothermal flow in horizontal pipes in the water-in-oil dispersion pattern. The model was formulated from the linear momentum conservation equations of the liquid mixture and the dispersed phase (water) and an algebraic slip relation was derived. A swarm function taking into account the concentration of dispersed phase was incorporated and fitted for the conditions of interest. The results obtained for the phase velocities were compared with experimental data with satisfactory agreement.*

Keywords: *Water-in-oil dispersion, Dispersed flow, Slipping, liquid-liquid flow*

1. INTRODUCTION

During the production of an oil field, it is common, after the first years of production, for water to reach the producing wells, causing the liquid phase to form an oil and water emulsion. The presence of water increases the flow complexity, as several new patterns can be formed in addition to the already known gas-liquid flow patterns Hewitt (1995).

Among the possible liquid-liquid patterns that can be formed in the presence of water and oil flowing through a pipe, the water-in-oil dispersion is of special interest. This flow pattern occurs usually in the early life of a production well, while the water volume fraction is still low. In this condition, when dispersions are formed in the flow, the oil flows as a continuous phase. For the formation of dispersions, it is important that the flow takes place at sufficient high velocities to cause the phases to mix, preventing them from flowing in a stratified manner. Figure 1 illustrates the formation of the oil-continuous dispersion pattern in a three-phase slug flow.

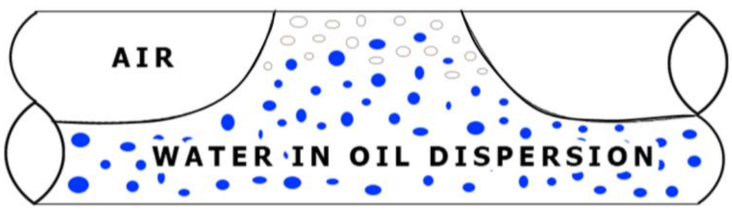

Figure 1 – Water-in-oil dispersion formed into a slug flow

Due to the great occurrence of the Dwo pattern, the correct modeling of this type of flow is an important tool for the development of oil production projects, especially large offshore projects, in which large investments are made long before the wells go into production. Furthermore, lifetime extension measures in mature fields often involve the evaluation of long distance transport of high water cuts well stream, where low operational margins require accurate model calculations involving such types of flows.

In the flow between water and oil in the Dwo pattern, the volumetric fraction of water plays an important role in the flow behavior. The viscosity values of the emulsion can vary exponentially with the increase in the water fraction, as described in Woelflin (1942). However, this occurs as long as the oil is the continuous phase and the dispersion is complete, that is, without coalescence and separation from the dispersed phase, which could lead to the appearance of a layer of lubricating water, as reported by Rodriguez et al. (2011). Therefore, it is evident the importance of the correct determination of the water fraction by the models that deal with this type of flow.

In two and three-phase flows involving dispersions, often the no-slip assumption is employed to determine the velocity of the dispersed phase. Bonizzi (2003) considered the slip velocities between the dispersed bubbles in gas-liquid slug flows, but assumed no-slip between the dispersed and continuous phases in water-oil dispersions in three-phase slug flows. However, several experimental works in the literature show that the slip between the phases may be significant for the flow of oil and water (Zhai et al., (2015)). This is evidenced in the experiments with the measurement of the local volumetric fraction of each phase along the pipe. In cases where slip occurs, the local phase volume fractions differ from the no-slip value, calculated through the volumetric flow rate ratio. This also leads to the variation of the physical properties of the mixture along the pipe.

Some works attempting to model the slip between the phases were selected from the literature to be analyzed in this work. Hapanowicz (2008) used an experimental database to adjust an equation based on the drift-flux model, in which the continuous phase velocity is determined as a linear function of the mixture velocity, with the equation coefficients adjusted to the experimental data available. The model is purely empirical.

Picchi et al (2015) modeled the liquid dispersion flow with a linear momentum conservation equation for each phase, considering a steady state, fully developed flow. In the dispersed phase equation, the drag force on the drops of the dispersion formed was considered. The model was developed to determine the volumetric fractions of the phases, but it can also be used to determine the slip velocity, employing the same base equations.

In this work, a model to determine the slip velocity is developed based on the momentum conservation equations of the liquid mixture and the dispersed phase, as described by Manninen & Taivassalo (1996). The model takes into account a swarm function F (α) incorporated in the slip relation. This function was adjusted with experimental data from the literature.

To validate the model, the calculated phase velocities are compared with experimental data from the literature, showing reasonable results. The model was also evaluated in a computational code for numerical simulation of multiphase flow, developed at DEM-PUC-Rio, showing good agreement with the experimental data.

An important feature of the model is that it takes into account the material acceleration of the mixture velocity, and can therefore be applied to assess flows of a transient nature, such as flow in the three-phase slug regime, for example.

2. MODEL

The slip model develop in the present work is based on the methodology described in Manninen & Taivassalo (1996). It consists in combining the momentum equations of the liquid mixture (subscript m) with the dispersed phase (subscript p), to eliminate the pressure, which are considered equal in both equations

$$\rho_m \frac{D\boldsymbol{U}_m}{Dt} = -\nabla P_m + \nabla . (\boldsymbol{\tau}_m + \boldsymbol{\tau}_{Tm} + \boldsymbol{\tau}_{Dm}) + \rho_m \boldsymbol{g} \tag{1}$$

$$\alpha_p \rho_p \frac{D\boldsymbol{U}_p}{Dt} = -\alpha_p \nabla P_p + \nabla . \left[\alpha_p (\boldsymbol{\tau}_p + \boldsymbol{\tau}_{Tp})\right] + \alpha_p \rho_p \boldsymbol{g} + \boldsymbol{M}_p \tag{2}$$

where ρ is density, $\boldsymbol{U}$ is the velocity vector, P is pressure, $\boldsymbol{\tau}$ is the viscous stress (liquid mixture, $\boldsymbol{\tau}_m$; dispersed phase, $\boldsymbol{\tau}_p$; turbulent dispersed phase, $\boldsymbol{\tau}_{Tp}$; turbulent liquid mixture, $\boldsymbol{\tau}_{Tm}$ and diffusion stress, $\boldsymbol{\tau}_{Dm}$). $\boldsymbol{g}$ is the gravity force and $\boldsymbol{M}_p$ is the drag force per unit volume. α_p is the dispersed phase volume fraction.

Here, the flow is considered isothermal, and based on the hypothesis of local equilibrium, the material derivatives of the dispersed phase and mixture equation can be approximated as equal to

$$\frac{D\,\boldsymbol{U}}{Dt} = \frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{U} \cdot \nabla \boldsymbol{U} \tag{3}$$

By considering the flow through horizontal pipes, the gravity force ($\boldsymbol{g}$) in both equations is neglected. Further, the disperse phase viscous stress as well as both turbulent stresses are neglected, as they are small in relation to the other terms of the equation for the cases analyzed by the model. However, the viscous stress of the liquid mixture ($\boldsymbol{\tau}_m$), which is usually also neglected is kept.

The drag force per unit volume $\boldsymbol{M}_p$ can be modeled assuming a spherical drop in a mixture as

$$M_p = -\frac{3}{4} \frac{C_D \alpha_p \rho_c |U_s| U_s}{d_p} \tag{4}$$

$$U_s = U_p - U_c \tag{5}$$

where U_s is the slip velocity between the dispersed drops and the continuous phase. The subscript c corresponds to the continuum phase and d_p refers to the diameter of the drop formed in the dispersion. In this work, the model by Brauner

(2001) was used to determine this parameter and all the drops of the dispersed phase are considered to have the same size and are homogenously distributed in the tube. For the drag coefficient C_D, the expression of Schiller & Nauman is used, as recommended by Manninen & Taivassalo (1996).

After applying the simplifying hypotheses and procedure described above, the slip velocity U_s can be obtained with

$$U_S = \tau_p^* \left[\frac{2 f_m \rho_m |U_m| U_m}{\rho_c\, D_m} - \frac{(\rho_p - \rho_m)}{\rho_c} \frac{D U_m}{Dt}\right] \quad (6)$$

where f_m is the friction factor of the liquid mixture, D_m is the hydraulic diameter of liquid mixture and τ_p^* is a corrected droplet shear stress, given by

$$\tau_p^* = \frac{\tau_p}{F(\alpha_p)} \frac{1}{[1 + 0.15 Re^{0.687}]} \quad (7)$$

$$\tau_p = \frac{\rho_c d_p^2}{18 \mu_c} \quad (8)$$

with Re as the dispersed phase particle Reynolds number.

$$Re = \frac{\rho_c d_p |U_s|}{\mu_c} \quad (9)$$

The function $F(\alpha)$ is a swarm function, introduced in the present work to take into account the effect of the volumetric fraction of the dispersed phase and was adjusted with experimental data. Rusche & Issa (2000) used a swarm function to fit the drag coefficient, arguing that the presence of many drops should be considered. It is important to note that the adjustment of this function is only valid for water-in-oil dispersions, where the water velocity is greater than the oil velocity.

After calculating the U_s, the velocities of the continuous and dispersed phases can be determined using the following equations, obtained from the equation for the center of mass of the liquid mixture:

$$U_c = U_m - \frac{\alpha_p \rho_p U_s}{\rho_m} \quad (10)$$

$$U_p = U_c + U_s \quad (11)$$

3. RESULTS

To evaluate the model, experimental data from the literature were used for the flow of water and oil in the dispersion pattern. Table 1 presents a summary of the main experimental conditions of the works used in this validation, with a wide range of pipe diameters, as well as of flow velocities:

Table 1 - Experimental works of liquid-liquid dispersed flows

	Lovick & Angeli (2004)	**Lum, *et al.*** (2006)	**Vielma, *et al.*** (2007)	**Zhai** (2015)
D (mm)	38	38	50.8	20
U_{so} (m/s)	1.8 – 2.7	0.20 – 2.25	1.75	0.06 – 2.77
U_{sw} (m/s)	0.2 – 0.3	0.20 – 2.25	0.248	0.11 – 2.21
ρ_o (kg/m³)	828	828	858	845
μ_o (cP)	6	5.5	13.5	11.98

The following expression was obtained by calibrating the swarm function $F(\alpha)$ with the experimental data referred in Tab. 1. An important feature of this function is that it tends to zero when the volumetric fraction of the dispersed phase (α_p) tends to zero.

$$F(\alpha_p) = 2.97\alpha_p^{-0.306} e^{-\left(\frac{19.6}{\alpha_p}\right)^{0.306}} \quad (12)$$

Figure 2 shows the result of calculating the velocity of the dispersed phase with the model developed for the cases shown in Table 1, where it can be seen a good agreement between the model prediction and the experimental, with differences below 20%

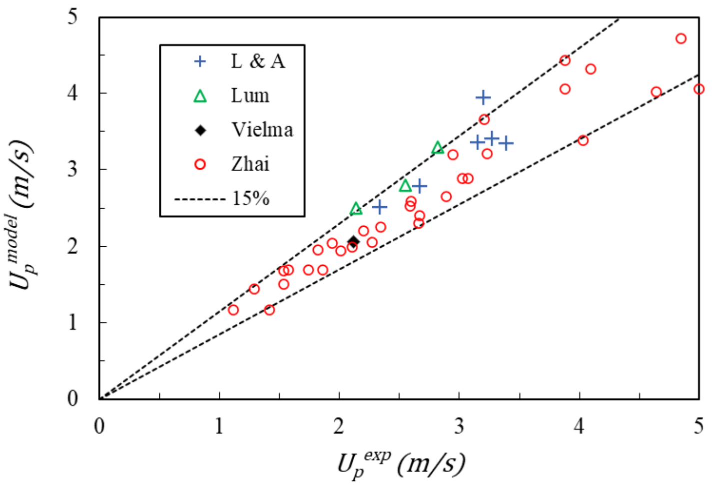

Figure 2 - Comparison of velocity of the dispersed phase of the experimental data with that calculated by the proposed model

Figures 3 and 4 show the importance of the swarm function $F(\alpha)$ for the model. The *Uslip model* data in Figure 3 was obtained by calculating the slip velocity with the swarm function $F(\alpha) = 1$. One can observe that the results clearly show poor agreement with the experimental data. In the Figure 4, the results obtained by calculating the slip velocity with the present swarm function $F(\alpha)$ model, which was calibrated with experimental data, is shown. Excellent behavior of the slip velocity was obtained, with the correct tendency with respect to the dispersed phase volume fraction.

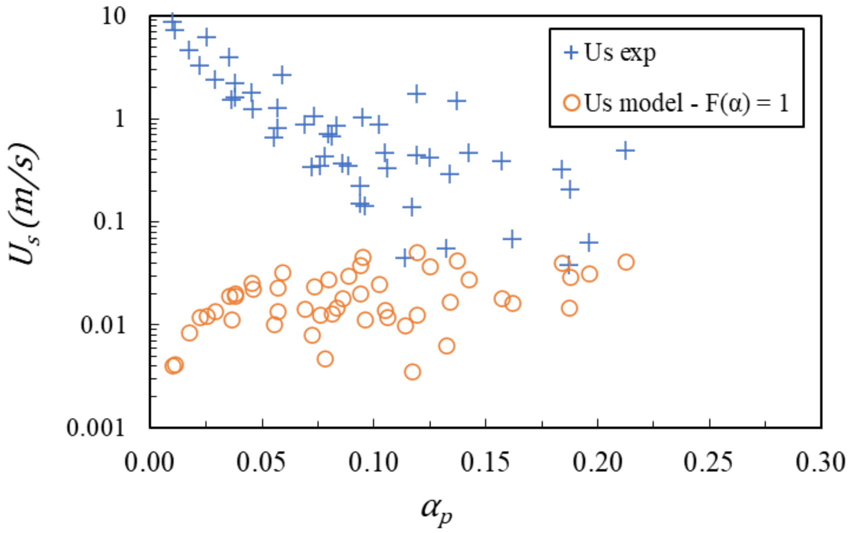

Figure 3 – Comparison of slip velocity experimental data $\boldsymbol{U_s}$ as a function of $\boldsymbol{\alpha_p}$ with data calculated by the model with the function $F(\alpha) = 1$

4. CONCLUSIONS

A model for calculating the slip velocity between the phases for the flow of water-in-oil dispersion was developed. The model was developed taking into account momentum equations for the mixture and the dispersed phase. An empirical swarm function was inserted in the model to take into account the influence of the volumetric fraction on the slip and was calibrated with aid of the experimental data available.

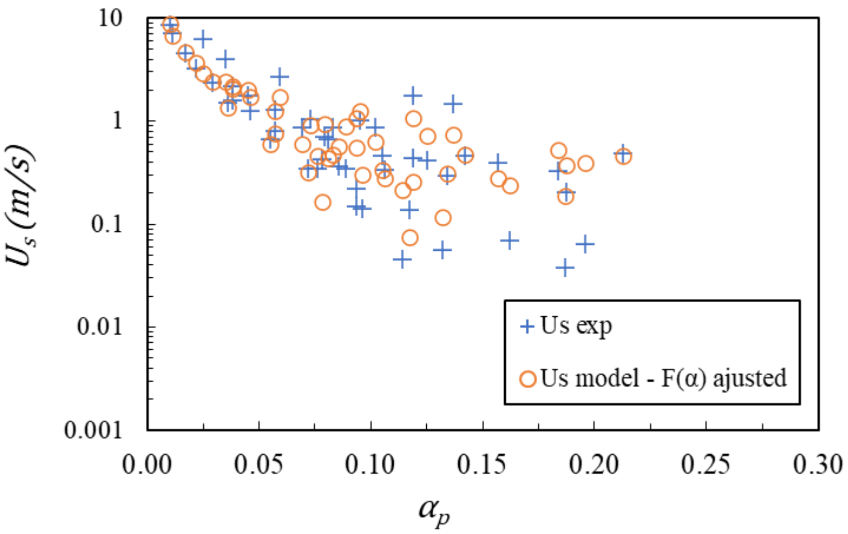

Figure 4 – Comparison of slip velocity experimental data $\boldsymbol{U_s}$ as a function of $\boldsymbol{\alpha_p}$ with data calculated by the model with the function $F(\alpha)$ present model

The results of the phase velocities calculations obtained are promising when compared with the experimental data. The correct determination of the phase velocities is necessary for the accurate calculation of the flow dynamics and phase distribution through the pipe. Although the model has been employed in two-phase oil-water flows, its incorporation in three-phase oil-water-gas flows is straightforward.

Another important feature of the model is that, as it considers the material derivative of the mixture velocities, it can be readily applied to simulate flows of a transient nature, as in the case of three-phase slug flow, which will be addressed in future work.

5. ACKNOWLEDGEMENTS

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