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Numerical Predictions in Wavy-stratified Viscous Oil-water Flow in Horizontal Pipe

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Abstract - Two-phase stratified flow is of common occurrence in directional oil wells and has been used as a suitable way to avoid the formation of emulsions of water in oil in pipelines. Energy losses and the high costs related to the transport of mixtures of immiscible fluids have been subject of interest of academia and industry. Several tools as the theory of hydrodynamic stability or CFD have been broadly used for modeling and prediction of the flow-pattern transition boundaries, which is necessary for proper design of wells and pipelines and for the significant increase of production and reduction of energy consumption, therefore reducing the project and operational costs. According to the former, flow-pattern transition can be assigned to hydrodynamic instabilities resulting from the amplification of a disturbance wave that develops at the interface between the phases. We suggest in this work that for a typical stratified liquid-liquid flow the interfacial wave is the result of the balance of forces acting on the two-phase flow. CFD is applied in order to try to understand better the interfacial phenomena associated to the interfacial shear stress, actual wetted perimeters, hydraulic diameters and friction factors. The goal is the better prediction of quantities as pressure drop and in-situ volume fraction. The results show good agreement with experimental data from the literature. A qualitative analysis of the wave's geometrical properties has also been performed.

***Keywords*:** Two-phase stratified flow, Interfacial wave, CFD, Holdup, Pressure drop.

1. Introduction

Stratified liquid-liquid flow has been used as a convenient way to avoid the formation of emulsions of water in pipelines and also has a common occurrence in directional oil wells. The energy losses and high costs related to the displacement of fluids have been subject of concern for the industry, especially in conditions of offshore production. Reliable prediction of flow patterns in specific conditions contribute to reducing energy consumption and significantly increase the production, also reducing both project and operational costs.

The theory of hydrodynamic stability has been widely used for modeling and prediction of the transition boundaries of two-phase flow patterns. According Santos (2010), in some cases flow-pattern transition can be attributed to instability resulting from the amplification of an interfacial disturbance wave. However, little attention has been paid to the interfacial wavy structure observed in stratified oil-water flow. The poor modeling of the interfacial energy dissipation can explain in part the unsatisfactory prediction of pressure drop by one-dimensional models available in the literature and used in commercial codes (de Castro et al., 2011a; Belt et al., 2011, Rodriguez and Baldani, 2012). De Castro et al. (2011b), in their work published about the geometric and kinematic properties of interfacial waves in stratified oil-water flow, suggest that the wave has a kinematic nature, i.e, it is a result of the balance of forces acting on the two-phase flow. The complexity of two-phase flow does not allow the analytical solution of the general governing equations. One of the options to access the details of the flow is the use of numerical methods or CFD (Computational Fluid Dynamics), which have been able to catch some details of two-phase flows in several circumstances. In this study, CFD is used as an attempt to understand in greater depth interfacial phenomena that are related to the interfacial shear stress. The ultimate goal is to be able to properly model the wetted perimeters, hydraulic diameters and friction factors. The quantities pressure drop and volume fraction are used for comparison purposes.

2. Methodology

2. 1. Experimental Work

An experimental work was conducted in the Multiphase-Flow Laboratory of the Thermal-fluids Engineering Laboratory (NETeF), São Carlos School of Engineering (EESC) of the University of São Paulo (USP) in 12m in length and 26mm in diameter horizontal borosilicate-glass pipe (Pereira, 2011).

All data acquisition was made through a remote workstation consisted of a microcomputer and an acquisition board NI-PCI-6224, brand National Instruments®. A data acquisition program was implemented in Labview® platform and was used for the automatic acquisition of the signals measured by flow meters, pressure and temperature meters. All collected data (Table 1) were processed and analyzed in another program implemented in Labview® platform.

Table 1. Water and oil superficial velocities, oil holdup (ε_o) and two-phase pressure gradient $-\left(dP/dz\right)$ data used in this work (Pereira 2011).

Uws **(m/s)**	***Uos*** **(m/s)**	ε_o	**-(*dP/dz*) (Pa/m)**
0.15	0.03	0.39	118.67
0.15	0.05	0.47	176.00
0.15	0.07	0.48	244.00
0.15	0.10	0.58	301.33
0.15	0.13	0.63	416.00
0.15	0.15	0.65	472.00

2. 2. Closure Equations

In order to verify the reliability of the CFD results, not only the experimental data of Pereira (2011), but also phenomenological models based on the steady-state 1-D two-fluid model were used for comparison purposes: the homogeneous model, the model of Trallero (1995), modified by Rodriguez and Oliemans (2006), and the model of Rodriguez and Baldani (2012). The flow was considered isothermal, incompressible, steady and no phase change or mass transfer was taken into account.

In the model proposed by Rodriguez and Baldani (2012), the wet perimeters of oil, water and interface and the cross-sectional areas of each phase are calculated considering a concave or convex interface geometry, corresponding to an arc of a circle as a function of the contact angle, in-situ volume fraction and the Eötvös number. In addition, it is assumed that the interfacial shear is a function of the wavy structure and, hence, it would be possible to model the energy dissipation related to the wavy interface by proposing an effective interfacial roughness. Therefore, the interfacial shear stress would be greater than that predicted by the model used by Rodriguez and Oliemans (2006). Furthermore, it was suggested that the effective roughness is proportional to the interfacial-wave amplitude α in wavy stratified oil-water flow.

2. 3. Computational Fluid Dynamics (CFD)

The formidable complexity of multiphase flows usually translates into a high time-consuming and computational expensive problem. Therefore, the modeling and the development of closure relations are still important research issues and they should be for a very long time, even considering the continuing growth of computing capability.

The simulations were performed using the commercial code ANSYS CFX 14.0® at the cluster of the Multiphase-Flow Laboratory of the Thermal-fluids Engineering Laboratory (NETeF), São Carlos School of Engineering (EESC) of the University of São Paulo (USP). A computer SGI Altix operating Linux system - Red Hat, 136 cores, 272 GB RAM through 10 CPU's, and 15 TB of HD memory was used. Two different meshes were tested and used for the simulations: coarse mesh, with approximately 200,000 nodes, and fine mesh, with approximately 3.2 million nodes, both for the same geometry: a pipe length of 2m and 26mm in diameter. A time step of 0.002 s was set so as to obtain, during the simulation, a considerably small value for the Courant number (around 0.4), in order to obtain a solution as precise as possible. Hypothesis: Newtonian fluids, two-fluid model, being the oil flow in the laminar regime and the water flow in the turbulent regime, transient, incompressible, isothermal, three-dimensional, symmetrical, no mass transfer between the phases and gravity acting. Symmetry was adopted to reduce computational cost.

3. Results

3.1. Quantitative Comparisons of *in-situ* Volume Fraction and Two-phase Pressure Gradient

The Fig.1 shows (a) the experimental data of *in-situ* oil volume fraction and (b) the pressure gradient obtained experimentally. It also shows the following models predictions: the model proposed by Rodriguez and Oliemans (2006), based on the model proposed by Trallero (1995), homogeneous model, Rodriguez and Baldani (2012) and the present results obtained via CFD for horizontal inclination. Uws corresponds to the water superficial velocity, Uos the oil superficial velocity, ε_o the *in-situ* oil volume fraction and $-(dP/dz)$ the pressure gradient (Pa/m). For both cases, it was used a constant $Uws = 0.15$ m/s.

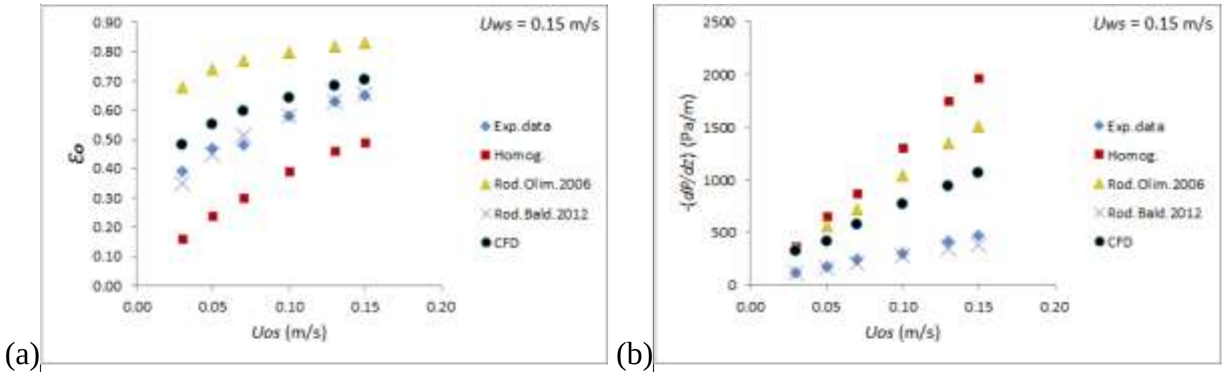

Fig. 1. (a) *In-situ* oil volumetric fraction and (b) two-phase pressure drop as functions of superficial velocity of oil for horizontal flow: experimental data, homogeneous model, Rodriguez and Oliemans (2006), Rodriguez and Baldani (2012) and present CFD results; $Uws = 0.15$ m/s.

One can note in Fig.1a that the volume fraction data were strongly underestimated by the homogeneous model and overestimated by the model of Rodriguez and Oliemans (2006). The model proposed by Rodriguez and Baldani (2012) gave the best predictions. The CFD predictions were slightly worse in comparison with the latter at low oil superficial velocities, but it gave quite similar results at high oil superficial velocities. The predictions of the model of Rodriguez and Oliemans (2006) presented an overall average relative error of 48.0% whereas those of the model of Rodriguez and Baldani (2012) presented an error of only 3.9%. The homogeneous model underestimated the data in 38.3%. The results of CFD simulations presented an overall average relative error of 15.4%.

The Fig.1b shows that the model proposed by Rodriguez and Baldani (2012) presented the best agreement with the pressure gradient data (Pa/m), when compared with the other models tested and CFD results. It’s important to point out that the CFD results are rather unsatisfactory. The pressure gradient predicted by homogeneous model, models of Rodriguez and Oliemans (2006) and Rodriguez and Baldani

(2012) and CFD showed overall average relative errors of 283.9%, 216.5%, 11.7% and 142.0%, respectively.

Rodriguez and Baldani (2012) proposed empirical adjustments regarding the effective roughness at the interface, the interfacial friction factor, the friction factor for laminar flow (in that case oil) and offered an equation for prediction the curvature of the interface as a function of the volume fraction, contact angle and Eötvös number. These can explain the good predictions for both holdup and pressure gradient.

The comparisons suggest an investigation focused on the closure relations. Although the volume-fraction data were satisfactorily predicted by one of the theoretical models and CFD, the same cannot be said about the pressure-drop predictions. As far as the stratified flow is concerned, a more detailed investigation of 1-D two-phase flow models and closure relations used in ANSYS CFX-Solver is in order. The results, according to Fig.1b, suggest that the error could be associated at least in part to the frictional pressure-gradient term.

3.2. Qualitative Analysis of the Geometrical Properties of Interfacial Waves

A qualitative comparison of the preliminary results obtained via CFD simulations with data obtained experimentally by Pereira (2011) regarding the characteristics of the interfacial wave can be seem in Fig.2. The wave profiles observed experimentally, Fig.2a, are quite similar to those obtained by numerical simulation, Fig.2b. The preliminary results are encouraging.

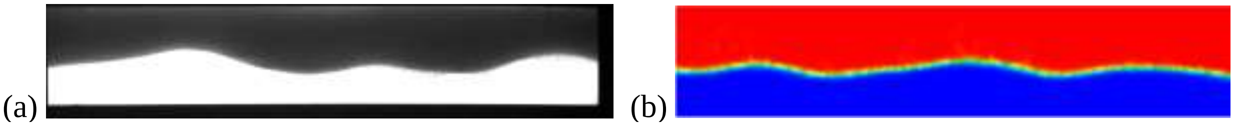

Fig. 2. Wavy profile: (a) image obtained experimentally by high-speed camera, Pereira (2011); and (b) image obtained from the numerical simulation (CFX-Post); *Uos* = 0.03m/s and *Uws* = 0.15m/s in horizontal flow.

A concave interface was predicted by Rodriguez and Baldani (2012) and the adoption of such interfacial geometry gave better results in comparison to other phenomenological models available in the literature. In Fig.3 one can see the variation of the cross-sectional interfacial geometry with position, at the wave crest and valley. More details can be seen in Fig.4. The concave interface, Fig.4a, is very similar to that suggested by Rodriguez and Baldani (2012). However, it presents a different geometry at the crest, Fig.4b, with a pronounced increase of the water height in the center of the tube. Such information is still to be verified experimentally. Once confirmed, it may be used to improve the closure relations used in the two-fluid model, more particularly to improve the interfacial shear stress term.

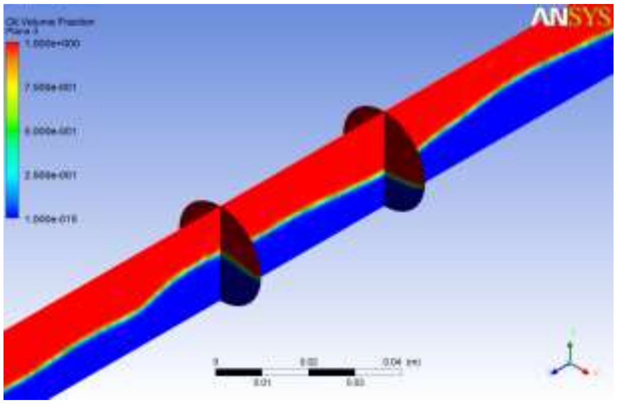

Fig. 3. Cross sections of pipe showing crest and valley of the interfacial wave (CFD-Post); *Uos* = 0.03m/s, *Uws* = 0.15m/s in horizontal flow.

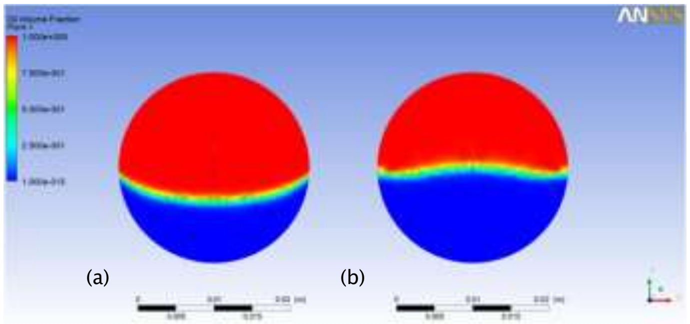

Fig. 4. Cross sections of pipeline showing (a) valley and (b) crest of the interfacial wave (CFD-Post); *Uos* = 0.03m/s, *Uws* = 0.15m/s in horizontal flow.

4. Conclusion

Computational Fluid Dynamics (CFD) was used for the analysis of wavy stratified liquid-liquid pipe flow. Comparisons of numerical simulation results with experimental and 1-D two-fluid model predictions were carried out. The following preliminary findings can be drawn:

1. The CFD results of *in-situ* volume fraction were compared with predictions of three phenomenological models available in the literature and data, showing good agreement with experimental data.
2. The CFD results of two-phase pressure gradient were also compared with predictions of the three phenomenological models available in the literature and data; the agreement between CFD's and data was rather unsatisfactory, probably due to the simulation of the frictional energy dissipation.
3. Preliminary qualitative results suggest that for the typical case investigated the interface had mainly a concave cross-sectional geometry; an interesting finding is that the wave shape varies along the wavelength.

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