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Prediction of pressure gradient and holdup in wavy stratified liquid–liquid inclined pipe flow

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ABSTRACT

Pressure gradient and holdup data are presented for oil–water flow in a horizontal and inclined 0.026 m i.d. pipe (borosilicate glass, 15.5 m length and pipe inclinations of -10°, -20° and $+10^\circ$). A wavy stratified flow in the laminar-turbulent regime with no dispersion whatsoever at the interface was observed. The relatively high-viscosity oil flow (280 mPa s) dominates the friction and the low Eötvös number indicates the existence of a wavy and curved interface. A new closure relation for the interfacial friction factor is suggested. Recent interfacial wave amplitude data are used for the proposition of a correlation for the interfacial friction factor based on the equivalent-sand-roughness concept. An explicit equation for the interface shape based on the constant-curvature-arc model is proposed, which is a function of the Eötvös number, holdup and contact angle. A discussion on the typical contact angles observed in liquid–liquid flow in pipes of different materials is carried out. It was found that for the slower lighter phase (oil) the effective wall friction factor is significantly lower than the single-phase friction factor, corresponding to an increase of the respective hydraulic diameter. CFD simulations provided an estimate of the cross-sectional wave shape and delivered holdup and pressure gradient results. The phenomenological model is validated against data from the literature and its predictions are compared with present data, models from the literature and CFD results. The favorable comparisons and simplicity of the proposed closure relations are promising, aiming to practical application.

1. Introduction

The flow of two immiscible liquids is present in a wide range of natural and industrial processes; however, studies on liquid–liquid flow are not as common as those on gas–liquid flow. There is no guarantee that the available information on the latter can be extended to liquid–liquid flow. The interest in liquid–liquid systems has recently increased mainly due to the petroleum industry, where oil and water are often transported together for long distances. Pressure drop, heat transfer, corrosion and structural vibration are a few examples of topics that depend on the geometrical configuration or flow patterns of the immiscible phases. The stratified flow pattern has a common occurrence in directional oil wells and pipelines. It has been suggested as a convenient way of avoiding undesirable water-in-oil emulsions in pipelines. Stratified flow is important since it is the flow pattern that occurs most in the pipeline, the largest part of the pipeline being nearly horizontal (Belt et al., 2011). It is characterized by a system of immiscible parallel phases divided by an interface that can be smooth, wavy and can present droplets of one phase into the other phase in a gravity field.

Pressure gradient and holdup (in-situ volume fraction) are the most important design parameters. Accurate predictions are crucial for the design of a directional well or pipeline as they allow the desired pressure drop over the line and liquid amount produced or transported. Their prediction is usually made via the 1-D two-fluid model. Nevertheless, the two-fluid model application depends on reliable closure relations for the wall and interfacial shear stresses and, also, on the interface shape. The closure relations should be able to correctly represent the effects of the phases' flow rates, tube diameter, physical properties, inclination and phases' flow regime (laminar or turbulent). Commercial simulators usually rely on empirical correlations such as the classical Lockhart and Martinelli (1949) and Hoogendorn (1959), which are obtained by fitting a significant amount of experimental data, regardless the flow pattern. Some correlations may present better results for a specific flow pattern, as Baker et al. (1988) that yields relatively good results for pressure gradients in stratified flow. However, the empirical approach is limited and commonly associated with high uncertainties. The stratified flow pattern can be subdivided into stratified smooth and stratified wavy. Stratified smooth is obtained only at very low flow rates. Waves may be observed, but they are too long in comparison to the pipe diameter. In liquid–liquid flow, the

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interface becomes easily wavy with increasing the relative velocity between the phases (de Castro et al., 2012). The relatively low Eötvös numbers observed in liquid–liquid systems indicate extended wall wetting, i.e., a curved rather than a plane interface. However, differently from gas–liquid systems, wettability and interfacial tension effects can be responsible for the formation of not only a concave interface, but also of a convex interface (Ng et al. 2001, 2002).

1.1. *Closure relations for stratified flow*

New closure relations have been recently proposed for stratified laminar flow. Ullmann et al. (2004) modified the two-fluid model to account for the interaction between the phases. The analytical solution valid for the simpler two-plate laminar flow configuration is used as a source of inspiration for the proposition of interaction terms for the wall and interfacial shear stresses. The model is validated against data from the literature and in comparison with an exact solution for laminar stratified pipe flow. However, the closure relations are only valid for a smooth and flat interface. Ullmann and Brauner (2006) extended that work introducing empirical corrections required for the wavy-stratified flow pattern. Based on experimental gas–liquid flow data available in the literature, new empirical correlations for the wave effect on the interface curvature, interfacial shear and liquid wall shear were obtained. The closure relations were extended to make them applicable also for the cases of turbulent flow in either or both of the phases. Those authors applied a model based on the assumption of an interface with constant curvature and gas–liquid flow data (Chen et al., 1997; Ottens et al., 1999) to obtain a correlation for the cross-sectional interface shape. The deviations between data from the literature and predictions in most of cases were of about 20% for both the holdup and pressure gradient. However, the model is restricted to gas–liquid flow with a concave interface shape.

In Chakrabarti et al. (2005) an attempt was made to predict pressure drop by considering the minimization of the total two-phase system energy and that the phases have the same pressure drop. The 1-D fully-developed combined momentum equation for stratified liquid–liquid flow is numerically solved together with the total energy equation of the system in order to obtain the position of the interface. A smooth and flat interface was considered. The closure relations for the shear stresses and hydraulic diameters are the same of Brauner and Maron (1989). Deviations between their own data and predictions were as high as 40% for pressure gradient, with an average deviation of 10%. The comparison with data from the literature was not satisfactory, with deviations of about 200% for pressure gradient. Raj et al. (2005) extended the model of Taitel and Dukler (1976) in order to include surface tension effects, which should be pertinent in liquid–liquid systems. The interface shape is obtained according to the model of Brauner et al. (1998) that considers a constant curvature and applies the principle of minimization of the total system energy. Deviations between their own data and predictions were as high as 10% for holdup, with an average deviation of 5%. The comparisons with liquid–liquid flow data from the literature presented deviations as high as 25% for holdup, with an average deviation of 11%. Those authors do not present pressure gradient data.

Recently, it was shown by de Castro et al. (2012) that one of the available 1-D fully-developed two-fluid models was not adequate to predict their data of wavy stratified liquid–liquid flow. The model of Trallero (1995), refined by Rodriguez and Oliemans (2006), was used to predict holdup and pressure gradient. The oil holdup data were systematically overestimated and the deviations were of about 35%. The pressure drop data were also overestimated, but the predictions were rather poor with deviations of about 200% for horizontal flow and of about 50% for inclined flow. Belt et al. (2011) compared two commercial multiphase flow simulators using gas–liquid flow experimental databases and field cases in the oil industry. The deviations between pressure-gradient laboratory data and predictions were of about 30% for stratified flow. However, the deviations were as high as 200% when the simulators were used to predict holdup in stratified flow. The comparisons with field data showed overestimation of the pressure drop of about 100% in the gravity dominated region, where stratified flow is likely to occur. The results suggest that even well established commercial softwares, commonly used by the oil-and-gas companies for design purposes, are not being able to predict pressure gradient and holdup in stratified flow with good accuracy.

1.2. *Wavy stratified flow pattern*

One of the reason of the almost inexistence of correlations or closure relations specific for wavy stratified liquid–liquid flow is the lack of experimental data. For instance, studies that distinguish wavy stratified from stratified with mixing at the interface are scanty. Trallero (1995) identifies smooth stratified and stratified with mixing at the interface, including into the latter the wavy-stratified flow pattern. However, it is expected that interfacial waves play an important role in energy dissipation and have relation with the cross-sectional shape of the interface (concave or convex). Thus, it should be interesting to isolate the wave interaction effects from the effects related to momentum transfer due to the dispersion of drops at the interface (Hadziabdic and Oliemans, 2007). Elseth (2001) was one of the first to classify the wavy-stratified flow pattern as having interfacial waves of short length and high amplitude and almost no dispersion at the interface. That author offers pressure gradient and holdup data for oil–water horizontal flow. Chakrabarti et al. (2005) also identified the wavy-stratified flow pattern and collected pressure gradient data for kerosene–water horizontal flow. Raj et al. (2005) used the same setup of the latter and obtained holdup data in horizontal wavy stratified flow. Rodriguez and Oliemans (2006) observed the wavy-stratified oil–water flow pattern and compared the predictions of 1-D models available in the literature with data of pressure gradient and holdup in horizontal and slightly inclined flow. Lum et al. (2004, 2006) also reported the wavy-stratified flow pattern; however, those authors do not offer pressure gradient data related to wavy stratified flow. Table 1 summarizes the data sets that have been used in this work.

1.3. *Interfacial wave and contact angle*

Information on the geometrical properties of interfacial waves and, also, on typical contact angles observed in stratified liquid–liquid flow in pipes of different materials is crucial for the development of closure relations for wall shear and interfacial shear stresses and interface shape. There is a significant amount of papers on interfacial waves in core-annular flow, in which kinematic and wave shape information has been discussed (Oliemans, 1986; Bai, 1995, Bannwart, 1998; Bai and Joseph, 2000; Rodriguez and Bannwart, 2006a, 2006b). Some works have dealt with the role played by the interfacial wave structure in gas–liquid flow (Bontozoglou and Hanratty, 1989; Bontozoglou, 1991; Li et al., 1997; Wang et al., 2004a, 2004b; Dyment and Boudlal, 2004; Berthelsen and Ytrehus, 2005). However, the literature is very poor with respect to waves in liquid–liquid flow. Quite recently, Al-Wahaibi and Angeli (2011) studied interfacial wave characteristics (wave amplitude and wavelength) in horizontal low-viscosity oil–water pipe flow during stratified flow. In de Castro et al. (2012), geometrical and kinematic