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Pressure drop and holdup predictions in horizontal oil–water flows for curved and wavy interfaces

*Lawrence C. Edomwonyi-Otu, Panagiota Angeli**

Department of Chemical Engineering, University College London, Torrington Place, London WC1E 7JE, UK

ABSTRACT

In this work a modified two-fluid model was developed based on experimental observations of the interface configuration in stratified liquid–liquid flows. The experimental data were obtained in a horizontal 14 mmID acrylic pipe, for test oil and water superficial velocities ranging from 0.02 m/s to 0.51 m/s and from 0.05 m/s to 0.62 m/s, respectively. Using conductance probes, average interface heights were obtained at the pipe centre and close to the pipe wall, which revealed a concave interface shape in all cases studied. A correlation between the two heights was developed that was used in the two-fluid model. In addition, from the time series of the probe signal at the pipe centre, the average wave amplitude was calculated to be 0.0005 m and was used as an equivalent roughness in the interfacial shear stress model. Both the interface shape and roughness were considered in the two-fluid model together with literature interfacial shear stress correlations. Results showed that the inclusion of both the interface curvature and the equivalent roughness in the two-fluid model improved its predictions of pressure drop and interface height over the range of studied superficial oil and water velocities. Compared to the two-fluid model with other interfacial shear stress correlations, the modified model performed better particularly for predicting pressure drop.

Keywords: Liquid–liquid flow; Curved interface; Interfacial waves; Interfacial roughness; Two-fluid model; Conductivity probes

1. Introduction

The maturing nature of oil wells increases the amount of water extracted, with water often added in the down-hole to enhance production. Oil–water mixtures need, therefore, to be transported over long distances. The prediction of the two-phase mixture flow properties poses a challenging task because of their dependence on several interrelated factors such as Reynolds number, pipe diameter and inclination among others. An accurate prediction of the pressure drop and holdup is needed for an effective design and maintenance of the fluid transport systems (Hadžiabdić and Oliemans, 2007; Rodriguez and Baldani, 2012). For separated flows the one-dimensional two-fluid model (Taitel and Dukler, 1976; Brauner and Moalem, 1992a) has been used to predict the pressure drop and liquid holdup. Its effectiveness has been found to depend on the closure relations for the wall (oil and water) and interfacial shear stresses as well as the nature of the interface geometry.

In particular, interfacial waves in multiphase flows, which are known to contribute to the observed frictional drag, have not been fully accounted for in the two-fluid model (Andritsos and Hanratty, 1987; Andritsos et al., 2008; Brauner and Moalem, 1993; Brauner et al., 1998; Brauner, 2002; Hadžiabdić and Oliemans, 2007). Although the use of the one-dimensional two-fluid model has yielded some success even in commercial simulators, its ineffectiveness has also been well documented. Rodriguez and Baldani (2012) gave a detailed compendium of the works done so far. Their two-fluid model which included a correlation for the interface curvature and a modified interfacial friction factor based on experimental liquid–liquid flow data and computational fluid dynamic simulations, was able to predict well their experimental results with heavy oil (viscosity of 280 mPas) and water as well as data from other works.

In most of the cited literature, the focus has been on large pipes with internal diameter greater than 20 mm while in recent years there is a growing number of papers on liquid–liquid flows in very small pipes driven by process intensification requirements (Kim and Mudawar, 2012; Tsaoulidis et al., 2012). However, reported data on intermediate pipe sizes (10–20 mmID) are very few in the open literature (Jin et al., 2013; Xu et al., 2010). The flow properties and geometry at

* *Corresponding author*. Tel.: +44 (0) 20 7679 3832.
E-mail address: p.angeli@ucl.ac.uk (P. Angeli).
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Nomenclature

Roman symbols

A_o and A_w	area occupied by oil and water phases
dp/dz	pressure gradient (Pa/m)
D_o and D_w	hydraulic diameter of oil and water phases
H_o and H_w	holdup of oil and water phases
h_w	interface height
m	flow regime constant
n	flow regime constant
Re	Reynolds number
Uso and Usw	superficial oil velocity and water velocity

Greek symbols

β	angle in Fig. 7
Δ	delta
γ	proportionality constant in Eq. (16)
α	pipe inclination angle
τ	Shear stress

Subscripts

c, i, o, w	annular core phase, interfacial, oil and water, respectively

these intermediate sizes are known to be greatly influenced by surface and interfacial forces, which become more significant as the diameter reduces, particularly for Eötvös number (E_o, ratio of buoyancy to surface tension forces) greater than 1.0 (Brauner and Moalem, 1992b; Das et al., 2010).

In the present work new experimental data of interface curvature and waviness are presented for separated oil–water flows in a 14 mmID horizontal acrylic pipe. Modifications are suggested to the one-dimensional two-fluid model based on these experimental data. The results of the modifications, particularly to the interface curvature and interfacial shear stress, are compared against predictions obtained when using other interfacial shear stress models available in literature.

2. The one-dimensional two-fluid model for liquid–liquid flows

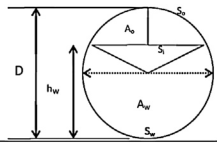
The one-dimensional two-fluid model (2FM) (Al-Wahaibi and Angeli, 2007; Al-Wahaibi et al., 2007; Brauner and Moalem, 1992a; Taitel and Dukler, 1976) is based on momentum balance equations. Two continuous fluids are considered to flow in layers in a circular pipe according to their density and assumed to be separated by a smooth and flat interface. For a fully developed steady state flow, the integral forms of the one-dimensional momentum equations for the two phases are given by:

$$-A_o\left(\frac{dp}{dz}\right) - \tau_o S_o \mp \tau_i S_i + \rho_o A_o \sin\alpha = 0 \quad (1)$$

$$-A_w\left(\frac{dp}{dz}\right) - \tau_w S_w \pm \tau_i S_i + \rho_w A_w \sin\alpha = 0 \quad (2)$$

The subscripts i, o and w stand for interfacial, oil and water, respectively. S_i, S_o, S_w, A_o and A_w are respectively the perimeters and areas of the phases. By equating the pressure drop in

Table 1 – Geometric parameters used in the two-fluid model.

Parameters (flat interface)	
Interfacial length (S_i)	$D\times\left(1-\left(\frac{2h_w}{D}-1\right)^2\right)^{0.5}$
Wall wetted perimeter of the oil phase (S_o)	$D\times\cos^{-1}\left(\frac{2h_w}{D}-1\right)$
Wall wetted perimeter of the water phase (S_w)	$\pi D - S_o$
Cross sectional area of the pipe (A)	$\frac{\pi D^2}{4}$
Area oil phase (A_o)	$\frac{D}{4}\times\left(S_o - S_i\times\left(\frac{2h_w}{D}-1\right)\right)$
Area water phase (A_w)	$A_w = A - A_o$
Oil hold-up (H_o)	$\frac{A_o}{A}$
Water hold-up (H_w)	$\frac{A_w}{A}$
In-situ oil velocity (U_o)	$\frac{U_{so}}{H_o}$
In-situ water velocity (U_w)	$\frac{U_{sw}}{H_w}$

the two phases, the following equation is derived where α (the pipe inclination) is zero for horizontal flow:

$$-\frac{\tau_w S_w}{A_w} + \frac{\tau_o S_o}{A_o} + \tau_i S_i\left(\frac{1}{A_w} + \frac{1}{A_o}\right) = 0 \quad (3)$$

τ_w, τ_o, τ_i are the water wall, oil wall and interfacial shear stresses, respectively. Table 1 shows the geometric parameters used in the two-fluid model.

The wall shear stresses, τ_w and τ_o are expressed in terms of the corresponding fluid friction factors, f_w and f_o:

$$\tau_w = \frac{f_w \rho_w U_w^2}{2};\ f_w = mRe_w^{-n} = m\left(\frac{D_w U_w \rho_w}{\mu_w}\right)^{-n} \quad (4)$$

$$\tau_o = \frac{f_o \rho_o U_o^2}{2};\ f_o = mRe_o^{-n} = m\left(\frac{D_o U_o \rho_o}{\mu_o}\right)^{-n} \quad (5)$$

The friction factors are Fanning type and the pipes are considered smooth. The coefficient m and the exponent n are equal to 0.046 and 0.2 respectively for turbulent flow, while 16 and 1.0 are used for laminar flow. D_w and D_o are the hydraulic diameters. Their values are based on the relative velocities of the two phases, which unlike gas–liquid flows are not necessarily different.

$$D_w = \frac{4A_w}{S_w + S_i};\ D_o = \frac{4A_o}{S_o}\ \text{for}\ U_w > U_o \quad (6)$$

$$D_o = \frac{4A_o}{S_o + S_i};\ D_w = \frac{4A_w}{S_w}\ \text{for}\ U_w < U_o \quad (7)$$

$$D_o = \frac{4A_o}{S_o};\ D_w = \frac{4A_w}{S_w}\ \text{for}\ U_w \approx U_o\ \left(0.98 \le \frac{U_o}{U_w} \le 1.05\right) \quad (8)$$

The parameters S_i, S_o, S_w, A_o and A_w are defined in Table 1. The interfacial shear stress is given by:

$$\tau_i = \frac{f_i \rho_i (U_o - U_w)\,|U_o - U_w|}{2};\ f_i = mRe_i^{-n} = m\left(\left(\frac{S_i}{\pi}\right)\left(\frac{U_i \rho_i}{\mu_i}\right)\right)^{-n} \quad (9)$$

where

$$\rho_i, U_i, \mu_i = \begin{Bmatrix} \rho_w, U_w, \mu_w\ \text{if}\ U_w > U_o \\ \rho_o, U_o, \mu_o\ \text{if}\ U_w < U_o \end{Bmatrix} \quad (10)$$

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