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Slip ratio in dispersed viscous oil–water pipe flow

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ABSTRACT

In this article, dispersed flow of viscous oil and water is investigated. The experimental work was performed in a 26.2-mm-i.d. 12-m-long horizontal glass pipe using water and oil (viscosity of 100 mPa s and density of 860 kg/m^3) as test fluids. High-speed video recording and a new wire-mesh sensor based on capacitance (permittivity) measurements were used to characterize the flow. Furthermore, holdup data were obtained using quick-closing-valves technique (QCV). An interesting finding was the oil–water slip ratio greater than one for dispersed flow at high Reynolds number. Chordal phase fraction distribution diagrams and images of the holdup distribution over the pipe cross-section obtained via wire-mesh sensor indicated a significant amount of water near to the pipe wall for the three different dispersed flow patterns identified in this study: oil-in-water homogeneous dispersion (o/w H), oil-in-water non-homogeneous dispersion (o/w NH) and Dual continuous (Do/w & Dw/o). The phase slip might be explained by the existence of a water film surrounding the homogeneous mixture of oil-in-water in a hidrofilic–oilfobic pipe.

1. Introduction

Two-phase liquid–liquid flow is common in several industrial processes; however it has not been studied as intensively as gas–liquid flow. The interest in liquid–liquid flow has increased recently mainly due to the petroleum industry, where a mixture of oil and water often flows through pipes for long distances during the production and transportation processes. In addition, there are only a few works particularly dedicated to the study of liquid–liquid dispersed flows (where one phase is dispersed as droplets into a continuous phase). Dispersed flow has not yet been studied to the same extent as separated flows, usually annular and stratified, or intermittent flow patterns such as slug flow. Moreover, the existing literature in liquid–liquid dispersed flow covers mainly the investigation of flows involving oil with low viscosity (close to the water viscosity), with few references to viscous oil–water flows. In the present study the oil is a hundred times as viscous as water.

The homogeneous model [1] is a candidate route for the prediction of the flow properties at high mixture velocities. The mixture may be treated as a pseudo-fluid with averaged properties that obey the usual equations of single phase flow. The main assumption of the model is the no-slip condition between the phases. However, phase slip has been detected in some experimental studies on oil–water dispersed flow, indicating that one of the phases is flowing faster. Trallero [2] reported values of slip ratio (s, defined as the oil–water *in situ* velocity ratio) greater than 1 in dual continuous flow (both phases retain their continuity while there is interdispersion of the phases) in a 50-mm-i.d. acrylic pipe using water and oil (884 kg/m^3 of density and 28.8 mPa s of viscosity) at mixture velocities from 0.9 m/s to 1.3 m/s, indicating the oil as the fastest-flowing phase. He suggests that the slip ratio could be related to the pipe material. Angeli [3] performed experiments in acrylic and steel pipes using oil (801 kg/m^3 of density and 1.6 mPa s of viscosity) and water as test fluids. At mixture velocities varying from 1.3 m/s to 2.2 m/s and 50% oil cut the slip ratio in most of the cases was less than 1 for the experiments performed in the acrylic pipe. The acrylic is preferentially wetted by oil, which would affect the contact area of the oil drop with the pipe wall. On the other hand, the slip-ratio values for the experiments performed in the steel pipe were close or greater than 1. Different properties of the fluids and pipe material could affect the distribution of the phases in a pipe's cross-section and subsequently the slip ratio.

Lovick and Angeli [4] investigated oil–water dual continuous flow in a 38-mm-i.d stainless steel test section, using water and oil (828 kg/m^3 of density and 6 mPa s of viscosity). They observed that the slip ratio increases with increasing oil cut. A change of the interface shape could explain this behavior. Cross-sectional images of the pipe cross-section showed that at low oil cuts the oil forms a thin continuous layer at the top of the pipe with a rel-

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Nomenclature

a,b	constant (dimensionless)
C	input volume fraction
D	pipe diameter (m)
e_r	average relative error (dimensionless)
f	friction factor
k	electrical permittivity (F/m)
Q	volume flow rate (L/min)
Re	Reynolds number (dimensionless)
s	slip ratio (dimensionless)
U_s	superficial velocity (m/s)
V	*in situ* velocity (m/s)
υ	electrical voltage (V)
(dp/dx)	pressure gradient (Pa/m)

Greek letters

ε	*in situ* phase volume fraction (dimensionless)
μ	viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

w	water
o	oil
m	mixture
MG	Maxwell–Garnett model
LOG	logarithmic model
QCV	quick-closing-valves measurements
T	time index
i, j	crossing point positions

Acronyms

Do/w & Dw/o	oil-in-water and water-in-oil dispersion
o/w H	oil-in-water homogeneous dispersion
o/w	NH oil-in-water non-homogeneous dispersion
PDF	probability density function
QCVs	quick-closing-valves

atively large wall contact area compared to its volume. The oil would experience higher shear; hence its velocity would be lower than that of water, which results in s being less than 1. At high oil cuts the water phase is forming a semi-annulus at the bottom of the pipe and has a larger wall contact area. Water would experience higher shear, which is in agreement with oil as the fastest-flowing phase (slip ratio greater than 1). At high mixture velocities (higher than 2 m/s) where fully dispersed flow is supposed to occur, they also found slip ratios greater than 1, but there is yet no well-accepted explanation for this phenomenon. In fully dispersed flow one of the phases is found as dispersed droplets and it does not retain its continuity at either the top or bottom of the pipe. Therefore, the slip ratio greater that 1 observed by those authors cannot be explained based on the effects of the wall contact area and associated viscous shear.

Dispersed flows have been frequently considered as homogeneous emulsions. Pal [5] suggests that dispersed flows could exhibit non-Newtonian behavior in turbulent flow. He proposed that in turbulent pipe flow the deformation of particles (droplets or bubbles) could cause a modification of the turbulent scales of the continuous phase and explain some phenomena associated to oil–water dispersed flows, such as the drag reduction phenomenon [6–8]. However, the theory does not explain the measured slip ratio.

The wire-mesh sensor is a flow imaging device which allows the investigation of multiphase flow with high spatial and temporal resolution. The first generation of this sensor based on conductivity measurements was introduced by Prasser et al. [9]. The wire-mesh sensor is a hybrid in between intrusive local measurement of phase fraction and tomographic cross-sectional imaging. The measuring principle of the conductivity wire-mesh sensor requires at least one continuous conductive phase. Therefore, they have almost exclusively been used for the investigation of air–water or steam-water systems [10–12]. Nevertheless, non-conducting fluids such as oil, air or organic liquids often occur in industrial applications. For this reason, a novel wire-mesh sensor based on measurements of the electrical permittivity (capacitance) was developed [13], which is suitable for the investigation of flows involving non-conducting fluids such as oil–air flows or oil–air–water flows.

The aim of this research is to investigate viscous oil–water dispersed flow at high mixture velocities with water as the dominant phase in order to obtain new experimental data and to explain the oil–water slip ratio. A further purpose of this study is to apply a wire-mesh sensor based in permittivity measurements for the investigation of flows involving viscous oil for the first time. This paper is structured as follows: in Section 2 the test facility, instrumentation and measurements are presented; in Section 3 slip ratio, flow patterns, holdup and wire-mesh measurements are shown and discussed. Finally, in Section 4 the main findings are summarized.

2. Experimental work

2.1. Test facility

The experiments were performed in the Multiphase-Flow-Loop Test Facility at NETeF (Thermal-Fluids Engineering Laboratory), Engineering School of São Carlos, University of São Paulo. A schematic view of the facilities is shown in Fig. 1. Table 1 describes the main instruments and equipments. The test section consists of a 2.62-cm-i.d. 12-m-long horizontal glass pipe. The two immiscible liquids used were oil (860 kg/m^3 of density and 100 mPa s of viscosity) and water. Both water and oil were kept in polyethylene tanks, (RW) and (RO), respectively. A positive displacement water pump (BW) and a positive displacement oil pump (BO), both remotely controlled by their respective variable-frequency drivers, pumped the phases to the multiphase test line. Oil and water joined at the beginning of the test section via a Y-junction. Positive displacement and vortex flow meters (FO1, FO2, FW1, FW2) were used to measure oil and water flow rate. After the test line the mixture goes to a coalescent-plate separator tank (SLL). The phases once separated are returned to their respective storage tanks by gravity (RW and RO).

In situ phase volume fractions (holdup) were measured using the quick-closing-valves technique (QCVs). Solenoid valves V1 and V2 are normally open and V3 is normally closed (Fig. 1). The solenoid valves V2 and V3 are located at the section inlet and V1 at the end of the pipe (12 m from the pipe inlet). These valves are globe valves with pneumatic actuators MGA, maximum torque of 63 N m at 5 bar. The open–close time is of 0.11 s. In steady-state flow regime, the solenoid valves V1 and V2 are open, allowing the fluid to pass through the test line, whereas V3 remains closed. During the tests, by energizing V1, V2 and V3, the mixture is trapped in the test line and the two-phase flow deviated to the by-pass line. Thus, after the drainage of the test line, it was possible to measure