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TURBULENT FLOW BEHAVIOR OF VISCOUS OIL-WATER DISPERSIONS

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RESUMO
Understanding the flow characteristics of oil-water dispersions is of prime interest for the design and operation of emulsion pipeline systems and industrial facilities. The behavior of oil-in-water dispersions under conditions of turbulent flow in a horizontal acrylic pipe has been investigated for a viscosity ratio of about 220 and density ratio of 0.88. Measurements were made for mixture superficial velocities varying from 1.2 to 4.6 m/s and input oil fractions from 1 to 50%. Pressure gradients were measured under this range of conditions. Effective viscosities of the dispersions were calculated from the single-phase flow equations. Results show a significant reduction of the effective viscosity of the dispersion with increasing oil fraction at high Reynolds numbers. Moreover, a reduction of mixture pressure gradient in comparison to the equivalent water pressure gradient was noticed.

INTRODUCTION

In oil production, the flow of oil-water mixtures in pipelines is common. For transporting viscous oil, water can be introduced into the pipeline in order to reduce the pressure drop. The turbulent regime often takes place in the pipeline, resulting in the formation of dispersions. Oil-water dispersions are known to exhibit drag reduction behavior in turbulent flow [1], [2], [3], [4], [5], [6], but the mechanism behind the phenomenon is not yet enlightened. Pal [2], [7] attributed this phenomenon to a reduction in effective viscosity of dispersion caused by processes of drop coalescence and breakup. The author also argues that the drag reduction activity in water-in-oil dispersions is stronger and it tends to reduce when turbulence becomes more intensive. Moreover, the degree of drag reduction becomes more intense with increasing the dispersed-phase concentration.

Rodriguez et al. [6] detected drag reduction in oil-in-water dispersions (O/W) at oil fractions up to 40% and high Reynolds numbers in a glass pipe. Mixture pressure gradient lower than that of single phase water at the same mixture velocity was observed. The authors proposed a phenomenological model to explain the drag reduction observed in O/W at high Reynolds numbers. The model is based on the existence of a thin water film near to the pipe wall that would be acting as a lubricant. Some other studies have reported a reduction in two-phase pressure gradient in comparison to single phase water values ([3], [4], [6], [8],[9], [10], [11] , [12]).

There are previous studies on pipe flow characteristics of oil-water dispersions giving special attention to the mixture viscosity behavior. If the dispersion is considered as pseudohomogeneous fluid the usual single-phase flow equations using averaged fluid properties can be applied to calculate the mixture viscosity

Cengel et al. [1] studied the laminar and turbulent flow behavior of oil-in-water emulsion using low-viscosity oil. The measured pressure drop data were used to calculate the effective viscosity from the well-known single-phase flow Blasius equation in turbulent flow. The effective viscosities obtained from the turbulent data were found to be lower than the corresponding laminar viscosities, and the relative viscosity (ratio of effective mixture viscosity to continuous-phase viscosity) increased with an increase in the dispersed phase (oil) fraction and the relative viscosity values were in all cases greater than 1. Some other authors reported the same behavior of relative viscosity in oil-water turbulent flow using also low-viscosity oil [1], [13],[14], [2], [7], [5]. Interestingly, Ward and Knudsen [14] observed the opposite behavior for heavy-oil dispersions. The relative viscosity tends to decrease with an increase in dispersed phase (oil) fraction.

The objective of this study is to investigate the behavior of heavy-oil dispersions flowing under intense turbulence in an acrylic pipe. The drag reduction phenomenon in oil-water dispersions is an open field of investigation. Thus, the obtaining of more experimental data and taking into account the role of pipe material, oil nature and rheological caracteristics of the flow could help to understand the phenomenon.

EXPERIMENTAL WORK

Test Facility

The experiments were performed in the Thermal-Fluids Engineering Laboratory (NETeF), of the Engineering School of São Carlos (EESC), University of São Paulo (USP). The multiphase-flow loop is shown schematically in Fig. 1. The main instruments of the facility are listed in Tab. 1. The test section consists of a acrylic line of 26-mm-i.d. and 12-m-length. A by-pass line allowed the usage of the quick-closing-valve technique to measure the *in-situ* volume fraction of the phases. The test fluids, water and oil (828 kg/m^3 of density and 220 mPa.s of (RO), respectively. Positive displacement water and oil pumps (BW and BO, respectively), both remotely controlled by their respective variable-frequency drivers (W VFP and O VFP), pumped the phases to the test line. Oil and water joins at the beginning of the test section via a Y-junction (Multiphase mixer (MGL)). Positive displacement and vortex flow meters (FO1, FO2, FW1, FW2) were used to measure the flow rates of the fluids. After the test section the oil-water mixture flows to a coalescent-plate liquids separator tank (SLL). Once separated by gravity, oil and water are returned to their respective storage tanks, (RO) and (RW).

Pressure gradient data were measured by a Differential pressure transducer (Validyne DP15 model) with ±0.5% full-scale (FS) accuracy. Pressure range of the diaphragms used in the tests is shown in Tab. 2. The pressure drop was measured at 2.8 m from the inlet section and the pressure taps were placed over a distance of 5 m.

A computer was used to conduct the tests and collect the data. The input water and oil flow rates were setup via PXI National Instruments™ and Lab View™.

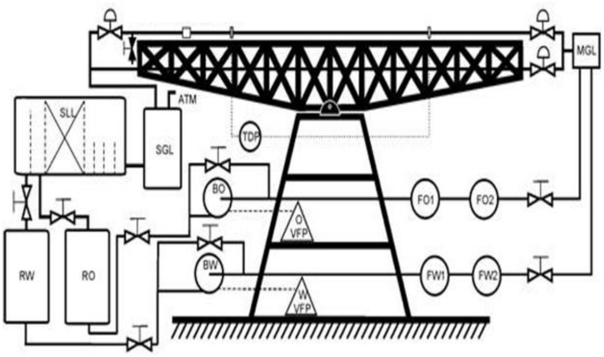

Figure 1. Schematic view of the multiphase flow loop.

Table1. Main instruments and equipments of the facility.

	W VFP – Water Variable-frequency driver O VFP – Oil Variable-frequency driver		FO1 – Oil High Flow Meter FO2 – Oil Low Flow Meter FW1 – Water High Flow Meter FW2 – Water Low Flow Meter
	Quick Closing Valve		Control Valve
	Differential Pressure Transducer		BW – Water Pump BO – Oil Pump
SLL	Coalescent-plates liquid-liquid separator		Drainage Valve
MGL	Multiphase mixer	RW	Water Tank
RO	Oil Tank	SGL	Gas-liquid separator Tank

Table 2. Pressure range chart (DP15 differential pressure transducer).

Range Dash No	Full-scale (Kpa)
34	22
36	35
38	55

The set of experimental points presented in this paper is formed by 78 points (a point means a pair of oil and water superficial velocities). Measurements were made for water superficial velocities of 0.95, 1.2, 1.5, 2.0, 2.5 and 3.0 m/s and for oil cuts between 1.0% and 50%. Figure 2 shows the experimental flow map used for horizontal oil-water flow.

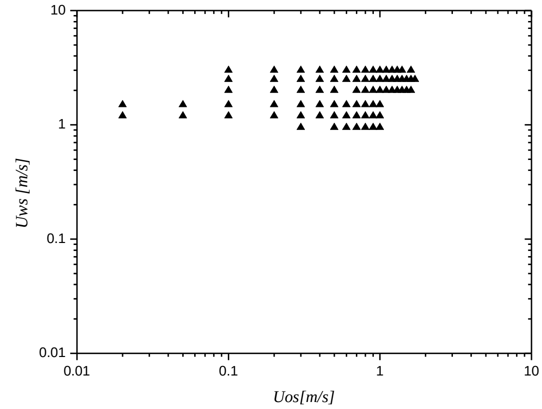

Figure 2. Experimental flow map (horizontal flow).

Effective Mixture Viscosity

Considering the oil-in-water dispersion as a pseudohomogeneous fluid (pseudo single-phase flow), the homogeneous model [15] can be applied and averaged physical properties are used. Thus, effective mixture viscosity can be determined from the measured pressure gradient using the well-known Blasius equation for single-phase turbulent flow (smooth tube):

$$f_m = b\mathrm{Re}_m^{-n} \tag{1}$$

where f_m is the mixture friction factor, the parameters b and n are assumed to be b=0.3164 and n=0.25 for Re_m <10^5 and b=0.184 and n=0.2 for Re_m >10^5 [15]. The mixture Reynolds number, Re_m, is defined as:

$$\mathrm{Re}_m = \frac{\rho_m U_{ms} D}{\mu_m} \tag{2}$$

in which D is the tube internal diameter, U_{ms} is the mixture superficial velocity, μ_m is the effective mixture viscosity. The mixture density, ρ_m, is given by:

$$\rho_m = \rho_o C_o + \rho_w (1 - C_o) \tag{3}$$

Where C_o and C_w and ρ_o and ρ_w are the oil and water cut (input fraction) and density, respectively.

The mixture frictional pressure gradient by the homogeneous model is defined as:

$$f_m = -\left(\frac{dp}{dx}\right)_m \frac{2D}{\rho_m U_{ms}^2} \tag{4}$$

where $(dp/dx)_m$ is the mixture pressure gradient. Based on that, the effective mixture viscosity can be determined by solving Eq. 4 with Blasius relation and pressure gradient value measured for each point.

The relative viscosity (η_r) was calculated for water superficial velocities varying from 0.95 to 3.0 m/s and for input oil fraction up to 0.5 as:

$$\eta_r = \frac{\mu_m}{\mu_c} \qquad (5)$$

Where μ_m is the effective mixture viscosity and μ_c is the continuous-phase viscosity (water).

Pressure drop measurements

Pressure gradient was recorded for the entire set of experimental points indicated on Fig. 2. The measured pressure gradient was used to calculate the effective mixture viscosity as described in the previous section (In total 78 experimental points). In addition, the equivalent single-phase water pressure gradient (pressure gradient measured for single-phase water flow at the same mixture velocity) was measured for each point to compare with the mixture pressure gradient in order to detect the occurrence of the drag-reduction phenomenon. The factor used to determine the occurrence of the phenomenon was defined as:

$$DRP = \frac{-\left(\frac{dp}{dx}\right)_m}{-\left(\frac{dp}{dx}\right)_w} \qquad (6)$$

where DRP is the drag reduction phenomenon factor, $(dp/dx)_m$ and $(dp/dx)_w$ represent the two-phase and single-phase water pressure gradients, respectively. Note that if the mixture pressure gradient is lower than that of water flowing alone in the pipe at the same mixture velocity the DRP-factor is less than 1, which indicates drag reduction.

The two-phase and equivalent water pressure gradient, respectively, were measured first for all 73 experimental points using a differential pressure transducer with 55 Kpa FS diafraghma in order to cover the range of dispersed flow pattern. The pressure drop range was between 3 and 36 Kpa. These data were used to calculate the effective mixture viscosity as described above. After detecting the range of pressure drop for the desired region of study, new pressure drop data were collected in order to maximize accuracy over the pressure measurements and ensure mainly accuracy in the measurement of DRP-factor. Consequently, pressure drop measurements using different diaphragms were carried out depending on pressure drop range. For pressure drops between 23 and 35 Kpa it was used a 35 Kpa FS diaphragm and for a pressure drop range between 15 and 22 Kpa it was used a 22 Kpa FS diaphragm. In this paper it will be presented only DRP-factors values for the higher water superficial velocities (2.0, 2.5 and 3.0 m/s), in total 47 experimental points. Measurements with other two diaphragms are in progress.

In general, the relative viscosity for the oil-in-water dispersions (O/W) at high mixture Reynolds number (43000-227000) and oil fractions up to 50% was below one, indicating that the mixture becomes effectively less viscous than the water phase under intense turbulence. For the higher water superficial velocities (2.0, 2.5 and 3.0 m/s), the relative viscosity seems to show a decreasing trend with increasing input oil fraction. For 2.5 and 3.0 m/s the decrease in relative viscosity becomes more evident from 20% oil fraction (Fig. 3a). For 2 m/s this decrease appears at slightly larger oil fraction. At lower water superficial velocities (0.95, 1.2 and 1.5 m/s) the opposite trend was observed (Fig. 3b). Increasing the oil fraction, the mixture viscosity reached higher values.

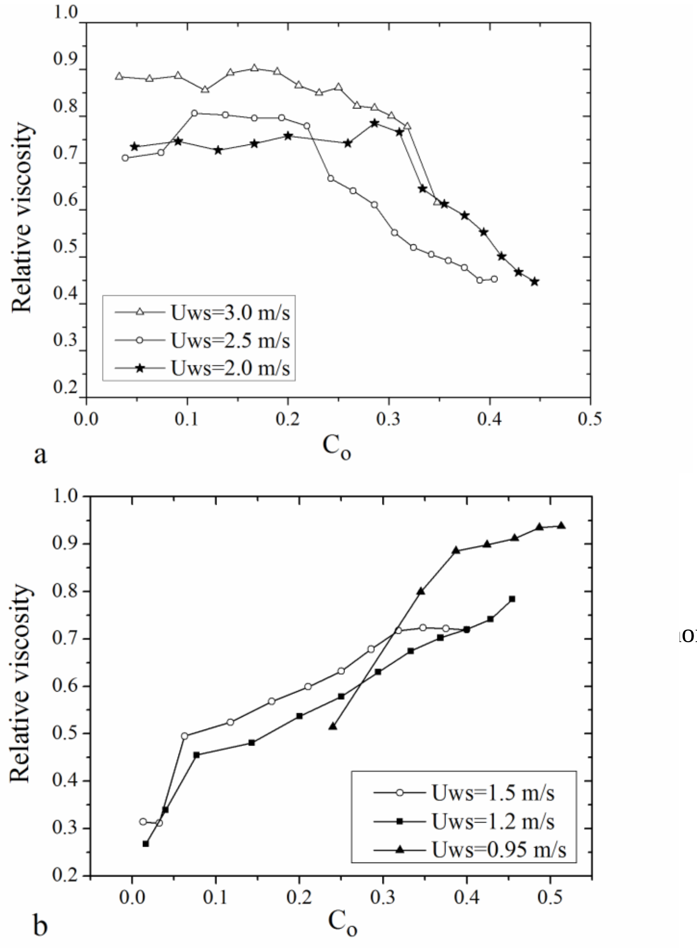

Figure 3. Relative viscosity as a function of oil cut for oil-in-water dispersions at different water superficial velocities.

Results from previous investigations differ from the current study. Relative viscosity always higher than unity has been reported for O/W and it increases with the increase of the oil fraction [1], [2], [7], [13], [14], [5]. Pal [2; 7] obtained relative viscosity less than one, but it was for a water-in-oil dispersion (W/O). In this case, values of relative viscosity lower than one indicate that the mixture viscosity becomes lower than the oil viscosity, differently from what was found in the current work, where water is the dominant phase. It should be noted that all these studies were performed with low-viscosity oil (Tab. 3). Ward and Knudsen [14] observed a different behavior for heavy-oil dispersion. The viscosity showed a tendency to decrease with oil fraction (up to 30%) likewise observed in the current study at high flow rates. However, viscosity values remained higher than one.

Table 3. Summary of experimental studies on oil-water dispersions behavior

Authors	Pipe material	Oil viscosity (mPa s)	Pipe diameter (mm)	Inclination
Cengel (1962)	copper	0.976	22.2 OD	horizontal and vertical
Faruqui and Knudsen (1963)	copper	1.0,15.6	21.08 ID	vertical
Ward and Knudsen (1967)	copper	0.95,13,162	21.08 ID	vertical
Pal (1993), Pal (2007)	stainless steel	2.41	8.89-25.54 ID	horizontal
Omer and Pal (2010)	stainless steel and PVC	2.5,5.4,6.0	8.9-23.74 ID	horizontal
Current work	acrylic	220	26 ID	horizontal

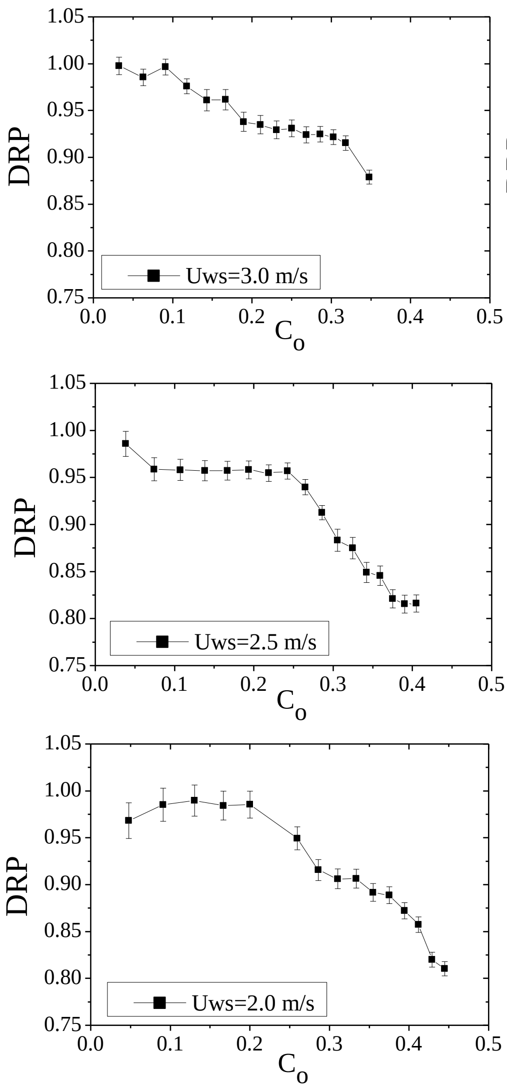

Figure 4. DRP-factor as a function of input oil fraction at different water superficial velocities.

The DRP-factor can be seen in Fig. 4 for the three higher water superficial velocities (2.0, 2.5 and 3.0 m/s) as a function of the oil cut. DRP-factor values lower than one were observed for all conditions (except two points at 3m/s and input oil fraction less than 15%). Therefore, the mixture pressure gradient was lower than the equivalent single-phase water pressure gradient, indicating drag reduction in turbulent flow. For lower input oil fractions (less than 20%) DRP factors are closer to one for all water velocities. The DRP-factor decreases with increasing the. Drag reductions of up to 19%, 18% and 12% were detected for 2.0 m/s, 2.5 and 3.0 m/s and the maximum oil cuts reached were 0.44, 0.40 and 0.35, respectively. The experimental uncertainties of the measured two-phase and related single-phase water pressure gradients were estimated to be ranged from ±0.55% to 1.36% and from ±0.47% to 1.32%, respectivelly. Moreover, the uncertainty of the DRP-factor was of up to 1.9%. It is important to note that the uncertainty of DRP was above 1.17% only for eight experimental points (relative to water velocities of 2.5 and 2 m/s and low oil fractions).

Drag reduction has been reported previously by Rodriguez et al. [6] in oil-in-water dispersed flow in a glass pipe. The current results, together with those obtained by Rodriguez et al. [6], confirm the reduction of the pressure gradient in oil-in-water dispersions when the flow regime is turbulent and oil fractions are below 50%.

The drag reduction in turbulent dispersed flow has been attributed to a reduction of the mixture effective viscosity [7]. This reduction in efective viscosity is supposed to occur due to processes of drop coalescence and breakup or stretching of droplets caused by turbulence. However, according to that theory, an increase of the intensity of the turbulence would cause attenuation of drag reduction. In the current study, the flow is highly turbulent. Nevertheless, a significant reduction in the pressure gradient was noticed simultaneously with a reduction in the effective mixture viscosity (obtained from measured pressure drop). This behavior could not be explained by deformation of droplets as proposed by Pal [7], because at high-turbulence conditions smaller averaged droplet size are present and as a consequence the process of drop deformation is not expected.

CONCLUSIONS

New two-phase pressure gradient data have been used for the study of dispersed oil-water flow using viscous oil as the dispersed phase. Effective mixture viscosity calculated from measured pressure drop showed values less than the water viscosity and also a decreasing function with input oil fraction for high water velocities, contrarily to results reported in previous studies. Also, a reduction in two-phase pressure gradient with respect to single-phase water pressure-gradient confirmed the occurrence of drag reduction in turbulent oil-in-water flow in a hydrophobic/oleophylic acrylic pipe. In the literature, current oil-water dispersions exhibit a different behavior. The results suggest that the turbulent behavior of oil-in-water dispersions depend on the nature of the oil and the oil phase fraction. Therefore, the drag reduction in heavy-oil dispersion could not be caused by coalescence/breakup processes because of the highly turbulent flow condition. More data of pressure gradient, phase distribution, holdup will contribute to the analysis of the phenomenon. Also tests with different oil viscosities and in pipes with different materials and geometries will assist in the analysis of the phenomenon.

RESPONSIBILITY NOTICE

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NOMENCLATURE

Symbol	Quantity	Unit
C	Input fraction	dimensionless
D	Tube internal diameter	m
f	Friction factor	dimensionless
Re	Reynolds number	dimensionless
U_s	Superficial velocity	m/s
(dp/dx)	Pressure gradient	Pa

Greek letters

ρ	Density R	kg/m^3
η_r	Relative viscosity	dimensionless
μ	Effective viscosity	mPa s

Subscripts

c	Continuous-phase
m	Mixture
o	Oil
w	Water

Acronyms

DRP	Drag reduction phenomenon factor
O/W	Oil-in-water dispersion
W/O	Water-in-oil dispersion
FS	Full-scale

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