A PROSPECTIVE MODEL FOR DRAG REDUCTION PHENOMENON IN OIL-WATER DISPERSED PIPE FLOW

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Abstract. *Liquid-liquid flows are present in a wide range of industrial processes; however they have not been studied as intensively as gas-liquid flows. The interest in two-phase liquid-liquid flows have increased recently mainly due to the petroleum industry where oil and water are often produced and transported together for long distances. Nevertheless, the frictional pressure gradient in oil-water pipe flow not rare cannot be predicted by correlations developed for gas-liquid flow. The dispersed flow pattern is common in crude oil transmission pipelines and offshore pipelines, with either oil or water as the dominant phase. An interesting feature of dispersed flow is that it can behave as a non-Newtonian fluid. There are several works on drag reduction in single and gas-liquid two-phase flows, but only few on liquid-liquid flow. The drag reduction phenomenon (DRP) in oil-water flows without the addition of any drag reduction agent has been detected in previous works, but the physics behind the phenomenon is yet not well understood. This work's goal is the suggestion of a model to explain how the drag reduction phenomenon would occur. To this aim, it is proposed that the homogeneous dispersion of oil in water would be surrounded by a thin film of water. A Couette-Poiseuille laminar velocity profile developed close to the pipe wall would explain the phenomenon and it is in accordance with the observed oil-water slip ratio. New data on holdup and pressure gradient at several oil and water superficial velocities are offered.*

Keywords*: liquid-liquid flow, dispersed flow, drag reduction, mathematical model, slip ratio*

1. INTRODUCTION

Liquid-liquid flows are present in a wide range of industrial processes; however, studies on such flows are not as common as those on gas-liquid flows. The interest in liquid-liquid flows has recently increased mainly due to the petroleum industry, where oil and water are often transported together for long distances. Nevertheless, correlations developed for gas-liquid flow, quite often, cannot predict the frictional pressure gradient in oil-water flows. Liquid-liquid dispersions not rare behave as a non-Newtonian fluid and can present higher or lower effective viscosity in comparison with the more viscous or the less viscous phase, respectively. A substantial research has been carried out on drag reduction in single and gas-liquid two-phase flows with the addition of drag reduction agents. On the other hand, there are few studies where such phenomenon is observed on dispersed liquid-liquid pipe flow without the addition of any drag reduction agent.

A number of researchers have detected the drag reduction phenomenon (DRP) in oil-water flows. Angeli and Hewitt (1998) measured pressure gradients in oil-water horizontal flow and found an evident drag reduction for high mixture velocities (2.6-3.0m /s) and low fractions of water, where the dispersed pattern prevails (being the oil the continuous phase).Experimental friction factors were measured in oil-water flows with either oil or water as continuous phases and also in single phase flow of water and oil. The two-phase friction factors were significantly smaller than the single-phase ones when the oil is the continuous phase and almost the same when the water is the continuous phase. Lovick and Angeli (2004) also observed a decrease in the two-phase pressure gradients with respect to equivalent single-phase values in oil-water horizontal dispersed flow.

Rodriguez (2005) found the same behavior observed by the previous authors in slightly-inclined oil-water flow. For the first time, it was verified that the phenomenon is a function of pipe inclination, the effect being increased in downward and reduced in upward inclinations. Ioannou *et al.* (2005) investigated the phase inversion and its effect in the pressure gradient in oil-water dispersed flow. They found a reduction in pressure gradient at low and high oil fraction compared to single phase water and oil values, respectively, for all velocities studied. Lum et al. (2006) studied the effect of pipe inclination on the flow pattern, pressure gradient and holdup in oil-water flow. A reduction of pressure gradient was observed until a minimum that was reached between 60 and 80% of oil for high mixture velocities. The frictional pressure gradient in upward and downward flows was in general lower than in horizontal flows while the minimum occurred at all inclinations at high mixture velocities. Hu and Angeli (2006) investigated experimentally the phase inversion phenomenon in a vertical steel pipe (co-current upward and downward flows). They observed a reduction in pressure gradient from the equivalent single phase oil and water values with the addition of small fractions of water or oil, respectively. Pal (2007) proposed a new mechanism for the modeling of drag reduction phenomenon in turbulent oil in water and water in oil dispersions. In this work was observed that oil-water emulsions and dispersions show drag reduction in turbulent flow. The measured friction factors in turbulent flow fall below the values expected on the basis of laminar flow. Based on the mixture effective rheological aspects, the phenomenon in oil-water dispersions is caused by a significant reduction of the effective viscosity of the dispersion when the flow regime passes from laminar to turbulent. It was observed that the degree of reduction is higher when the oil is the continuous phase.It is interesting to note that the drag reduction phenomenon in oil-water dispersed flows has been detected by some researchers, but the physics and the mechanism behind the phenomenon is yet not well understood.

The main purpose of this prospective study is the suggestion of a physical mechanism to explain the DRP in liquid-liquid dispersed pipe flow. A new mathematical model is proposed and developed based on new data of holdup and slip ratio flow acquired at the Thermal-Fluids Engineering Laboratory (NETeF) of the University of Sao Paulo at São Carlos (EESC-USP). These data agree with those of Lovick e Angeli (2004) that studied an oil-water dispersed horizontal flow, with oil six times more viscous than water, and reported slip between the phases with oil flowing faster than the water phase. The main point is that the DRP depends not only on the effective rheological properties of the dispersion and on the hydrodynamics, but also on wettability effects. The presence of a thin film of water between the homogenously dispersed flow and the pipe wall can explain the observed decreases of the two-phase friction factor in liquid-liquid dispersed flows.

The paper is divided in experimental setup (Section 2), where the setup and experimental work will be explained, experimental results (Section 3), where holdup, slip ratio, flow pattern and drag reduction phenomenon data will be shown; mathematical model (Section 4), where, based on the experimental results, it is explained and developed. The predicted film thickness is then presented and discussions are made on the possibilities and limitations of the model (Section 5). Finally, some conclusions are drawn (Section 6).

2. EXPERIMENTAL SETUP

2.1. Setup

The hydrophilic-oilphobic glass test line of 26-mm i.d. and 12-m length of the multiphase flow loop of the NETeF was used to produce the dispersed oil-in-water flows. A by-pass line allowed the usage of the quick-closing-valves technique to measure *in-situ* volumetric fraction of water and oil. A schematic view of the facilities is shown in Fig. 1 and Tab. 1 describes the main instruments. 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. Positive displacement and vortex flow meters (FO1, FO2, FW1, FW2) were used to measure the volumetric flow of each fluid and, consequently, the superficial velocity of each one. After the test line the fluids entered a gas-liquid separator tank (SGL). The mixture of water and oil enters, by gravity, the coalescent-plates liquid-liquid separator (SLL). Finally, water and oil return by gravity to their tanks, (RW) and (RO), respectively.

A control algorithm was designed, implemented and operated via LabView™ to enable the quick-closing-valves technique. Solenoid valves V1 and V2 are normally open and V3 is normally closed (Fig.1). In case of operational incautiousness, it prevents an increase of pressure that could damage the glass test line. They are globe valves with pneumatic actuators MGA, maximum torque of 63N.m at 5 bar. The open-close time is of 0.11s. In steady-state flow regime, the solenoid valves number 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 would be 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 the value of the volumetric fraction of each phase. In this case, oil and water *in-situ* volumetric fractions.

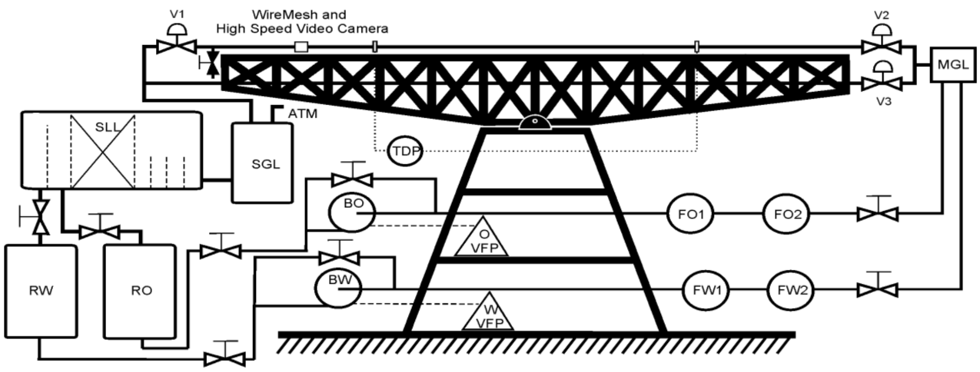

Figure 1. Schematic view of the multiphase flow loop of the NETeF.

Pressure-gradient data of oil-water two-phase flow and single-phase water flow at the same mixture velocity were collected. It was used a previously calibrated differential pressure transducer (SMAR LD301D). The pressure taps were 6.1 m apart from each other and the first located at 2.8 m from the test section inlet. The measurement of other flows quantities and the characterization of flow patterns are described in Rodriguez *et.al.* (2009).

Table 1. Main instruments and equipments of the multiphase flow loop of the NETeF.

	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

2.2. Holdup Measurement

When the two-phase flow was fully developed the quick-closing valves (QCV), described in Section 2.1, were locked and the flow trapped. Then, the line was drained. The drainage process took 30 (thirty) minutes for each run. Water is much less viscous than oil (100 mPa.s); so, it was assumed that after that period of time all the water was drained from the line, but some small amount of oil might still remain sticking to the pipe wall. This source of uncertainty was suppressed by assuming that after the period of drainage the difference between the total volume of the pipe line (6400 mL) and the total drained volume was composed only by the oil that remained in the test line.

The volume of the drained fluids (water and oil) was measured with a beaker of 2000 mL, with a minor graduation of 20 mL. Therefore, each drainage process required four volume measurements. Some replicates were performed for each flow conditions to confirm the accuracy of the results.

A rigorous analysis of propagation of uncertainties was carried out to confirm the reliability of the data (Holman, 1978). The uncertainties were between 0.89% and 2.89% for the oil *in-situ* volumetric fraction. The value of twice the standard deviation was smaller than the calculated uncertainties. Such strictness was necessary since the holdup data were also used for validating a new type of capacitive wire-mesh probe for holdup measurement (Rodriguez *et. al.* 2009).

3. EXPERIMENTAL RESULTS

Three different flow patterns were observed in the tests: homogenous dispersion of oil in water (**Do/w H**), non-homogenous dispersion of oil in water (**Do/w NH**) and a dual flow made of dispersion of oil in water and dispersion of water in oil (**Do/w & Dw/o**) (refer to Rodriguez *et al.*, 2009, for more details). The measurement of holdup showed that oil flows with higher *in-situ* velocity than water; so, its *in-situ* volumetric fraction is smaller than that the homogenous no-slip model predicts. However, it is not clear *a priori* that there would be any slip between phases in a fully dispersed horizontal flow at high mixture Reynolds numbers (mixture Reynolds numbers between 30000 and 120000).

The slip ratio (s) is defined as:

$$s = \frac{\dfrac{\varepsilon_w}{\varepsilon_o}}{\dfrac{C_w}{C_o}} = \frac{V_o}{V_w} \tag{1}$$

where C_o and C_w are defined as the oil and water cuts, ε_o and ε_w represent the *in-situ* volumetric fraction of oil and water (holdup), respectively, measured by the quick-closing-valves technique, and V_o and V_w are the *in-situ* velocities of oil and water, respectively. The oil and water cuts are given by:

$$C_o = \frac{Q_o}{Q_w + Q_o} = \frac{J_o}{J} \tag{2}$$

$$C_w = \frac{Q_w}{Q_o + Q_w} = \frac{J_w}{J} \tag{3}$$

where Q_o and Q_w are the flow rates, J_o and J_w are the superficial velocities of oil and water, respectively, and J is mixture velocity ($J = J_o + J_w$).

In Tab.2, one can see all the collected experimental data. For all tests, the slip ratio was higher than 1, regardless the flow pattern. It also contains the pressure drop of the mixture (ΔP_m) and the pressure drop of water flowing at mixture velocity (ΔP_w). Note that if the pressure drop of the mixture is lower than that of the water flowing alone, the drag reduction phenomenon has then been detected. In this work, the mixture pressure gradient normalized with respect to the water pressure gradient flowing at the mixture velocity, DRP = ΔP_m / ΔP_w , is used as an indicator of the drag reduction phenomenon. The proposed mathematical model was developed on the basis of the observed drag reduction phenomenon and slip ratio.

Table 2. Experimental results of oil holdup, flow patterns, slip ratio, two-phase and single-phase water pressure drops.

Run	J_w[m/s]	J_o[m/s]	Oil holdup, ε_o (QCV)	Flow Pattern	Slip, s	ΔP_m [Pa]	ΔP_w [Pa]
9	3.0	0.2	0.0593	Do/w H	1.06	23560	21210
10	3.0	0.5	0.1359	Do/w H	1.06	27110	24480
52	3.0	0.8	0.2008	Do/w H	1.06	28040	28690
11	3.0	1.0	0.2339	Do/w H	1.09	32970	31020
43	2.5	0.2	0.0711	Do/w H	1.05	15131	15847
44	2.5	0.3	0.1015	Do/w H	1.06	15922	16676
45	2.5	0.4	0.1292	Do/w H	1.08	16963	17677
46	2.5	0.5	0.1542	Do/w H	1.10	17845	18779
47	2.5	0.6	0.1891	Do/w H	1.03	18786	19916
48	2.5	0.7	0.2016	Do/w H	1.11	19666	21210
49	2.5	0.8	0.2260	Do/w H	1.10	20640	22350
50	2.5	0.9	0.2499	Do/w H	1.08	21570	23410
51	2.5	1.0	0.2729	Do/w H	1.07	22490	24480
29	2.0	0.3	0.1162	Do/w H	1.14	12156	12216
30	2.0	0.4	0.1500	Do/w H	1.13	12895	13214
31	2.0	0.6	0.2124	Do/w H	1.11	14097	15058
32	2.0	0.7	0.2411	Do/w H	1.10	14680	15847
33	2.0	0.8	0.2687	Do/w H	1.09	15454	16676
34	2.0	0.9	0.2953	Do/w H	1.07	16203	17677
41	1.5	0.3	0.1602	Do/w NH	1.05	6475	8239
40	1.5	0.4	0.1988	Do/w NH	1.07	7117	8969
39	1.5	0.5	0.2319	Do/w NH	1.10	7812	9703
38	1.5	0.6	0.2609	Do/w NH	1.13	8777	10466
37	1.5	0.7	0.2880	Do/w NH	1.15	9527	11089
36	1.5	0.8	0.3120	Do/w NH	1.18	10332	12216
35	1.5	0.9	0.3333	Do/w NH	1.20	11092	13214
21	1.0	0.3	0.2188	Do/W &Dw/o	1.07	11724	5200
22	1.0	0.4	0.2692	Do/W &Dw/o	1.09	4898	5846
23	1.0	0.5	0.3123	Do/W &Dw/o	1.10	5140	6700
24	1.0	0.6	0.3492	Do/W &Dw/o	1.12	5948	6900
25	1.0	0.7	0.3813	Do/W &Dw/o	1.14	6640	7538
26	1.0	0.8	0.4091	Do/W &Dw/o	1.16	7440	8239
28	1.0	0.9	0.4335	Do/W &Dw/o	1.18	8245	8969

4. MODELLING

Considering the literature, one may expect that the two-phase flow of oil and water in dispersed patterns at mixture velocities as high as 3 m/s (mixture Reynolds numbers of the order of 75000) should behave as a homogeneous no-slip mixture. However, for all runs the oil holdup predicted by the homogenous model is higher than that measured by the quick-closing-valves technique. Deviations of about 8% are observed, which is far higher than the maximum uncertainty of 2.89% (refer to Section 2.2). A slip ratio (Eq. 1) of about 1.10 can be seen in Tab. 2, which means that oil is flowing about 10% faster than water. A possible explanation may be the presence of a thin water film between the pipe wall and the homogenous no-slip mixture. This paper proposes a simple model, analogous to the idea of the core-annular flow model (Rodriguez *et al.*, 2009), to explain the occurrence of the drag reduction phenomenon. In the core-annular flow pattern the two-phase pressure gradient is lower than that of single-phase water flow at mixture velocity (Rodriguez and Bannwart, 2009), similarly to what was obtained in the present oil-water dispersed flow (Tab. 2).

4.1. Film Model

The model is based on the idea that there is a thin film of water adjacent to the pipe wall, surrounding an axisymmetric homogeneous mixture of oil in water. The water holdup (ε_w) can be split into water-film holdup ($\varepsilon_{w,f}$) and holdup of water in the mixture ($\varepsilon_{w,m}$), *i.e.*:

$$\varepsilon_w = \frac{J_w}{V_w} = \varepsilon_{w,f} + \varepsilon_{w,m} = \frac{J_{w,f}}{V_{w,f}} + \frac{J_{w,m}}{V_{w,m}} \tag{4}$$

where $J_{w,f}$ and $J_{w,m}$ are the superficial velocities and $V_{w,f}$ and $V_{w,m}$ are the *in-situ* velocities of the water film and of the water phase in the mixture, respectively. The oil holdup is defined as:

$$\varepsilon_o = \frac{J_o}{V_o} \tag{5}$$

and the water flow rate can be divided in:

$$Q_w = Q_{w,f} + Q_{w,m} = J_{w,f}A + J_{w,m}A = J_wA \tag{6}$$

where $Q_{w,f}$ and $Q_{w,m}$ are the water-film flow rate and the mixture-water flow rate, respectively, and A is the cross-sectional area of the pipe.

So, with Eqs. (1), (2), (3), (4), (5) and (6), s becomes:

$$s = \frac{\dfrac{\varepsilon_{w,f} + \varepsilon_{w,m}}{\varepsilon_o}}{\dfrac{C_w}{C_o}} = \frac{J_{w,f}V_o}{V_{w,f}\left(J_{w,f} + J_{w,m}\right)} + \frac{J_{w,m}V_o}{V_{w,m}\left(J_{w,f} + J_{w,m}\right)} \tag{7}$$

At this point, some assumptions are needed. The superficial velocity of the film is assumed to be much lower than the superficial velocity of the water phase in the mixture, *i.e.*, $J_{w,f} << J_{w,m}$; so, $J_{w,m}$ tends to the superficial velocity of water, J_w. The *in-situ* velocity of water in the mixture, $V_{w,m}$, is supposed to be equal to the *in-situ* velocity of the oil, V_o. In other words, it is assumed that the oil-water mixture in the core of the pipe flows as a homogeneous no-slip mixture, uniformly distributed over the respective fraction of the cross section of the pipe. Therefore, the second term of the Eq. (7) tends to 1. The slip ratio is then given by:

$$s = \frac{V_o}{V_{w,f}}\left(\frac{Q_{w,f}}{Q_w}\right) + 1 \tag{8}$$

Here, s is a function of two unknowns: $V_{w,f}$ and $Q_{w,f}$ (V_o and Q_w can be determined from Eqs. (5) and (6), respectively). So:

$$s = s\left(V_{w,f}, Q_{w,f}\right) \tag{9}$$

The *in-situ* velocity of the water film, $V_{w,f}$, is estimated by supposing that the film velocity profile can be modeled as a linear Couette flow, where the pipe is the static plate and the mixture is the moving plate, with velocity $V_{w,m} = V_o$. The hypothesis makes sense if it is assumed that the water film is very thin. Thus:

$$V_{w,f} = \frac{V_{w,m}}{2} = \frac{V_o}{2} \tag{10}$$

So, Eq. (8) becomes:

$$s = 1 + 2\left(\frac{Q_{w,f}}{Q_w}\right) \tag{11}$$

Therefore, the water-film flow rate, $Q_{w,f}$, can be readily calculated if the slip ratio, s, is a known quantity.

A Couette-Poiseuille profile is assumed for the determination of the water film thickness:

$$V_{w,f}(y) = \left(\frac{\Delta P_m}{L}\right)\frac{1}{2\mu_w}\left(ey - y^2\right) + \frac{V_o y}{e} \tag{12}$$

where y is the spatial coordinate, starting from the pipe wall, ΔP_m is the pressure drop of the mixture flow, given by Tab.2, L is the distance between the pressure meters (=6.1m), e is the film thickness, and μ_w is the water viscosity. Figure 2, below, shows the velocity profile of the flow.

The water-film flow rate can be calculated by integrating the velocity profile (Eq. (12)) from pipe wall ($y = 0$) to the water film thickness ($y = e$), and multiplying it by the length of the film, L_f (Eq. (13)):

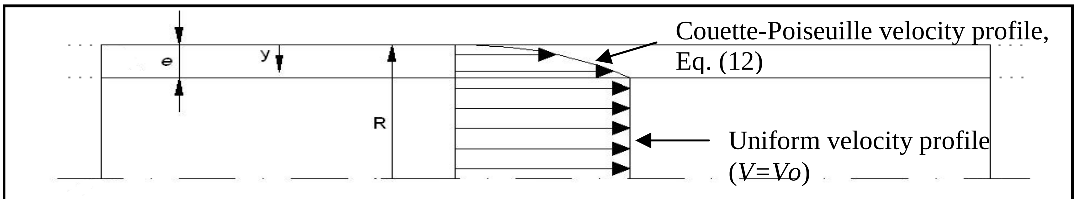

Figure 2. Velocity profiles: water film and mixture of oil in water; *e* - water film thickness, *R* - radius of the pipe.

$$Q_{w,f} = \left[\int_0^e V_{w,f}(y)dy\right] L_f \tag{13}$$

where:

$$L_f = \pi(2R - e) \tag{14}$$

and *R* is the pipe radius. The film flow rate can also be calculated from Eq. (11):

$$Q_{w,f} = \frac{(s-1)Q_w}{2} \tag{15}$$

Therefore, Eqs. (13) and (15) are used together to interactively calculate the film thickness, *e*.

$$\pi(2R - e)\left[\int_0^e V_{w,f}(y)dy\right] - \left[\frac{(s-1)Q_w}{2}\right] = 0 \tag{16}$$

Hence, the Reynolds number of the water film is calculated as below in Eq. (17), where ρ_w is the water density, $V_{w,f}$ is the *in-situ* velocity of the water film, *e* is the water film thickness and μ_w is the water viscosity.

$$\mathrm{Re}_f = \frac{\rho_w V_{w,f} e}{\mu_w} \tag{17}$$

4.2 Mixture laminar sub-layer

An analogy with single-phase turbulent pipe flow is adopted to define the effective mixture laminar sub-layer. In order to verify whether the present model would predict the existence of a water film between the pipe wall and the homogeneous oil-in-water mixture, the ratio between the film thickness and the thickness of the effective mixture laminar sub-layer was obtained. It is assumed that the mixture flows at the oil *in-situ* velocity V_o.

According to the homogeneous model (Wallis, 1969); it is possible to analyze the dispersion of oil in water as a no-slip mixture or pseudo-fluid. The shear stress at the wall, τ_w, is calculated as a function of the two-phase pressure gradient (ΔP_m) :

$$\tau_w = -\left(\frac{R}{2}\right)\left(\frac{\Delta P_m}{L}\right) \tag{18}$$

where *L* and *R* are the distance between the pressure meters and the radius of the pipe, respectively. The density of the mixture, ρ_m , can be calculated as a function of the density of the phases, in this case, water, ρ_w, and oil, ρ_o, , and the holdup of each phase, ε_w and ε_o, respectively, for water an oil:

$$\rho_m = \varepsilon_w \rho_w + \varepsilon_o \rho_o \tag{19}$$

For water cuts higher that 40% ($C_w > 0.40$) the effective viscosity of the dispersion of oil in water can be assumed to be equal to de viscosity of pure water (Ghet *et al.*, 2006). Then, the mixture friction velocity ($V_{frict,\,m}$) was calculated as:

$$V_{frict,m} = \left(\frac{\tau_w}{\rho_m}\right)^{1/2} \tag{20}$$

and the effective mixture laminar sub-layer, $\delta_{sub,m}$, is given as a function of the friction velocity, $V_{frict,m}$, the mixture density, ρ_m, and the water viscosity, μ_w :

$$\delta_{sub,m} = \frac{5\left(\frac{\mu_w}{\rho_m}\right)}{V_{frict,m}} \tag{21}$$

Finally, the mixture Reynolds number is calculated using the density of the mixture, ρ_m, calculated in Eq. (19), the mixture velocity J, defined after Eq. (2), the radius of the pipe R, and the water viscosity μ_w:

$$\mathrm{Re}_m = \frac{\rho_m J 2R}{\mu_w} \tag{22}$$

5. RESULTS

Figure 3 shows the DRP indicator as a function of slip ratio. One can see that for a constant slip ratio the DRP level tends to change depending on the flow pattern. As a whole, the drag reduction phenomenon is stronger for the **Do/w & Dw/o**, it is less evident for the **Do/w NH** and it approaches to the unity (or even higher) for the **Do/w NH** flow pattern.

One may see in Fig. 4 the relationship between slip ratio and film thickness. The film thickness increases as the slip ratio increases. Results suggest that the detected slip ratio would happen as a result of a "lubrication" effect produced by the water film. Therefore, the bigger the film thickness is, the higher the slip ratio between the homogeneous mixture and water film.

Figure 5 shows the ratio between the film thickness and the mixture laminar sub-layer as a function of the water cut. The film thickness is from 4 to 15 times bigger than the laminar sub-layer, which suggests that there may be, indeed, a “lubrication” effect produced by the water ring. A relation can be seen for the **Do/w & Dw/o** and **Do/w NH** flow patterns with the normalized film thickness decreasing with the increase of the water cut. Another remark is that the normalized film thickness depends on the flow pattern, *i.e.*, the same film thickness occurs at different water cut depending on the flow pattern.

The DRP (drag reduction phenomenon indicator) can be observed as a function of the Reynolds number of the water film for all experimental points in Fig. 6. The linear regression (red line) shows that the DRP increases with the increase of the film Reynolds number. The DRP tends towards the unity at higher film Reynolds numbers, *i.e.*, the drag reduction effect tends to disappear at higher film Reynolds numbers. One can expect that higher Reynolds numbers would mean eventual transition from laminar to turbulent flow regime. According to the proposed model, transition would occur around Re_f = 1100; however, in the experiments the flow conditions were quite different from plain Couette-Poiseuille flow. There were quite likely disturbances imposed by the homogeneous mixture on the water film caused by the relative motion between oil droplets and the turbulent continuous water flow. Thus, it’s not unreasonable to think that the critical Reynolds number for the film flow would be rather smaller than that valid for laminar Couette-Poiseuille flow.

Figure 7 shows the normalized film thickness as a function of the Reynolds number of the water film. The relation is clearly linear and for all flow patterns the normalized film thickness increases with the increase of the film Reynolds number. Therefore, an increase of the film thickness leads to an increase of the Reynolds number of the film (Fig. 6), which in turn leads to an increase of the DRP indicator, *i.e.*, the drag reduction effect tends to disappear (Fig. 5). The results clearly suggest that the drag reduction phenomenon may be indeed related to the existence of a laminar water film between the pipe wall and the homogeneous mixture of oil in water. The presence of a laminar water film and its transition to turbulent regime may be a possible explanation for the drag reduction phenomenon observed in this work. The model, off course, has some limitations. The most important is that it is based on the idea that the flow is axisymmetric. This is not absolutely true, as Rodriguez et al. (2009) show in their paper by means of detailed local holdup measurements accomplished via a novel wire-mesh probe. Those authors show that even in the homogenous dispersion of oil in water there was a slightly higher fraction of water at the bottom of the pipe. The model would perhaps be more suitable if applied to vertical flow.

Last but not least, the holdup of the laminar film ranges from 2% to 15% of the total water holdup (Fig. 8). There is a function between the water holdup of the film normalized with respect to the water holdup and the water cut (C_w) for the **Do/w NH** and **Do/w & Dw/o** flow patterns. The ratio of holdups decreases with the increase of the water cut. For small water cut, just the flow patterns **Do/w NH** and **Do/w & Dw/o** are seen, and in those, the water film tends to be bigger, so it is holdup, and the ratio (water holdup of the film normalized with respect to the water holdup) is bigger, all these, because of the asymmetry.

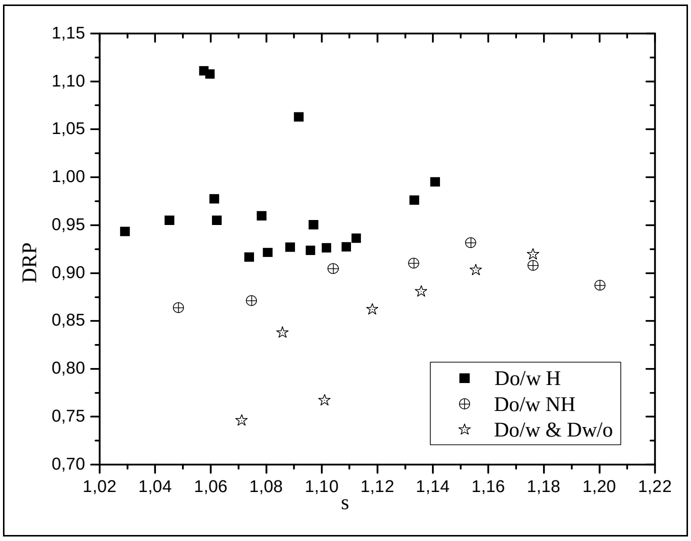

Figure 3. DRP indicator x slip ratio (s).

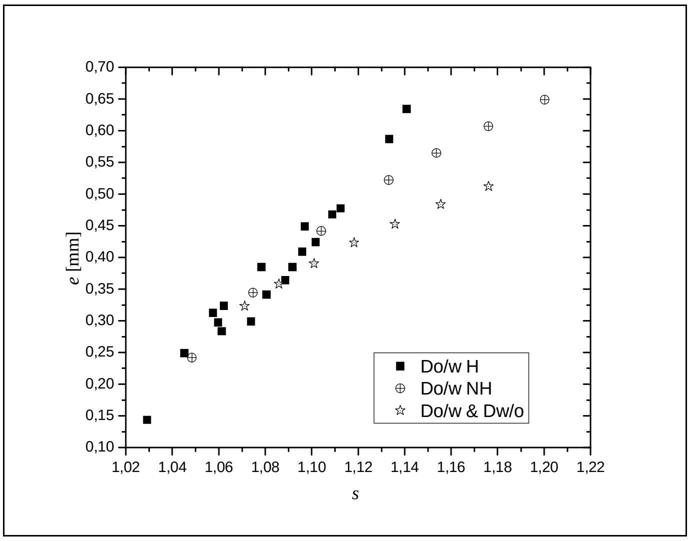

Figure 4. Calculated film thickness (e) x slip ratio (s).

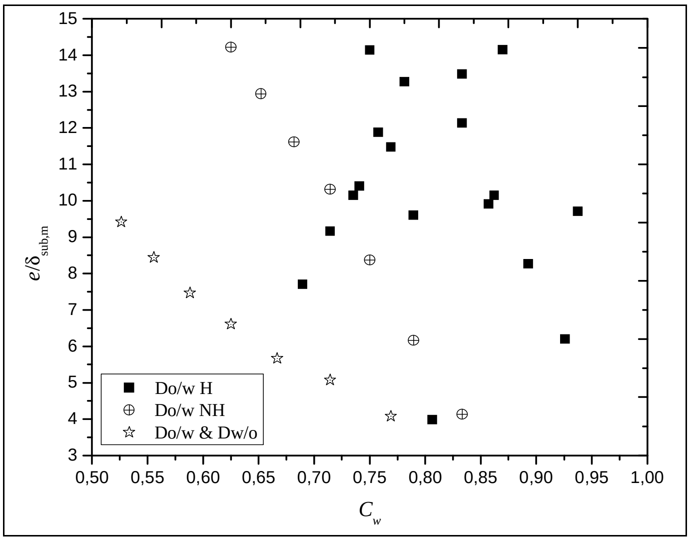

Figure 5. Normalized film thickness x water cut.

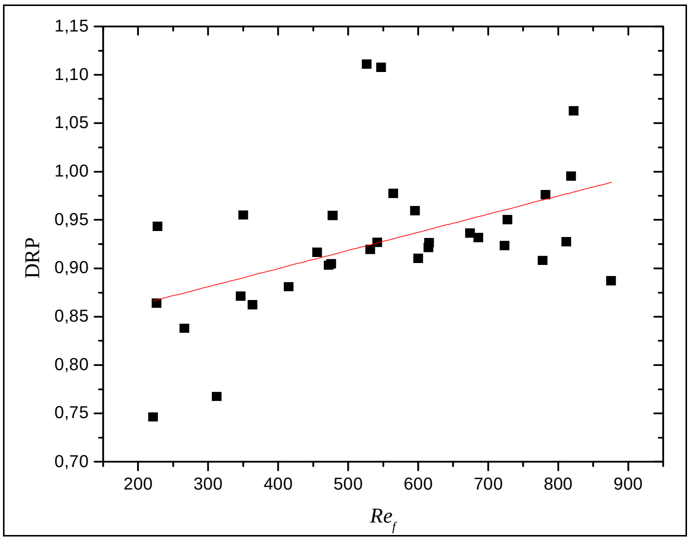

Figure 6. DRP indicator x Reynolds number of the water film (red curve is linear regression).

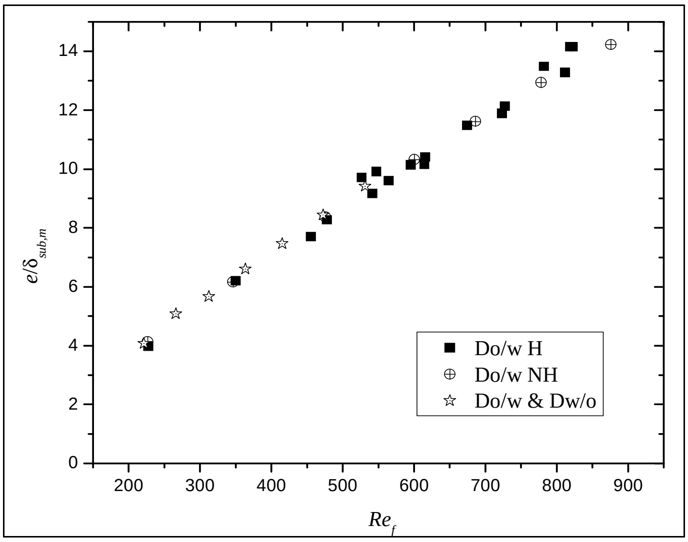

Figure 7. Normalized film thickness x Reynolds number of the water film.

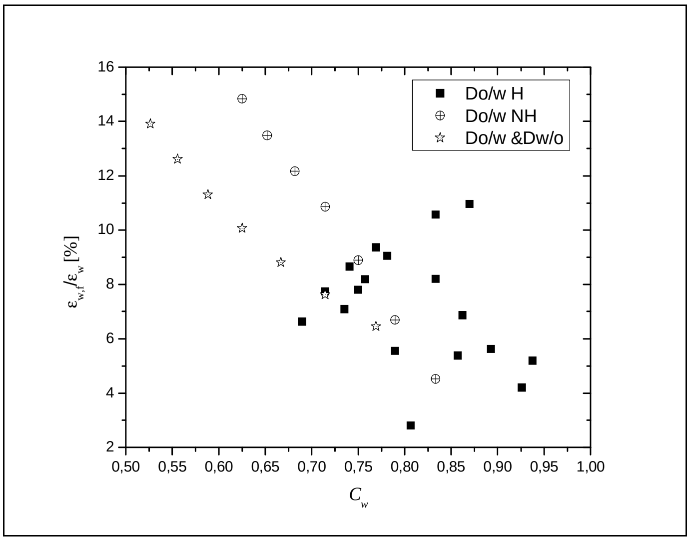

Figure 8. Normalized water holdup of the film x Water cut.

6. CONCLUSIONS

New holdup and two-phase pressure gradient data of dispersions of oil in water and water in oil, are offered. Three different dispersed flow patterns were observed: homogenous dispersion of oil in water (**Do/w H**), non-homogenous dispersion of oil in water (**Do/w NH**) and a dual flow made of dispersion of oil in water and dispersion of water in oil (**Do/w & Dw/o**).

A new model is proposed to explain the physical mechanism of the drag reduction phenomenon (DRP) observed in dispersed oil-water pipe flow without the addition of any drag reduction agent. The main idea is that the DRP depends not only on the effective rheological properties of the dispersion and on the hydrodynamics, but also on wettability effects. The presence of a thin film of water, between the homogenously dispersed flow and the hydrophilic-oilphobic pipe wall, can explain the observed decreases of the two-phase pressure gradient in the liquid-liquid dispersed flows. The transition of the water film flow from turbulent to laminar regime is a possible explanation for the occurrence of the drag reduction phenomenon observed in this work. The relation of the DRP with the Reynolds number of the water film is shown and a possible transition Reynolds number may be around 900. An algorithm to predict the presence of the DRP with good approximation based on the proposed model would be: with the oil holdup and the water cut the slip can be calculated from Eq. (1); with the slip and Fig. 4 the film thickness can be obtained. With Eq. (21) and Fig. 7 it is possible to acquire the Reynolds number of the water film; and with the Reynolds number of the water film and Fig. 6 the occurrence or not of the DRP can be predicted.

The results clearly suggest that the drag reduction phenomenon may be, indeed, related to the existence of a water film between the pipe wall and the homogeneous mixture of oil in water. Although the proposed model is simple, it seems to capture the physics behind the DRP. Nevertheless, more data of the **Do/w H** flow pattern seem to be needed in order to find out more reliable relations for this specific flow pattern.

7. ACKNOWLEDGEMENTS

The authors are grateful to FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo, proc. 2008/06922-9) and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior**)** for the grants. Sincere thanks are extended to José Roberto Bogni for the help in the measurement of the volumetric fractions.

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