AN EXPERIMENTAL STUDY OF UPWARD-VERTICAL OIL-WATER-GAS THREE-PHASE FLOW: FLOW PATTERN, PRESSURE DROP AND VOLUMETRIC PHASE FRACTION

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Abstract. *The presence of water and gas is common in the offshore oil production scenario. Several techniques, such as the gas-lift and the water-assisted technique, utilize gas or water to increase oil-production productivity. Further research on natural or artificial three-phase flow in oil wells is in order. Several studies on three-phase flow have been published over the last years, but the results so far are not as conclusive as those on two-phase flow. In this work some characteristics of three-phase flow are investigated and compared with available data from the literature. New data of pressure drop and volumetric fraction are reported and different oil viscosities are tested. A classification of flow patterns in three-phase flows is presented as a function of superficial velocities. The hypothesis of no-slip between water and oil is evaluated and the benefits of water and gas injection in the reduction of the total pressure gradient are investigated.*

Keywords*: three-phase flow, flow pattern, pressure gradient, volumetric fraction.*

1. NOMENCLATURE

Sow – Slip ratio between oil and water
jw - Superficial water velocity
jo - Superficial oil velocity
jg - Superficial air velocity
FR - Reduction factor
dP/dz - Pressure gradient
εg – Air volumetric fraction
εw – Water volumetric fraction
μo - Oil viscosity

2. INTRODUCTION

From the physical point of view, in oil production scenario the oil is not the only element extracted, but also many other elements such as sand, minerals, gases and water are extracted too. Several of these elements are immiscible, so that multiphase flow is usually present in the production and transportation of petroleum. Thus, the physical understanding of multiphase flow becomes extremely important and strategic in the design and development of oil wells.

Studies of three-phase flows are more limited than the works done on two-phase flow. This is due to the greater complexity of the three-phase flow, and due to the assumption that the mixture of liquids can be treated as a single phase in engineering applications. However, the occurrence of three-phase flows in oil production is common, particularly in offshore oil wells.

In many cases, the three-phase flow is treated as a two-phase flow, in which the liquid phase is considered as a homogeneous pseudo phase composed by oil and water. Many authors support the idea that the slip between oil and water can be neglected. However, other authors argue that in certain situations the slip between the phases should be considered.

Tek (1961) was one of the first to propose a model for water-oil-air flow. Tek (1961) obtained a friction factor for multiphase flow through a vast database based on the hypothesis that the liquid phase was a pseudo phase composed by oil and water. Thus, for pressure-drop calculations the three-phase flow could be reduced to a two-phase flow.

Shean (1976) studied the feasibility of treating water and oil as a pseudo phase without slippage. He obtained the distribution parameter and the weighted average drift velocity for the air phase, as in two-phase flow. The model developed by Shean (1976) has good agreement with experimental data. However, high systematic error occurs comparing the model with experimental data of other authors, indicating that the model is not unified but specific to his test condition. Shean (1976) also notes that the frictional pressure drop is closely related to the continuous phase in contact with the pipe wall.

Lahey et al. (1992) determined the drift-flux parameters for horizontal three-phase flow in several flow patterns based in an extensive experimental data. The model developed by these researchers showed that the drift-flux model can be used in horizontal three-phase flow. However, in the vertical three-phase flow, the volumetric fractions could not be predicted with the drift-flux model directly. Shi et al. (2005) developed a slip model for the vertical three-phase flow based on experimental data collected in ducts of larger diameter. They propose an unified model between two-phase flow (oil/water) and three-phase flow (oil/water/gas) where the two-phase model is changed by a parameter that quantifies the effect of the gas flow in the oil/water flow. Shi et al. (2005) found that for vertical flow the slippage between water and oil is often not appreciable and may be neglected.

Most of works performed in the study of three-phase flow were made for low oil viscosities. The models and conclusions obtained for low viscous oils when applied in high viscous oil generally result in high errors. Moreover, the three-phase flow of very viscous oil has shown to be a promising technique due to the reduction of frictional pressure gradient. Several authors have been studying very viscous oil-water-gas flow in the last years. Bannwart et al. (2005) observed six flow patterns in vertical three-phase flow of high viscous oil and concluded that the increase of the gas superficial velocity and the addition of water decrease the total pressure drop. Trevisan and Bannwart (2006) carried out an extensive experimental investigation about horizontal three-phase flow of a very viscous oil and developed a classification of flow patterns. Trevisan and Bannwart (2006) concluded that the addition of water reduces the three-phase pressure drop due to the water lubricant effect. Bannwart et al. (2009) carried out a similar experimental investigation on liquid-liquid-gas flow and showed that a reduction factor (relation between the total pressure gradient in monophasic oil flow and total pressure gradient in three-phase oil-water-gas flow with the same oil flow rate) in vertical three-phase flow up to 20 can be achieved. In the horizontal three-phase flow, the reduction-factor values reached 30 to 60.

Although several authors have contributed for the understanding of three-phase flow, the investigation of some aspects is in order, such as the influence of slip between the phases and flow pattern on the total and frictional pressure gradients. Therefore, this work aims to contribute for the understanding of upward-vertical oil-water-gas flow through the analysis of new data of pressure drop, volumetric fraction and flow patterns with different viscosities.

3. DESCRIPTION OF EXPERIMENTS

The experimental work was accomplished at the Multiphase-flow loop of the Thermal-fluids Engineering Laboratory of the São Carlos School of Engineering (EESC), University of São Paulo (USP). The facility used was made of a 50-mm-i.d. and 12-m-long vertical borosilicate-glass pipe. Two pumps are used to pump water and oil separately until the nozzles. All the equipment was remotely controlled.

The 3.6m-long test section (between the quick-closing valves QV) was located at 130 diameters from the nozzle injectors and can be seen in the Fig. 1. The nozzle injectors were made in such a way that the oil was injected in the core and water around the core. The air was injected through different injectors to obtain bubble, intermittent and separated flow pattern. Two differential pressure transducers Endress Hauser® (EH) were used to measure the pressure loss in the test section at three different taps (TP1, TP2 and TP3). Through a combination of valves, the pressures taps resulted in two differential-pressure lengths of 1,52m and 2,65m, chosen based on the limits of the sensors. One thermocouple (TE) and one differential pressure transducers (SM) were used to measure the temperature and absolute pressure in line.

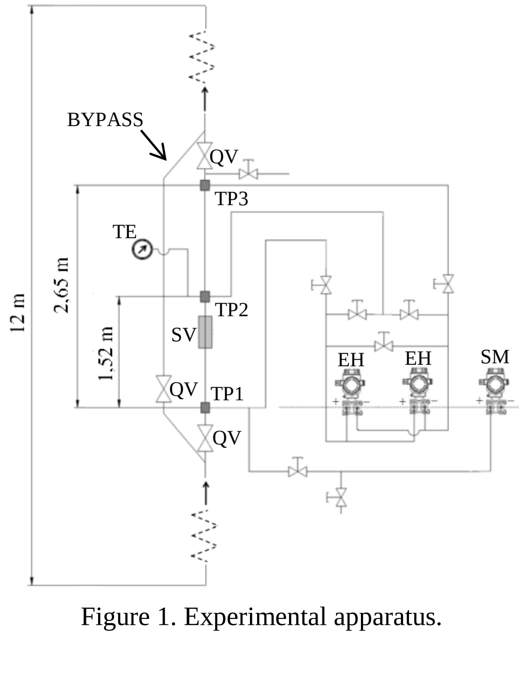

Figure 1. Experimental apparatus.

The experiments consisted in injecting oil, water and air in the pipe at several flow rates. For each combination of flow rates, data of pressure drop and flow rate in the test section were collected. After that, the volumetric fractions were measured by the closing of quick-closing valves (QV). A high-speed camera (SV) was used to capture images for the determinations of flow patterns.

Oil with viscosity of 235cP and density of 830kg/m³ at 25°C, tap water and compressed air were used in the experiments. To obtain different oil viscosities, a heater and refrigeration system were used to control the oil temperature. Thus, oil at 20°C, 25,8°C and 38°C were used with viscosities of 325cP, 220cP and 100cP, respectively. The viscosity values were estimated through the measurement of oil viscosity in a rheometer (Brookfield, LVDV-III), made before and after the experimental campaign.

4. FLOW PATTERNS OBSERVED

Four main gas-liquid flow patterns were observed, considering the liquid mixture and the gas phase: slug flow, churn flow, bubble flow and annular flow. The models developed by Taitel et al. (1980) were able to predict with good accuracy the flow patterns. The water and oil fractions and oil viscosity showed little effect on the gas-liquid flow patterns for each continuous-phase case (phase in contact with the tube wall, which can be either water or oil).

On the other hand, each main flow pattern observed can be subdivided into two secondary flow patterns, which are dependent of the continuous phase. Considering phase inversion, it is possible to conclude that the water cut has a decisive effect on the flow patterns.

As can be seen in the Fig. 2, it is possible to identify some common characteristics. In the flow patterns where the continuous phase is water (Fig. 2 A), the oil flows as spherical oil drops along the entire tube making a cluster of oil drops. However, there is not coalescence of oil drops. With the increase of oil in the liquid fraction, the oil drops get closer, then the liquid phase gradually inverts into water in oil dispersion (Fig. 2 B). At this moment, the oil adheres to the tube wall. This was observed through change of pressure drop tendency and visual analysis of movies made by the high-speed camera. In intermittent flow, the descending flow of liquid around the air bubble was more evident depending on the superficial liquid velocity.

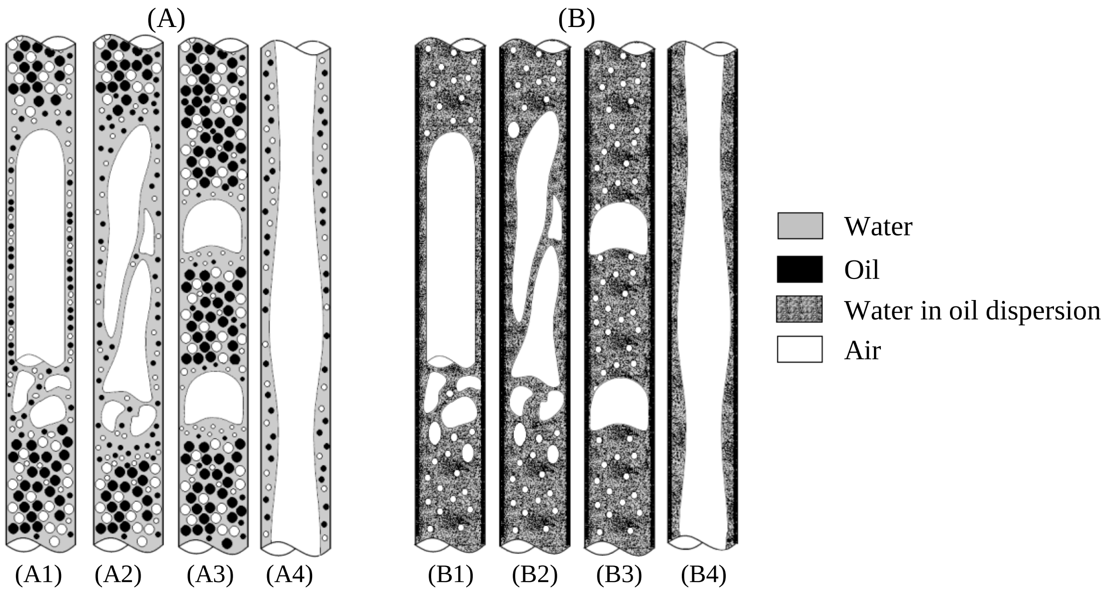

Figure 2. Main flow patterns in water continuous flow (A) and in oil continuous flow (B).

The characteristics of each flow pattern presented in Fig. 2 are:

A1: WPiBoDo: Water continuous phase (W) with Taylor bubbles (Pi), spherical bubbles (Bo) and oil drops (Do).

A2: WChBoDo: Water continuous phase (W) with churn flow (Ch), bubbles (Bo) and oil drops (Do).

A3: WBoDo: Water continuous phase (W) with cap and spherical bubbles (Bo) and oil drops (Do).

A4: WAnBoDo: Water continuous phase (W) with annular flow (An), bubbles (Bo) and oil drops (Do).

B1: OPiBoDi: Oil continuous phase (O) with Taylor bubbles (Pi) and spherical bubbles (Bo) in dispersion of water in oil (Di).

B2: OChBoDi: Oil continuous phase (O) with churn flow (Ch) and bubbles (Bo) in dispersion of water in oil (Di).

B3: OBoDi: Oil continuous phase (O) with cap and spherical bubbles (Bo) in dispersion of water in oil (Di).

B4: OAnBoDi: Oil continuous phase (O) with air in annular flow (An) and bubbles (Bo) in dispersion of water in oil (Di).

5. PRESSURE GRADIENT AND VOLUMETRIC FRACTION

5.1 Pressure gradient

The data of pressure gradient are presented in Fig. 3 to 5. The reduction factor showed on the graphs (FR) is defined as the ratio between the single-phase oil laminar pressure gradient (calculated) and the total three-phase flow pressure gradient (measured), with the same oil flow rate in both cases, Eq. (1). Hence, it is possible to evaluate the effect of water and gas injection on the pressure drop. The data are shown as a function of the gas-oil input fraction (jg/jo), for three different viscosities and different superficial water velocities.

$$FR = \frac{dP/dz_{total}\ single-phase\ oil\ \ flow}{dP/dz_{total}\ three-phase\ \ flow\ (same\ oil\ \ flow\ rate)} \tag{1}$$

In all the cases, it is possible to observe the benefits of the three-phase flow in the reduction of the total pressure gradient. In all viscosities, the reductions factor can reach 5 approximately. In addition, it is possible to observe an existence of a maximum point of reduction factor (Fig. 3, 4 and 5 with jw = 0,05 m/s). This occurs when the oil fraction is high (oil continuous phase). This point indicates that the frictional pressure gradient becomes relevant in the total pressure gradient, showing the increase of the mixture viscosity. For low oil fractions (water continuous phase: Fig. 3, 4 and 5 with jw $\geq$ 0,2 m/s) it is observed a logarithmic increase of the reduction factor, showing an existence of a level (plateau) of maximum efficiency.

The reduction factor tends to the unit in all the curves when the gas injection tends to zero. This shows that, for the flow patterns observed and viscosity values, the water does not cause a significant effect of reducing the total pressure gradient for low mixture superficial velocities. In these cases, the frictional pressure gradient is irrelevant before the total pressure gradient, which is composed mainly by the gravitational pressure gradient.

However, observing the peaks of reduction factor at different water superficial velocities it is possible notice that the lower peaks occur with low water cut (WC). In these cases, the oil becomes the continuous phase and then the frictional pressure gradient increases. The gravitational pressure gradient can increase too due to the increase of the liquid volumetric fraction. This shows an advantage in adding water to reduce the total pressure gradient.

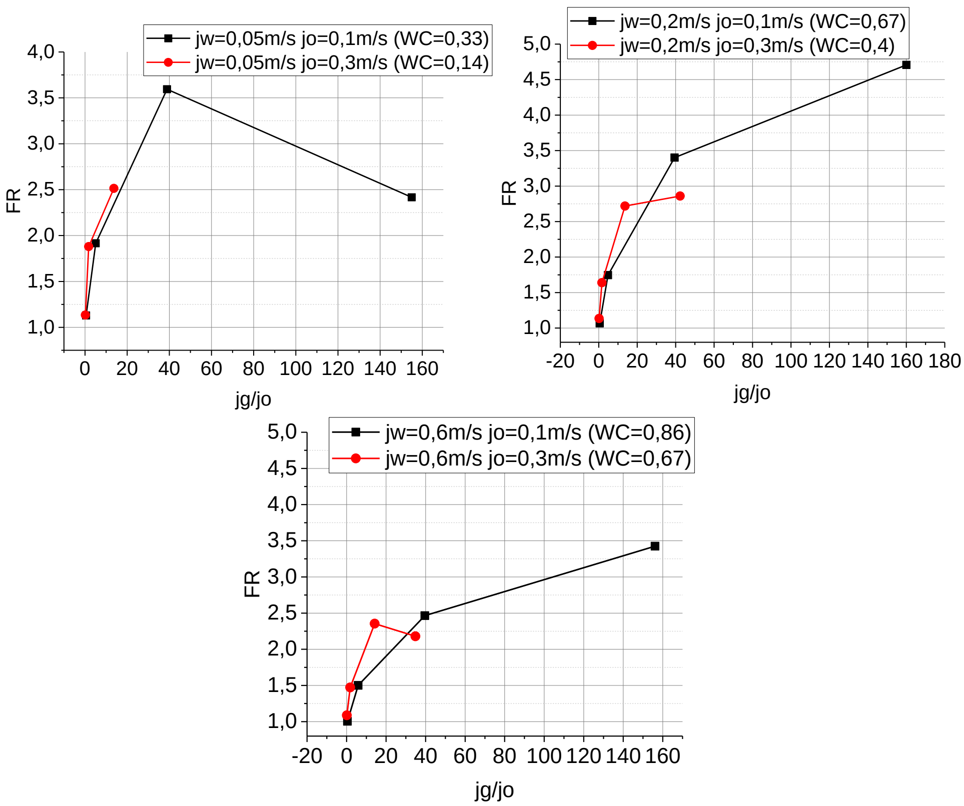

Figure 3. Graphs of reduction factor for μo = 325cP (0,325Pa.s).

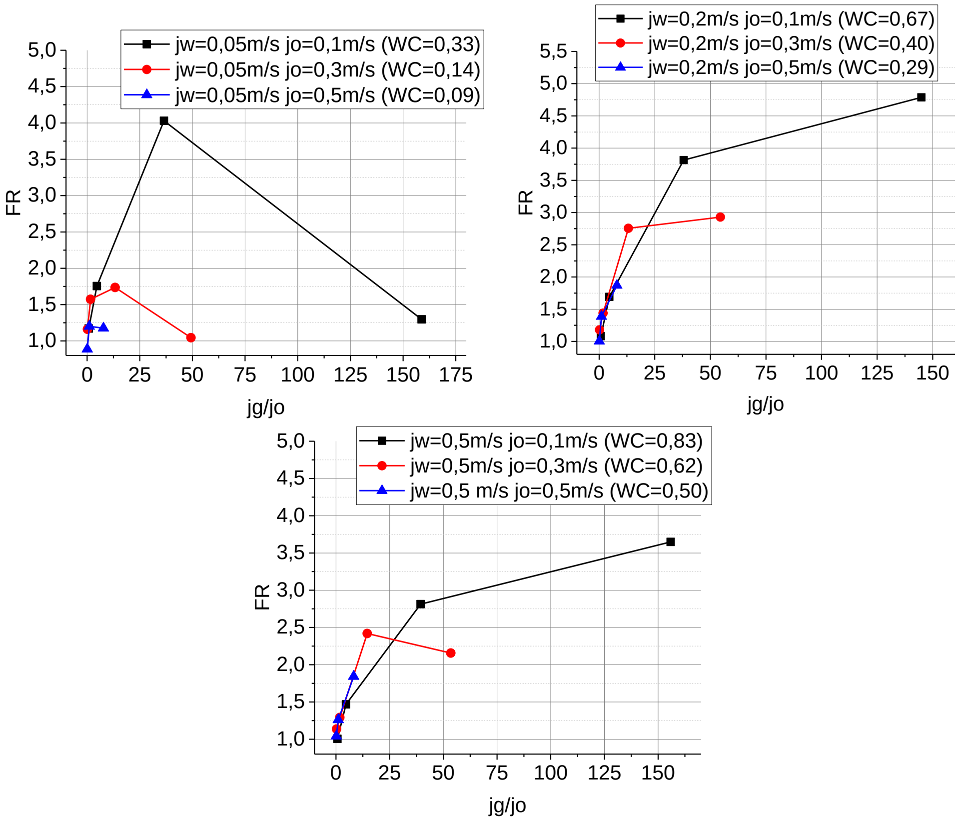

Figure 4. Graphs of reduction factor for μo = 220cP (0,22Pa.s).

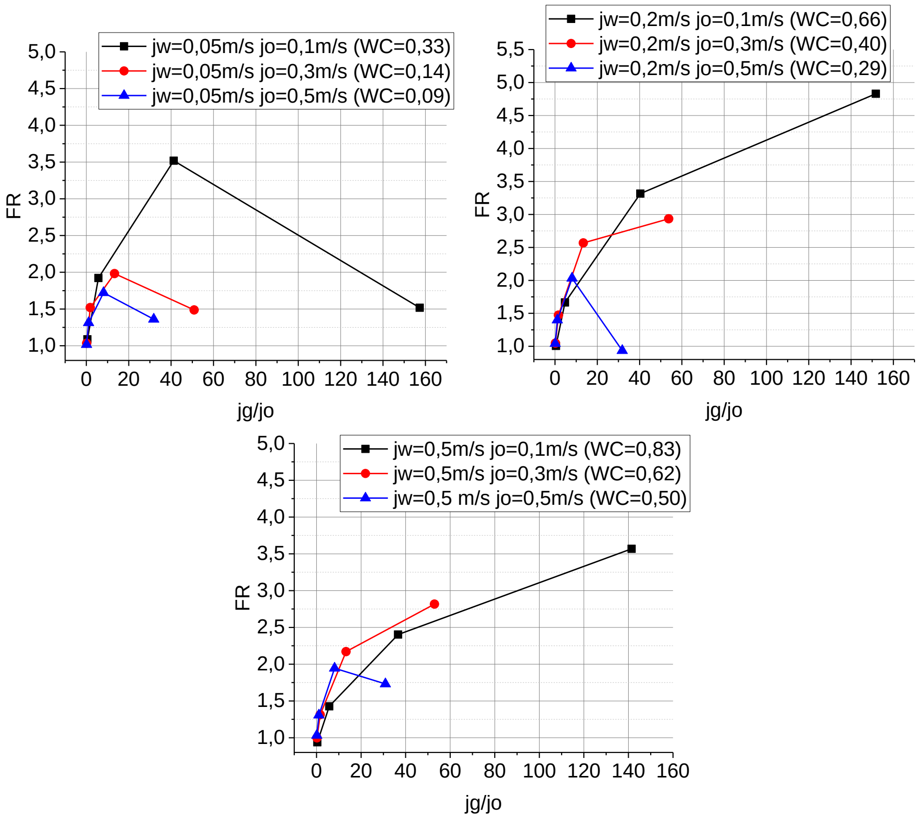

Figure 5. Graphs of reduction factor for μo = 100cP (0,1Pa.s).

Also, it is possible to observe a decrease of the reduction factor with the increase of superficial liquid velocity in the case of water as continuous phase flow (Fig. 3, 4 and 5 with jw ≥ 0,2 m/s). This shows that there is a liquid superficial velocity related to optimum reduction factor. This is clear in the curves (jw = 0,2m/s and jo = 0,1m/s) and (jw = 0,6m/s and jo = 0,3m/s) in the Fig. 3. In these cases, the water cut is the same but the reduction factors decrease with the increase of the input superficial liquid velocity (decrease of jg/jl). In this case, the high superficial liquid velocity increases the liquid volumetric fraction increasing the gravitational pressure gradient and then decreasing the reduction factor.

5.2 Volumetric fraction

Figure 6 shows the drift curves for air and water for the flow pattern WPiBoDo (Fig. 2 A1), which show a linear tendency for each viscosity. According to the drift-flux model, it is possible to determine the drift equations for air and water phases from the weighted drift velocity and the distribution parameter of each curves. With these equations it is possible to predict the three volumetric fractions in the three-phase flow. Further studies are in order.

From Fig. 6, it is possible to observe that the drift curves do not depend significantly on the oil viscosity and water cut.

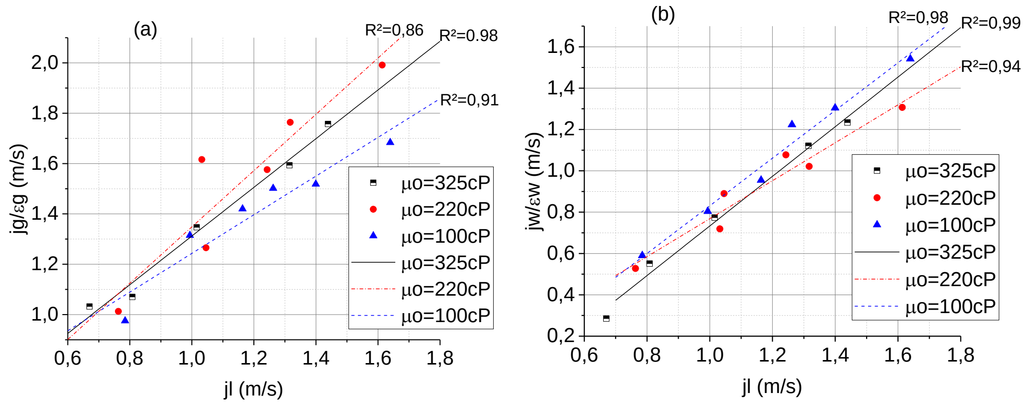

Figure 6. Drift curves for air phase (a) and water phase (b) with jg = 0,5 m/s.

The slip ratio between oil and water for different values of water cut and oil viscosities for the WPiBoDo and OPiBoDi flow patterns can be observed in Fig. 7. As can be seen, for values of water cut greater than 0,3 practically all the points show a slip ratio (Sow) greater than the unit. This show that the oil is not in contact with the tube wall and, consequently, it flows faster than water. On the other hand, for water cuts less than 0,3 the oil gets in contact with the tube wall and then the water flows faster than the oil. It is observed in Fig. 7 that the greater the fluid viscosity, the smaller the water cut at which phase inversion occurs.

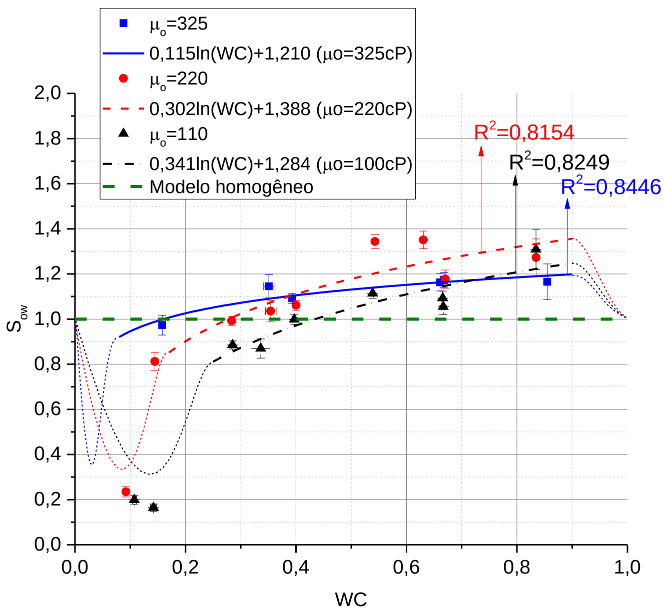

Figure 7: Slip between oil and water for jg = 0,5m/s.

6. CONCLUSIONS

New data about flow patterns, pressure drop and volumetric fractions in viscous oil-water-air vertical pipe flow are presented. The general conclusions about this experimental work are listed as following.

1. Reduction factors up to 5 were obtained in the experiments showing that the use of gas and water is promising to reduce the total pressure gradient in vertical pipe flows with viscous oil.
2. Eight flow patterns and their characteristics were reported. The water and oil fractions of injection and oil viscosity showed little effect on the gas-liquid flow patterns.
3. Drift equations for both water phase and air phase are offered. However, it is still necessary further analysis of the interference of the various three-phase-flow factors in the drift equations.
4. The slip ratio between oil and water and the total pressure gradient show evident and clear dependency on the phase in contact with the tube wall.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE