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EXPERIMENTAL STUDY FOR CHARACTERIZATION OF OIL-WATER FLOW PATTERNS IN HORIZONTAL PIPES BASED ON VISUALIZATION AND PRESSURE-GRADIENT ANALYSIS

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Abstract. *The characterization of liquid-liquid flow patterns is important for the oil industry, especially in situations where water is used as an artificial means of facilitating the oil production and transport. This article investigates the flow of oil-water in horizontal steel pipes, with 51.5 mm internal diameter (i.d.), evaluating the effects of viscosity on the formation of flow patterns. The mixture pipe flow was studied at two different average temperatures, 26 ºC and 45 ºC, which provided different viscosity and density ratios. The experimental procedure consisted of fixing a given superficial oil velocity with subsequent variation of the water superficial velocity, where flow patterns, pressure gradients and other parameters were recorded. The observed flows were recorded with a high-speed camera. The flow patterns were initially visually classified, according to the classification proposed by Ibarra* et al. *(2014), and subsequently, this classification was refined by analyzing the variation of pressure-gradient. When analyzing the experiments conducted with oil of lower viscosity, neither Trallero's (1995) nor Ibarra* et al. *(2014) classifications of flow patterns were in accordance with the experimental pressure-gradient curves. It was noticed that at low superficial velocities of water there was a pressure-gradient drop attributed to a change in the flow pattern. The analysis of these flow patterns showed the possible need to modify the flow-pattern classification model proposed by Ibarra* et al. *(2014), adding the flow pattern DO/W&O, observed by Tan* et al. *(2015). The theoretical model of Trallero (1995) showed unsatisfactory predictions of the areas of occurrence of some flow patterns. The dimensionless flow-patterns map proposed by Ibarra* et al. *(2015) was somehow consistent with the experimental results the flow with low oil viscosity. However, in the experiments with higher oil viscosity, there was a significant discrepancy.*

Keywords: *two-phase flow, oil-water flow, flow patterns, horizontal pipe, oil viscosity effect*

1. INTRODUCTION

Some countries recognize the strategic importance of developing technologies aimed at multiphase flow systems. The industrial use of such systems requires methods for predicting their behavior, this explains the high number of scientific publications in this field in the last 50 years (Kolev, 2015).

The flow of petroleum, from the well to primary treatment facilities, is formed by the flow of oil, gas, water, emulsions and sediments, and in general, the latter being disregarded in multiphase modeling (Andreolli, 2016). After the pre-treatment of the oil, means are needed to transport it economically to the refineries. With reduction of viscosity being the major benefit and with abundance of water supply, the formation of oil-water mixtures proves to be an attractive option for pipeline transportation (Loh and Premanadhan, 2016). Accurate knowledge of behavior of the oil-water flow in pipelines is crucial to design and optimize production, transportation, and processing facilities (Ismail *et al.*, 2015).

The interest in liquid-liquid flow has increased since off-shore oil production is on the rise over the last decades, even though investigations on such flows are not as common as those on gas-liquid flow (Castro and Rodriguez, 2015).

Two immiscible liquids assume different geometrical and topological configurations of the phases in the pipe, defined as flow patterns, inside a pipe, due to the differences between their physical properties (Elseth, 2001). These flow structures differ from each other in the spatial distribution of the interface, resulting in different flow characteristics, such as velocities and phase distribution.

Often the characterization of liquid-liquid flows includes, besides flow pattern identification, the analysis of flow patterns transition, estimation of effective viscosity and pressure drop, identification of phase-inversion, droplet formation and droplet sizes distribution (Ahmed and John, 2017).

In this context, understanding different flow patterns in liquid-liquid systems is of great importance for predicting the holdup and pressure gradient because each flow pattern has unique hydrodynamic flow characteristics (Nguyen, 2016). The hydrodynamic behavior of liquid-liquid flows is more complex than that of gas-liquid flows, because of density ratio, viscosity ratio, interfacial forces, and pipe wettability. This means that a significant number of different flow patterns can be obtained from different fluid properties and pipe characteristics (Ibarra *et al.*, 2014).

This work presents oil-water flow patterns observed in experiments carried out in horizontal 2" galvanized steel pipes, for a range of temperature conditions, which allowed the oil viscosity variation and the formation of different flow patterns. The main objectives of this work are: to classify the flow patterns according to the classification proposed by Ibarra *et al.* (2014) through visual analysis; then, reassess whether that classification is consistent with the changes of trend of the pressure-gradient curves obtained in the experiment. Finally, if necessary, reclassify flow patterns. In addition, the predictions of the flow-pattern transition model of Trallero (1995) and the dimensionless flow-pattern map proposed by Ibarra *et al.* (2015) are evaluated.

1.1 Definitions

Given a two-phase oil-water flow, which occurs in a pipe with cross-sectional area A, the average superficial velocities of the oil (j_o) and water (j_w) are defined, respectively, by

$$j_o = \frac{Q_o}{A} \tag{1}$$

$$j_w = \frac{Q_w}{A} \tag{2}$$

where Q_o and Q_w constitute, respectively, the average volumetric flow rates of the oil and water phases. The mixture velocity is defined by $j = j_o + j_w$.

Oil injection fraction or oil cut (OC) and water injection fraction or water cut (WC) are determined, respectively, by equations (3) e (4).

$$OC = \frac{Q_o}{Q_o + Q_w} \tag{3}$$

$$WC = \frac{Q_w}{Q_o + Q_w} \tag{4}$$

The dimensionless number of Eötvös (E_o) and mixture Reynolds number (Re_m) are defined by the equations (5) e (6), respectively.

$$E_o = \frac{(\rho_w - \rho_o)gD^2}{\gamma} \tag{5}$$

$$Re_m = \frac{\rho_m j D}{\mu_m} \tag{6}$$

where ρ_o, ρ_w, μ_o and μ_w are oil and water densities, oil and water viscosities, respectively, g is the gravity, D is the pipe i.d. and γ is the interfacial tension. ρ_m and μ_m constitute, respectively, density and viscosity of the oil-water mixture, which, according to Ibarra *et al.* (2015), are determined by the equations (7) and (8), respectively.

$$\rho_m = \rho_w WC + \rho_o(1 - WC) \quad (7)$$

$$\mu_m = \mu_w WC + \mu_o(1 - WC) \quad (8)$$

Superficial velocities and injection fractions are often used in the axes of experimental flow pattern maps. The flow pattern map proposed by Ibarra *et al.* (2015) uses the dimensionless parameters WC, E_o and Re_m.

1.2 Oil-Water Flow Patterns in Horizontal Pipes: Literature Review

There is a relative consensus among researchers that liquid-liquid flow patterns can be classified into four basic categories: Stratified Flow - S; Disperse Flow - D; Intermittent Flow- IT; and Core-Annular Flow - CAF, according Brauner (2002), Ibarra *et al.* (2014) and Tan *et al.* (2018). However, each category can be subdivided into flow patterns with specific topological characteristics. The stratified category can be divided into smooth stratified (smooth interface), wavy stratified (wavy interface) and stratified with mixing at the interface (droplets at the interface). The disperse category can be divided into oil dispersed in water, oil dispersed in water and water layer, water dispersed in oil, water dispersed in oil and oil layer e dual continuous (oil dispersed in water and water dispersed in oil). In general, the intermittent category is formed by the occurrence of lumps and large slugs (elongated or spherical) of oil in water continuous phase. The core-annular category represents a condition where one of the liquids forms the core (oil) and the other liquid flows in the annulus (water). The core-annular flow can be divided into annular flow and semi-annular flow, or else, core-annular flow (core flow), core wavy flow or perfect core-annular flow. It is emphasized that different researchers may divide these flow categories or flow patterns in other ways, using their own nomenclatures.

The main techniques for identifying and characterizing flow patterns in liquid-liquid flows are: Visual Observation – VO; High Frequency Impedance Probe – HFIP; Conductivity Analysis – CA; Conductance Probe – CP; Differential Pressure Transducers (Pressure Gradient Test) – DPT; Gamma-Ray Densitometer – GRD; High-Speed Photography – HSP; Laser Doppler Anemometer – LDA; Planar Laser-Induced Fluorescence – PLIF; Particle Image Velocimetry – PIV; and Particle-Tracking Velocimetry – PTV (Ibarra *et al.*, 2014).

Table 1 shows, in chronological order, some experimental studies on oil-water flows in horizontal pipes.

Russell et al. (1959) identified three flow patterns and inferred that increasing the flow rate increases the turbulence thus promoting droplet formation.

Charles et al. (1961) studied oil and water flows with liquids with close densities; they did not observe the occurrence of the stratified flow patterns.

Oglesby (1979) carried out experiments with oils of three different viscosities, indicating the occurrence of fourteen flow patterns, classified in three groups: segregated, oil dominant e water dominant. The terms *oil dominant* defines the flow conditions when the oil is the continuous phase and the water is the dispersed phase. On opposite, the term *water dominant* refers to water as the continuous phase and oil as the dispersed phase.

Arirachakaran (1983) used two different pipe diameters to perform experiments, with oils of six different viscosities, identified eight different flow patterns. These researchers established that flow patterns depend on mixture velocity, input water fraction, and oil viscosity. They also studied the inversion of the phases, in which the water cut was gradually increased, in such a way that the flow pattern of water dispersed in continuous oil phase was inverted, forming the flow pattern of oil dispersed in continuous phase of water. According to Oliveira (2019), the correlation proposed by Arirachakaran (1983), to predict the point of phase inversion, shows reasonable agreement with the experimental databases analyzed in his work.

Trallero (1995) classified the flow patterns into six basic types: Stratified Flow (ST); Stratified Flow with Mixing at the interface (ST&MI); Dispersion of Oil in Water and Water (DO/W&W); Oil in Water Emulsion (O/W); Water in Oil Emulsion (W/O); and Dispersion of Water in Oil and Dispersion of Oil in Water (DW/O&DO/W). Based on Kelvin-Helmholtz instability theory and theories of maximum and minimum sizes of oil drops in continuous water, he also developed a theoretical model to determine the boundaries transitions between the flow-patterns (Trallero's boundaries). The Author built maps that localize the areas of occurrence of all his flow patterns, as shown in Figure 1. The comparison of flow patterns maps obtained experimentally with the predicted transition boundaries of Trallero (1995) is observed in many articles. In Nädler and Mewes (1995) there is only one difference; the latter observed the occurrence of an additional flow pattern, called three layers (3L), which has the following topological characteristic: oil-in-water dispersion at the top, water-in-oil dispersion layer at the middle and water layer in the bottom of the pipe. Nädler and Mewes (1995) observed a peak in pressure gradient at the point of phase inversion.

Ibarra *et al.* (2015) proposed that the flow patterns maps could be standardized for horizontal liquid-liquid flows, adopting dimensionless groups based on the mixture Reynolds number (Re_m), Eötvös number (E_o) and Water Cut (WC). Figure 2 illustrates the standard flow pattern map proposed by Ibarra *et al.* (2015), contemplating the following flow patterns: Stratified flow (ST); Stratified flow with droplets at the interface (SWD), Dual Continuous (DC), Dispersion of oil in water with water layer (DO/W & W) and Dispersed (DO/W or DW/O).

Table 1. Experimental works in oil-water flows in horizontal pipes.

Authors	D [*mm*]	Pipe material	ρ_o [*kg/m³*]	μ_o [*mPas*]	Controlled flow parameters	Observed categories[1] (Techniques)[2]
Russel et al. (1959)	25.4	clear thermoplastic	838	18	j_o $(0.04 \leftrightarrow 1.08)^3$ j_w $(0.01 \leftrightarrow 1.00)$	S, D (VO)
Charles et al. (1961)	25.4	clear thermoplastic	998	6.3 16.8 65.0	j $(0.05 \leftrightarrow 2.09)$ OC $(0.09 \leftrightarrow 0.91)$	D, IT, CAF (VO)
Oglesby (1979)	41.0	clear thermoplastic	851 861 868	32 61 167	j_o $(0.07 \leftrightarrow 2.71)$ j_w $(0.03 \leftrightarrow 3.19)$	S, D, IT, CAF (VO)
Arirachakaran (1989)	38.1 25.4	steel	867	5; 58; 84 / 115; 237; 2,116	j $(0.46 \leftrightarrow 3.66)$ OC $(0.10 \leftrightarrow 0.95)$	S, D, IT, CAF (VO)
Trallero (1995)	50.1	acrylic	884	28.8	j $(0.25 \leftrightarrow 3.00)$ OC $(0.00 \leftrightarrow 1.00)$	S, D (VO)
Nädler e Mewes (1995)	59.0	perspex	841	31.0	j $(0.09 \leftrightarrow 1.64)$ OC $(0.01 \leftrightarrow 0.95)$	S, D (VO)
Angeli e Hewitt (1998; 2000)	24.0 24.3	acrylic and stainless steel	801	1.6	j $(0.25 \leftrightarrow 4.00)$ OC $(0.05 \leftrightarrow 0.85)$	S, D (HSC and HFIP)
Soleimani (1999)	24.3	stainless steel	801	1.6	j $(0.24 \leftrightarrow 3.50)$ WC $(0.10 \leftrightarrow 0.96)$	S, D (HSP)
Elseth (2001)	58.0	acrylic	790	1.6	j $(0.04 \leftrightarrow 3.00)$ WC $(0.00 \leftrightarrow 1.00)$	S, D (GRD and LDA)
Bannwart et al. (2004)	28.4	glass	926	488	j_o $(0.01 \leftrightarrow 2.50)$ j_w $(0.04 \leftrightarrow 0.50)$	S, D, IT, CAF (VO and HSC)
Rodriguez and Oliemans (2006)	82.8	steel	830	7.5	j_o $(0.02 \leftrightarrow 3.00)$ j_w $(0.02 \leftrightarrow 2.55)$	S, D (HSP, GRD)
Yusuf et al. (2011)	25.4	acrylic	875	12	j_o $(0.06 \leftrightarrow 1.20)$ j_w $(0.10 \leftrightarrow 2.10)$	S, D, IT, CAF (VO and HSC)
Ibarra et al. (2015)	32.0	acrylic	825	5.4	j $(0.25 \leftrightarrow 1.25)$ WC $(0.10 \leftrightarrow 0.90)$	S, D (HSP)

[1]The categories observed experimentally are: S – Stratified; D – Dispersed; IT – Intermittent; and CAF – Core-Annular Flow.
[2]As described earlier in this article, these acronyms represent techniques for identifying and characterizing flow patterns.
[3]The scheme $x(x_1 \leftrightarrow x_2)$ represents the parameter x and the interval between maximum and minimum values x_1 and x_2.

Angeli and Hewit (1998) and Angeli and Hewit (2000) carried out two studies on two types of pipes, one made of steel and the other of acrylic, both with approximately similar diameters. These researchers identified six types of flow patterns: Stratified Wavy (SW); Stratified Wavy with Drops (SWD); Three Layer (3L); Stratified Mixed/Water (SM/water); Stratified Mixed/Oil (SM/oil); and Mixed (M). Those researchers mapped the flow-pattern transitions as a function of the water cut and the mixture velocity. Angeli and Hewit (2000) noticed some differences in the flow patterns maps related to stainless steel and acrylic tubes, which were attributed to the surface roughness and wettability parameters. The increase in surface roughness in a pipe tends to amplify the turbulent effects, facilitating the mixing of phases. The oil has greater wettability on acrylic than on stainless steel, which tends to increase the possibility of the occurrence of continuous oil phases in the acrylic pipe. Soleimani (1999) used part of Angeli and Hewit (1998) experimental facilities, but characterizing the flow patterns only through the HSP technique. It was based on a large number of experimental points, generating a very detailed flow pattern map for the specific conditions of his experiments.

Elseth (2001) used low viscosity oil in its experiments, identifying eleven flow patterns. Besides that, that researcher sought to determine the characteristics of the turbulence distribution and velocity profiles.

Bannwart *et al.* (2004) conducted studies with high viscosity oil, classifying the flow patterns observed in four categories: Stratified (E); Bubbles/Stratified (BE); Dispersed Bubbles (BD); and Annular (A). These researchers reported that core-annular flow would tend to occur in a pipe when the two fluids have very dissimilar viscosities but relatively close densities. This situation is often satisfied by heavy oils, crude or refined, since their viscosity is greater than 100 $mPas$

and density is close to water.

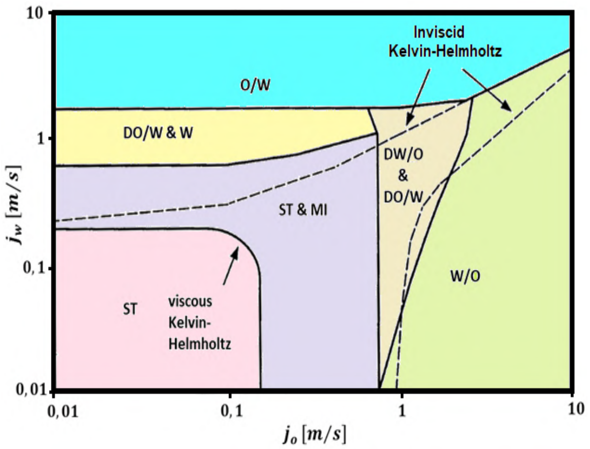


Figure 1. Theoretical map developed by Trallero (1995), contemplating the transition boundaries between the flow patterns for horizontal oil-water flows.

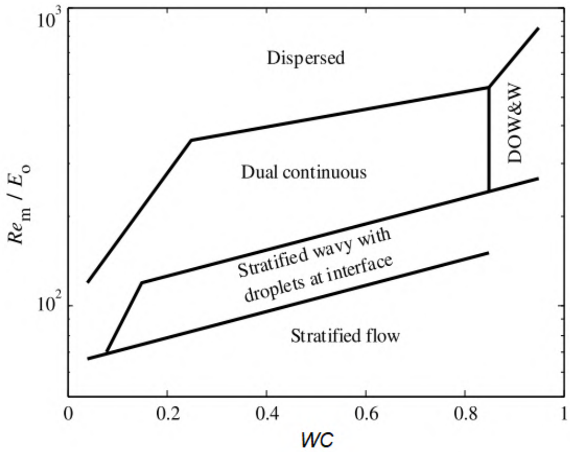


Figure 2. Dimensionless map of flow patterns in horizontal liquid-liquid flows, proposed by Ibarra et al. (2015).

Rodriguez and Oliemans (2006) conducted low-viscosity-oil/brine two-phase flow experiments in a pipe with 82.8 mm *i.d.*, which is relatively large when compared to other experimental studies. Those researches observed that flow patterns are reasonably well described by the Trallero's (1995) theoretical flow-pattern map. The only difference was the observation of wavy-stratified flow, but at inclinations different from horizontal.

Yusuf *et al.* (2012)) studied the effect of oil viscosity on the flow structure and pressure drop gradient in acrylic pipes, with 25.4 mm in diameter. They identified six different flow patterns: Stratified (ST); Dual Continuous (DC); Annular (AN); Bubbly (Bb); Dispersed Oil in Water (DO/W); and Dispersed Water in Oil (DW/O). They compared the results of their experiments with the results obtained by other researchers, who used acrylic pipes and sought inferences about the effects of viscosity on flow patterns or on pressure-gradient. They evaluated the models to predicts the phase inversion and the domain of occurrence of each flow pattern as the superficial velocities of the phases varied.

Ibarra *et al.* (2014), when analyzing a significant amount of experimental work, on horizontal liquid-liquid flow or slightly inclined pipes, proposed a new way of classifying the flow patterns, aiming at standardizing their nomenclature. The nine basic types of flow patterns proposed by them are shown in Figure 3. When comparing the classification of flow patterns proposed by Ibarra et al. (2014) with the classification of Trallero (1995), it is noticed that there is similarity between the flow patterns ST (ST), SWD (ST&MI), DO/W&W (DO/W&W), DO/W (O/W) and DW/O (W/O), DC (DW/O&DO/W).

Tan *et al.* (2015) showed that, in flows at low superficial water velocities, an increase in oil injection fraction leads to change in the SWD flow pattern to a pattern called here DO/W&O. In DO/W&O flow pattern, oil flows in the upper region of the pipe to form an oil layer, whereas the oil droplets are dispersed in water at the low region of the pipe. According to these researchers, DO/W&O flow pattern is not listed in Trallero's (1995) flow pattern observations as an individual flow pattern, because it was included in the DW/O&DO/W flow pattern. However, DO/W&O flow is slightly different from DW/O&DO/W flow, because it occurs at lower water superficial velocity compared with DW/O&DO/W flow pattern, thus the water phase has insufficient dynamic energy to break the continuous oil layer and flows underneath the oil layer with entrained oil droplets.

Shi and Yeung (2016) suggested that the flow patterns can be studied in groups, related to the viscosity and density ratios between the oil and water phases. The reason for this argument are the discrepancies observed in the topology of the oil phase, especially when comparing flow patterns in low, high and ultra-high viscosity oils.

Brauner (2002), Xu (2007), Ibarra *et al.* (2014), Ismail *et al.* (2015) and Ahmed and John (2017) presented reviews on the main studies on liquid-liquid two-phase flows, mainly regarding oil-water system.

2. EXPERIMENTAL SETUP

The experiments with oil-water flows occurred in two campaigns, these being defined by: Campaign 2" Cold Mixture and Campaign 2" Hot Mixture. The terms 2" indicate the nominal diameter of the pipe, while Cold Mixture and Hot Mixture establish the temperature range of the oil-water mixture, as described in Table 2.

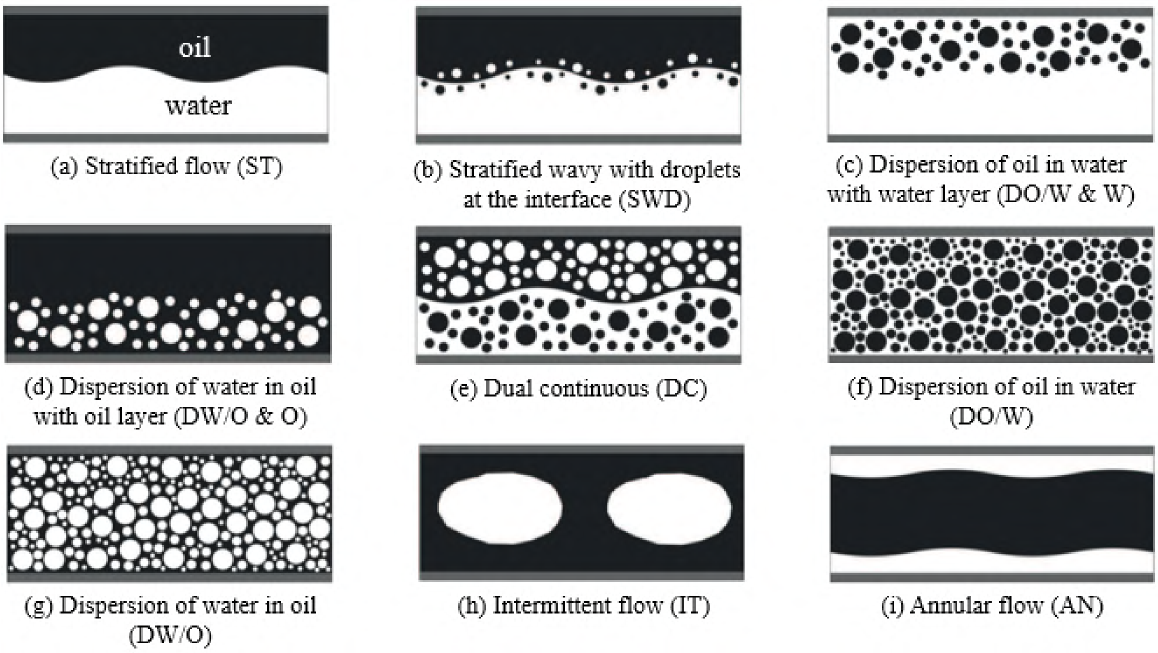


Figure 3. Flow patterns proposed by Ibarra *et al.* (2014), where the white color represents water and the black color oil (Adapted from Ibarra et al., 2014).

The experiments were conducted in the facilities of the Experimental Laboratory of Petroleum - LabPetro, located at the Center for Petroleum Studies - CEPETRO, of the University of Campinas - UNICAMP. The LabPetro experimental facilities have oil and water storage and separation tanks, oil and water pumps with volumetric flow rates controlled by frequency variable drivers, oil and water Coriolis mass flow meters, oil and water heat exchangers, absolute and differential pressure transducers, Pt100 RTD, water-in-oil concentration meter, quick-closing valves, chokes, flow and safety control valves. The flow control and the collection of experimental data occur through mechanical, electromechanical and electronic systems, the latter two being integrated into a control panel developed with the LabVIEW® software. A visualization section made of acrylic allows flow filming. A high-speed camera records the flow. The experiments took place on a $15\ m$ long horizontal pipes, made of galvanized steel. CEPETRO also has laboratories specialized in physical and chemical analysis for petroleum and related products. The details of the equipment, instruments, sensors and actuators that make up the experimental installations, including the measurement uncertainties specific to each element, are described by Ruschel (2020).

Table 2. Synthesis of experimental campaigns for two-phase oil-water flows.

Parameter	Campaign 2" Cold Mixture	Campaign 2" Hot Mixture
Number of experiments	54	63
$D\ [mm]$	51.5	51.5
$j_o\ [m/s]$	$(0.1 \leftrightarrow 1.1)^1$	$(0.2 \leftrightarrow 1.0)$
$j_w\ [m/s]$	$(0.1 \leftrightarrow 1.5)$	$(0.1 \leftrightarrow 1.3)$
Temperature [ºC]	$26\ (24 \leftrightarrow 35)^2$	$45\ (42 \leftrightarrow 47)$
Oil viscosity $[mPas]$	$189\ (112 \leftrightarrow 219)$	$63\ (58 \leftrightarrow 73)$
Water viscosity $[mPas]$	$0.89\ (0.75 \leftrightarrow 0.93)$	$0.65\ (0.64 \leftrightarrow 0.67)$
Oil density $[kg/m^3]$	$865\ (859 \leftrightarrow 866)$	$853\ (852 \leftrightarrow 855)$
Water density $[kg/m^3]$	$997\ (994 \leftrightarrow 997)$	$991\ (990 \leftrightarrow 992)$
Interfacial tension $[mN/m]$	$36\ (34 \leftrightarrow 37)$	$31\ (30 \leftrightarrow 31)$
Percentage of water in oil[3]	$5.6\ (0.5 \leftrightarrow 13.9)$	$2.9\ (0.2 \leftrightarrow 10.2)$

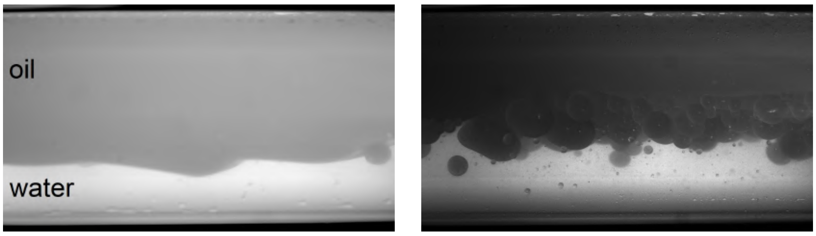
[1] The scheme $(y_1 \leftrightarrow y_2)$ represents the interval between minimum and maximum values y_1 and y_2 for that parameter.
[2] The scheme $z(z_1 \leftrightarrow z_2)$ represents the average value of the parameter z and its interval between minimum and maximum values z_1 and z_2.
[3] Laboratory analyzes indicated Newtonian rheological behavior, for temperatures of 15 ºC to 55 ºC and values of up to 15% water emulsified in oil.

The experimental procedure is based on fixing the superficial velocity of the oil phase, followed by an increase in the superficial velocity of the water phase, in such a way that experimental points are determined for a steady flow condition.

With the application of this procedure, flow patterns maps are obtained, defined by the superficial velocities of the phases, depending on the temperature of the mixture.

3. EXPERIMENTAL RESULTS

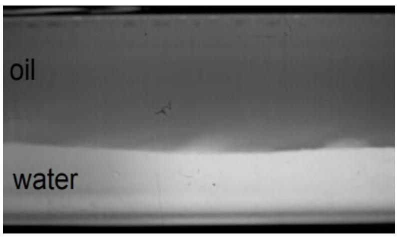
In Campaigns 2" Cold Mixture and 2" Hot Mixture, five and four different of flow patterns were identified, respectively, as shown in Figures 4 and 5. Initially, the flow patterns were classified according to Ibarra *et al.* (2014). Subsequently, this classification was reevaluated by analyzing the pressure-drop data, according to the procedure adopted by Castro (2013), where changes in pressure gradient trends may indicate transition between flow patterns.



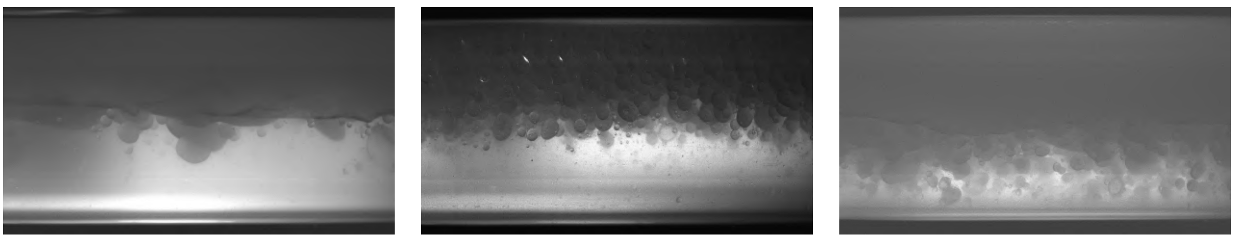
(a) ST ($j_o = 0.11 m/s, j_w = 0.34 m/s$). (b) SWD ($j_o = 0.19 m/s, j_w = 0.33 m/s$).

(c) DO/W&W ($j_o = 0.41 m/s, j_w = 0.43 m/s$). (d) DO/W ($j_o = 1.08 m/s, j_w = 1.32 m/s$). (e) AN ($j_o = 1.03 m/s, j_w = 0.47 m/s$).

Figure 4. Sample images of the five types of flow patterns to Campaign 2” Cold Mixture.



(a) ST ($j_o = 0.11 m/s, j_w = 0.21 m/s$).



(b) SWD ($j_o = 0.20 m/s, j_w = 0.53 m/s$). (c) DO/W&W ($j_o = 0.32 m/s, j_w = 0.81 m/s$). (d) DO/W&O ($j_o = 0.84 m/s, j_w = 0.54 m/s$).

Figure 5. Sample images of the four types of flow patterns to Campaign 2” Hot Mixture.

In Figure 5(d) there is a picture of a flow pattern that does not belong to the group of flow patterns defined by Ibarra *et al.* (2014). Initially, it was visually classified as SWD; however, a further analysis based on the variation of the pressure-gradient data indicated that possibly classification was not correct. The reading of the work of Tan et al. (2015) provided the necessary background to reclassify the flow pattern 5(d) as DO/W&O.

In Figures 6, for the Campaign 2” Cold Mixture, the superficial velocity of the oil was set at approximately $0.1\ m/s$. Sudden drops in the pressure-gradient values were observed by increasing the water superficial velocity, as well as changes in the curve trends, and it can be associated with transitions between the flow patterns ST to SWD, SWD to DO/W&W and DO/W &W to DO/W. A similar behavior was observed in Campaign 2" Hot Mixture, Figure 7.

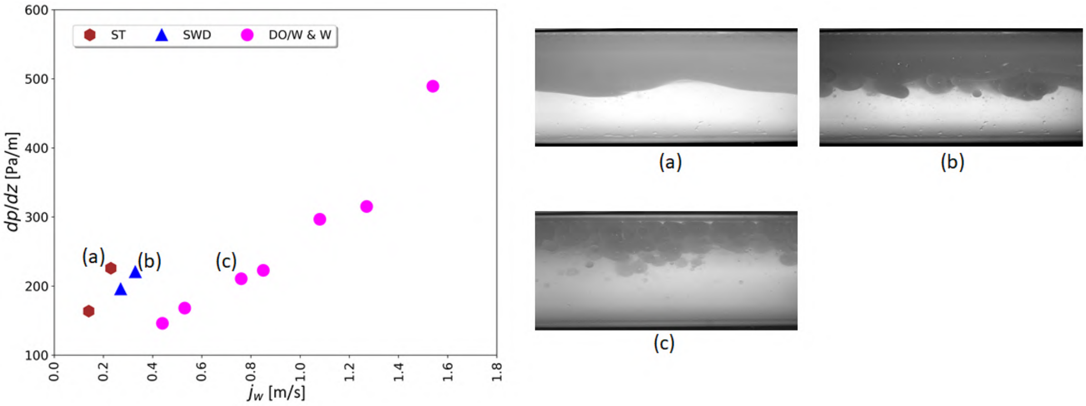


Figure 6. Transition between flow patterns ST to SWD and SWD to DO/W&W for an average superficial oil velocity of $0.1m/s$, in Campaign 2" Cold Mixture.

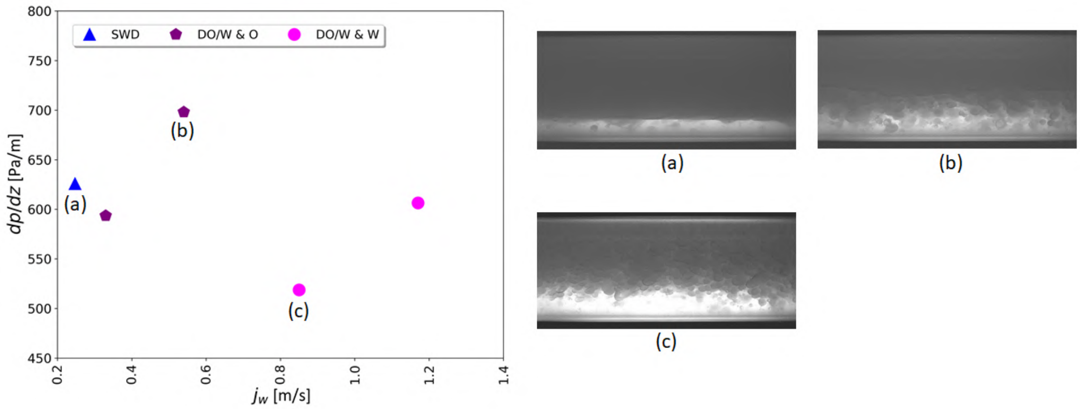


Figure 7. Transition between flow patterns SWD to DO/W&O and DO/W&O to DO/W&W for an average superficial oil velocity of $0.8m/s$, in Campaign 2" Hot Mixture.

In the present work we propose that the visual and pressure-gradient analyzes should-complementary, providing a better characterization of the flow patterns than the isolated use of these techniques.

Figures 8-11 show the flow patterns maps, obtained experimentally, where the reclassification procedure has already been carried out through pressure-gradient data analysis, in Campaigns 2" Cold Mixture and 2" Hot Mixture, for two different coordinated systems: the traditional map j_o versus j_w used by Trallero (1995) and the dimensionless map WC versus Re_m/E_o proposed by Ibarra *et al.* (2015). It is noteworthy that, due to operational limitations of the experimental installation, especially when flowing oil of higher viscosity, it was not possible to obtain experimental points for the flow patterns DC and DW/O.

In Figures 8 and 9, the points referring to the flow patterns are classified according to Ibarra *et al.* (2014), with the exception of the flow pattern DO/W&O, while the black lines define the transitions boundaries between flow patterns proposed by the Trallero's (1995) model, as shown in Figure 1. The adherence of the experimental results to the Trallero's (1995) model is unsatisfactory, and an explanation is that his model was developed for flow water and low viscosity oil.

Again, in Figures 10 and 11, the points referring to the flow patterns are classified according to Ibarra *et al.* (2014), with the exception of the flow pattern DO/W&O. The adherence of the experimental results to the Ibarra *et al.* (2015) flow pattern map is satisfactory for the case of flow of oil low viscosity, but it is just reasonable for high viscosity oil. To simplify the analysis of the Figures 10 and 11, comparing it to Figure 4, that the flow patterns AN and DO/W&O could according to Yusuf *et al.* (2012) and Tan *et al.* (2015), respectively, observed as forms related to the Dual Continuous flow patterns. The experimental results referring to the points within the hatched area of Figure 10 are currently going through further analysis, which may indicate the need to include a new flow pattern, not proposed by Ibarra *et al.* (2014).

4. CONCLUSIONS

Experiments in oil-water two-phase flow were conducted in horizontal steel pipes, with $51.5\ mm$ *i.d.*, for two different average mixture temperatures, 26 ºC (Cold Mixture) and 45 ºC (Hot Misture). The average oil viscositiy at 26 ºC was 189 $mPas$ and at 45 ºC was 63 $mPas$. The conclusions regarding this work are:

- The characterization of the flow patterns for the oil-water system based only on visual analysis of the flow can lead to

an incorrect characterization of these flow patterns. The analysis of the pressure-gradient data together with the visual observations of the oil-water flows showed the possible need to modify the flow-pattern classification proposed by Ibarra *et al.* (2014), by adding the flow pattern DO/W&O observed by Tan *et al.* (2015).
- The theoretical model of Trallero (1995) that determines the boundary transitions between oil-water two-phase flow patterns showed unsatisfactory predictions for the typical cases studied in this work, for both higher (Campaign 2" Cold Mixture) and lower viscosity (Campaign 2" Hot Mixture) flows.
- The dimensionless flow-patterns map proposed by Ibarra *et al.* (2015) was consistent with the experimental results of oil-water flow with low oil viscosity (Campaign 2" Hot Mixture). However, for those with higher oil viscosity (Campaign 2" Cold Mixture), there was a greater discrepancy. It should be noted that the flow patterns map proposed by Ibarra *et al.* (2015) was developed using results of oil-water flow experiments with oil viscosities below 10 $mPas$.

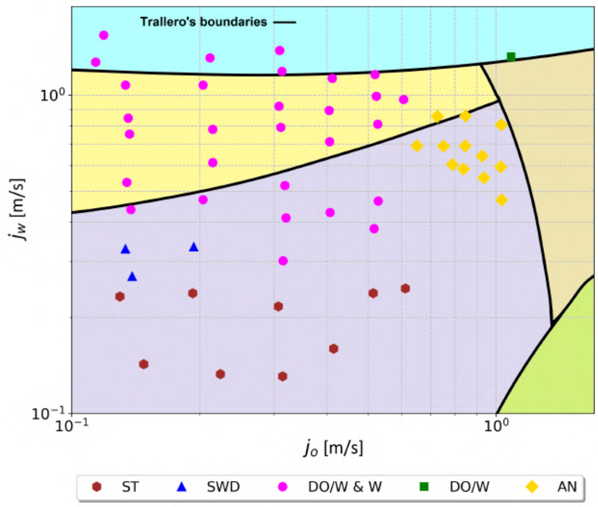


Figure 8. Experimental flow patterns map j_o versus j_w for Campaign 2" Cold Mixture.

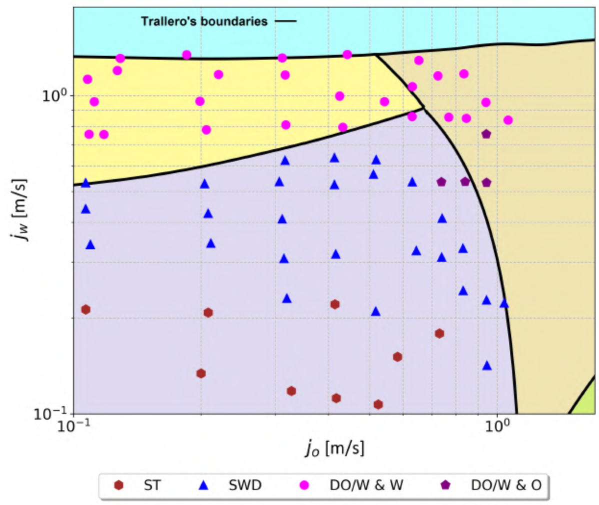


Figure 9. Experimental flow patterns map j_o versus j_w for Campaign 2" Hot Mixture.

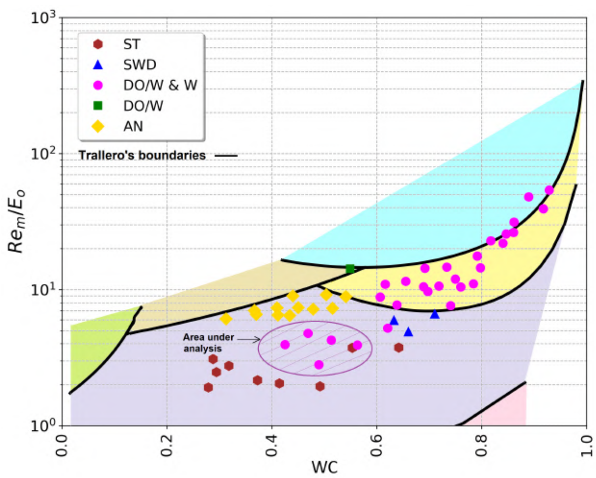


Figure 10. Experimental flow patterns map WC versus Re_m/E_o for Campaign 2" Cold Mixture.

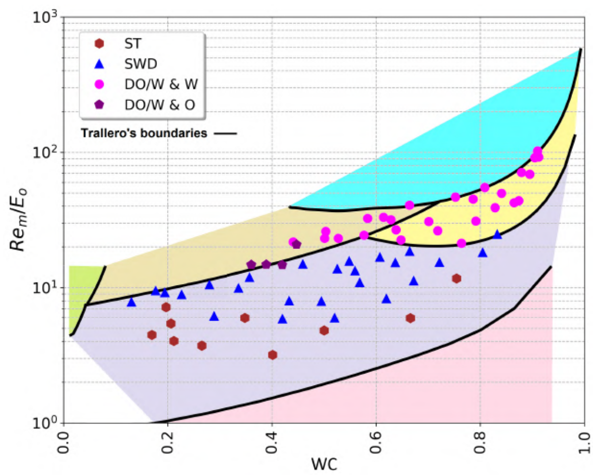


Figure 11. Experimental flow patterns map WC versus Re_m/E_o for Campaign 2" Hot Mixture.

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