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FLOW PATTERN AND PRESSURE DROP IN HORIZONTAL VISCOUS OIL-WATER FLOWS

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ABSTRACT

Despite recent discoveries of light oil in the Brazil's pre-salt layer, about 25% of its' reserves will still consist of viscous oil. In the case of light oil, commercial software are able to provide, with an admissible uncertainty, pressure drop and holdup of oil-water flows, however when they are used for the same flow predictions involving viscous oils there is a large discrepancy between the experimental data and predictions. In this work, experimental data of pressure gradient, characterization of flow patterns in horizontal viscous oil-water flows and spatial transition of the stratified flow to intermittent flow were acquired at the experimental facility of the LETeF (Thermal and Fluids Engineering Laboratory) of the Engineering School of Sao Carlos of the University of Sao Paulo in Brazil. The experimental facility consists of 12 m length glass pipeline of 26 mm i.d. It is equipped with positive displacement pumps and volumetric flow meters for oil and water. Oil with viscosity of 300 mPa.s and density of 845 kg/m³ at 20°C and tap water were the working fluids. A high speed camera was used to film the flow and characterize flow patterns. The movies were taken at transparent sections placed at the pipeline filled with water to reduce distortion effects. The observed flow patterns were: smooth stratified, wavy stratified, stratified with mixture at the interface, drops of oil in water, plug flow (intermittent flow), core-annular flow, and dispersion of oil in water. The pressure drop was measured using a high speed differential pressure transducer from Validyne™. It was observed that as the flow pattern changes, the behaviour of the variation of the pressure drop also changes. The experimental data are being used to improve the two-phase flows models, e.g. the one dimensional two-fluid model.

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. Pressure drop, heat transfer, corrosions and structural vibration are a few examples of topics that depend on the geometrical configuration or flow patterns of the immiscible phases.

An experimental work on liquid-liquid flows where a flow loop was presented and visual classification of the flow patterns was done can be seen in the article of Trallero, Sarica and Brill [1]. In that paper data for horizontal flow were presented including characterization of stratified and semi-stratified flows, dispersions and emulsions for oils of low viscosity, however, the authors did not differ the wavy stratified flow from stratified with mixture at the interface. A more detailed oil-water horizontal flow pattern classification, dividing the observed flow patterns of Trallero, Sarica and Brill [1] into several sub-patterns was given by Elseth [2]. Elseth [2] observed the wavy-stratified liquid-liquid flow pattern. The work of Trallero, Sarica and Brill [1] was continued by Alkaya, Jayawarderna and Brill [3], but now introducing the effects of pipe inclination and the wavy stratified flow pattern was reported. All the quoted authors have dealt with relatively low viscosity oils. On the other hand, Bannwart et al. [4] studied a very viscous oil-water flow and reported the stratified, core annular, oil-plug flow and flow of drops of oil in water flow patterns. The oil-plug flow was also observed by Oddie et al. [5]. Oil-water flow maps are not as common as those of gas-liquid flow, and the transition boundaries have a stronger dependence on the oil viscosity. Examples of oil-water flow maps can be seen in Bannwart et al. [4], Trallero [6] and Rodriguez and Oliemans [7].

The stratified flow pattern is present in directional oil wells and pipelines and it is characterized by the heavier and lighter phases at the bottom and top part of the pipe, respectively, divided by an interface. The interface can be smooth or wavy.

The spatial development of an unstable wavy structure in liquid-liquid stratified flow, which could lead to flow-pattern transition, was experimentally observed by Al-Wahaibi and Angeli [8]. The authors worked with low viscous oil and water as work fluids and measured the characteristics of the interfacial wave in two different points along the test line. They concluded that the interfacial wave amplitude grows with distance from the pipe inlet. The amount of mixing at the interface also seems to increase downstream.

In the following sections, the experimental setup and procedure are presented, experimental data on flow patterns and pressure gradient in heavy oil-water flows are given as well as an experimental flow map, and comparison with a theoretical flow map. Finally, an experimental study of the spatial transition from stratified flow to other flow patterns is discussed.

NOMENCLATURE

Uws	[m/s]	*Water superficial velocity*
Uos	[m/s]	Oil superficial velocity
ST	[-]	Smooth stratified flow pattern
SW	[-]	Wavy stratified flow pattern
SW&MI	[-]	Stratified with mixture at the interface flow pattern
G	[-]	Drops flow pattern
P	[-]	Oil plug flow pattern
A	[-]	Core-annular flow pattern
Do/w&w	[-]	Dispersion of oil in water and water layer flow pattern

EXPERIMENTAL SETUP AND PROCEDURE

Experimental Facility

The hydrophilic-oilphobic glass test line of 26 mm i.d. and 12 m length of the multiphase flow loop of the Thermal-Fluids Engineering Laboratory, Sao Carlos School of Engineering, University of Sao Paulo, was used to produce different oil-water flow patterns. A by-pass line allows the quick-closing-valves technique to measure in-situ volumetric fraction of water and oil. Water and oil were kept in polyethylene tanks. Positive displacement pumps, both remotely controlled by their respective variable-frequency drivers, pump the phases to the multiphase test line. Before entering the multiphase test line the phases are mixed in the multiphase mixer. Positive displacement and vortex flow meters were used to measure the volumetric flow of each fluid and, consequently, the superficial velocities. A thermocouple measures the temperature of the oil before it enters the test line. After the test line the fluids entered a liquid-gas separator tank, after this, the mixture of water and oil enters, by gravity, the coalescent-plates liquid-liquid separator. Finally, water and oil return by gravity to their tanks.

The test section has seven transparent boxes used to film the flow, in order to correct any remaining distortion of light due to lens and parallax effects, the boxes were filled with water.

The first box is placed at 1.3 m from the beginning of the test line; the others are placed 1.5m apart of each other. A schematic view of the flow loop and details related to the holdup measurement technique can be seen in Rodriguez et al. (2011). The water used in the experiments had density of 988 kg/m³ and viscosity of 1 mPa.s at temperature of 20 °C. The oil used has density of 854 kg/m³ and viscosity of 329 mPa.s at 20°C. The viscosity was measured with a rheometer Brokfield™ model LVDV-III+ with rotor SC4-18. The oil-water interfacial tension was of 0,045 N/m. The oil-water contact angle with the borosilicate glass was 29° (hydrophilic-oilphobic). The interfacial tension and contact angle were measured with an optical tensiometer of KSV™ model CAM 200.

The test line has eight pressure taps used to measure pressure drop. The first pressure tap is placed at the entrance of the section, and the others 1.5m apart each other.

A schematic view of the flow loop is presented in Fig. 1. Details related to the holdup measurement technique and flow loop can be seen in Rodriguez et al. [9].

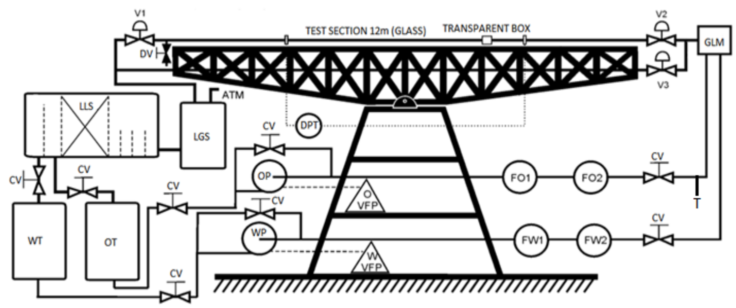

Figure 1 Schematic view of the inclinable multiphase flow loop used in this work.

Experimental Procedure

The flow was filmed using a high speed video camera (i-SPEED 3 OLYMPUS™) to acquire flow-pattern data. The camera was installed on a pedestal and two xenon lamps were used to illuminate the flow. After reaching steady state the flow was recorded at various frame rates, depending on the flow pattern. Stratified, stratified with mixture at the interface were filmed at 100 frames/second, drops and core-annular flow at 200 frames/second and dispersion of oil in water at 1000 frames/second. The transparent box used was at 5.8 m from the inlet of the test section. Data on pressure drop were acquired via a LabView™ based program at a rate of 5 kHz. The pressure taps were placed at 3 m apart of each other, for oil superficial velocities up to 0.28 m/s and at 1.5 m from each other for higher oil superficial velocities. The experiments on the spatial transition of the stratified flow were done filming the flow at different points of the test section.

EXPERIMENTAL RESULTS

Flow Patterns and Pressure Drop

Data on flow patterns in horizontal heavy oil-water flow were acquired. Seven different flow patterns were seen, and the classification is based on the work of literature [3] and [4]. This classification is based on visual observation and pressure drop data. The observed flow patterns are: smooth stratified (ST); wavy stratified (SW); stratified with mixture at the interface (SW&MI); drops of oil (G) (two sub patterns were placed together in this classification: diluted and dense stratified drops); oil plug flow (P); dispersion of oil in water and water layer (Do/w&w); and core-annular flow pattern (A).

Table 1 presents the respective range of superficial velocities.

Table 1 Flow patterns and range of superficial velocities.

Uos [m/s]	Uws [m/s]	Observed Flow patterns	Number of Experiments
0.02	0.03-2.0	ST, SW, SW&MI,G, Do/w&w	18
0.04	0.02-2.0	ST, SW, SW&MI,G, Do/w&w	18
0.06	0.02-2.0	ST, SW, SW&MI,G, Do/w&w	14
0.08	0.02-2.0	ST, SW, SW&MI, G, P, Do/w&w	14
0.1	0.02-2.0	ST, SW, SW&MI, G, P, Do/w&w	14
0.12	0.02-2.5	ST, SW, SW&MI, G, P, Do/w&w	15
0.14	0.02-2.5	ST, SW, SW&MI, G, P, Do/w&w	16
0.16	0.02-3.0	ST, SW, SW&MI, G, P, Do/w&w	17
0.18	0.03-3.0	SW, SW&MI, G, P, Do/w&w	18
0.2	0.03-3.0	SW, SW&MI, G, P, Do/w&w	18
0.22	0.03-3.0	SW, SW&MI, G, P, Do/w&w	18
0.25	0.03-3.0	SW, SW&MI, G, P, A, Do/w&w	21
0.28	0.03-3.0	SW, SW&MI, G, P, A, Do/w&w	22
0.31	0.03-3.0	SW, SW&MI, G, P, A, Do/w&w	21
0.35	0.04-3.0	SW, G, P, A, Do/w&w	18
0.4	0.04-3.0	SW, G, P, A, Do/w&w	16
0.45	0.04-1.22	SW, G, A	10
0.5	0.1-3.0	SW, G, P, A, Do/w&w	12
0.6	0.12-3.0	SW, G, A, Do/w&w	11
0.7	0.4-2.5	A, Do/w&w	7
0.8	0.3-2.5	A, Do/w&w	7
0.9	0.3-2.0	A	6
1	0.3-1.5	A	5

Flow Patterns – Visual Observation

By visual observation given by the acquired images the flow patterns characteristics are:

- Smooth Stratified (ST): oil and water flowing as separated layers with a smooth interface (Fig. 2).

Figure 2 Smooth stratified flow (ST)
(*Uws* = 0.03m/s, *Uos* = 0.02m/s).

- Wavy stratified (SW): oil and water flowing as separated layers with a wavy interface between them. The waves are fairly visible and there is no dispersion at the interface whatsoever (Fig. 3).

Figure 3 Wavy stratified flow (SW)
(*Uws* = 0.1 m/s, *Uos* = 0.04 m/s).

- Stratified with mixture at the interface (SW&MI): oil and water flowing as separated layers with a wavy interface, but with small oil drops in the water phase. The flow can be considered as a transitional flow pattern, between stratified and drops or oil plug flow (Fig. 4).

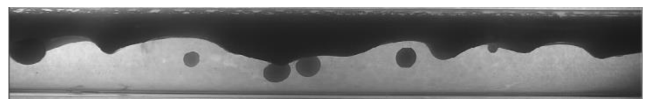

Figure 4 Stratified with mixture at the interface (SW&MI)
(*Uws* = 0.23 m/s, *Uos* = 0.06 m/s).

- Oils drops (G): oil drops, smaller than the pipe diameter, flowing one after another (Fig. 5), or lumped (oil-drop train) above a continuous water layer (Fig. 6).

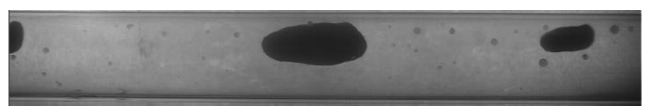

Figure 5 Drops or diluted drops (G)
(*Uws* = 0.3 m/s, *Uos* = 0.06 m/s).

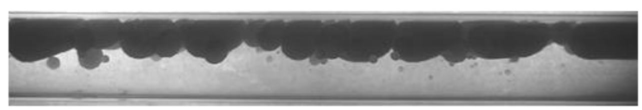

Figure 6 Drops or dense drops (G)
(*Uws* = 0.35 m/s, *Uos* = 0.28 m/s).

- Oil plug flow (P): elongated drops, longer than the pipe diameter, flowing above a continuous water layer and intermittently intercalated by water. The oil drop does not stick to the pipe wall and it is completely surrounded by water (Fig. 7).

Figure 7 Oil plug flow (P) (*Uws* = 0.45m/s, *Uos* = 0.1m/s).

- Core-annular flow (A): the oil phase flows in the core of the pipe, however closer to the top part of the pipe wall, and water flows as an annulus, surrounding the oil (Fig. 8).

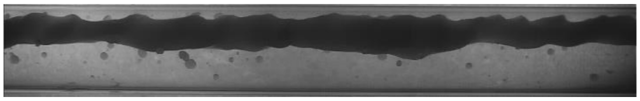

Figure 8 Core-annular flow pattern (A) (*Uws* = 1.5m/s, *Uos* = 0.5m/s).

- Dispersion of oil in water and water layer (Do/w&w): it is characterized by oil droplets that flow over a water layer (Fig. 9).

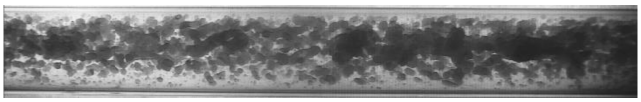

Figure 9 Dispersion of oil in water and water (Do/w&w) (*Uws* = 3m/s, *Uos* = 0.5 m/s).

Flow Patterns – Pressure Gradient

With the change of flow pattern several variations were observed in pressure gradient data; this was used to confirm the classification given by the visual observation. Graphs of Figs. 10-13 present the pressure gradient variation as the water superficial velocity increases for constant oil superficial velocities. This is the way that several authors studying gas-liquid and liquid-liquid flows in pipes present their data, e.g. Rodriguez and Oliemans [7], Rodriguez and Baldani [12] and Mandhane, Gregory and Aziz [13].

For low oil superficial velocities (0.02 m/s ≤ *Uos* ≤ 0.08 m/s), three distinct trends are observed as the surface velocity of the water increases.

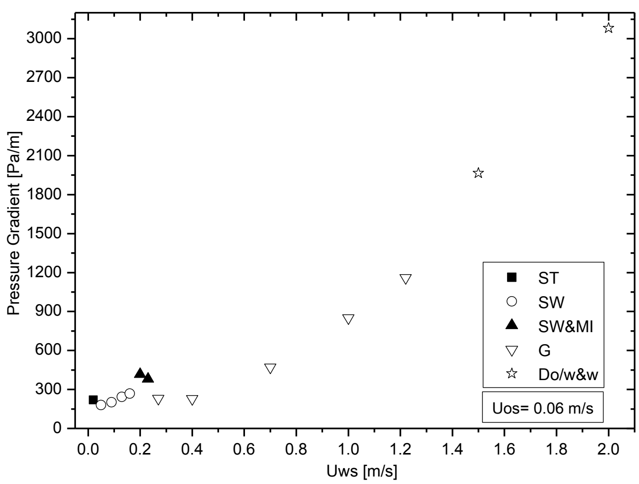

Figure 10 Experimental pressure drop variation for low oil superficial velocities (0.02 m/s ≤ *Uos* ≤ 0.08 m/s).

Initially there is an increased pressure gradient to reach a local maximum, it decreases and then increases again. These changes in the pressure gradient trend are due to the change in the flow pattern. Thus, in Fig. 10, initially stratified patterns are observed (ST, SW) till *Uws* = 0.2 m/s then the SW & MI flow pattern is observed, and there is the transition to the drops flow pattern (G) and finally dispersion of oil in water flow pattern (Do / w & w). The core-annular flow pattern (A) is not present.

Phenomenologically, it is observed that the pressure gradient increases with the increasing of the water superficial velocity. After this, the effects of wall shear tends to decrease, as the oil starts to be pulled from the pipe wall, and the flow transits to another flow pattern, in this case SW to SW&MI and from SW&MI to G. Then, effects of inertia increase the pressure gradient, and the flow pattern becomes dispersed (Do/w&w).

Four different trends are observed in the pressure gradient variation with the water superficial velocity for medium oil superficial velocities.

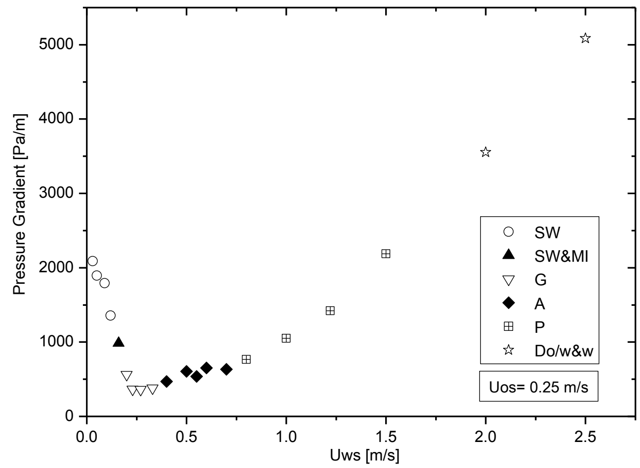

Figure 11 Experimental pressure drop variation for medium oil superficial velocities (0.1 m/s ≤ *Uos* ≤ 0.28 m/s).

Initially there is a decrease of the pressure gradient till a minimum value, this becomes constant and starts to increase at different rates. Again, it can be said that the pressure gradient pattern is maintained for the same flow pattern. In this graph, the transition of the stratified patterns (SW and SW & MI) to drops and core-annular flow (G and A) patterns are observed, then to oil plug flows (P) and finally the transition to the dispersed pattern (Do / w & w). For medium oil superficial velocities (Fig. 11), the stratified flow pattern occurs till the same limit given in Fig. 10, around *Uws* = 0.2 m/s. In this case, the pressure gradient decreases in the region of stratified flow pattern, but as the water superficial velocity increases transition to another flow pattern occurs (SW to SW&MI), and for the same reasons concluded in Fig. 10, the pressure drop decreases, and another flow pattern transition is observed, where the pressure gradient remains constant (SW&MI to G). As the water superficial velocity increases it is observed the coalescence of the drops and formation of the core-annular flow (A). As the inertia effects become higher, the oil core is broken into elongated bubbles and a different rate in the pressure gradient increase is observed. Finally, the pressure gradient increases till the last transition (P to Do/w&w).

Figure 12 shows the variation of the pressure gradient for superficial velocities of moderate to high oil superficial velocities (0.31 to 0.6 m/s). There are four different trends in the pressure gradient as the water superficial velocity increases. Initially, there is a region of constant pressure gradient where the wavy stratified flow pattern is observed (SW). An abrupt decrease of the pressure gradient occurs and the flow pattern changes to drops (G), in this flow pattern there is no oil in contact with the pipe wall, causing reduction of friction losses and confirming the reduction of the pressure gradient. A small increase in the pressure gradient without changing the flow pattern with increasing water superficial velocity is observed, it is due to the increase of friction losses due to the increased velocity of the water phase. The flow pattern changes to core-annular flow with increasing water velocity, and this also causes increase of the pressure gradient. With the change to the dispersed flow pattern the increase of water velocity causes an increase in the level of turbulence which increases the pressure gradient. Thus, changes in the trend of the pressure gradient are associated with transitions flow pattern. Initially there is the stratified pattern (SW and SW&MI), drops flow pattern (G), core-annular flow (A), and finally dispersion (Do/w&w).

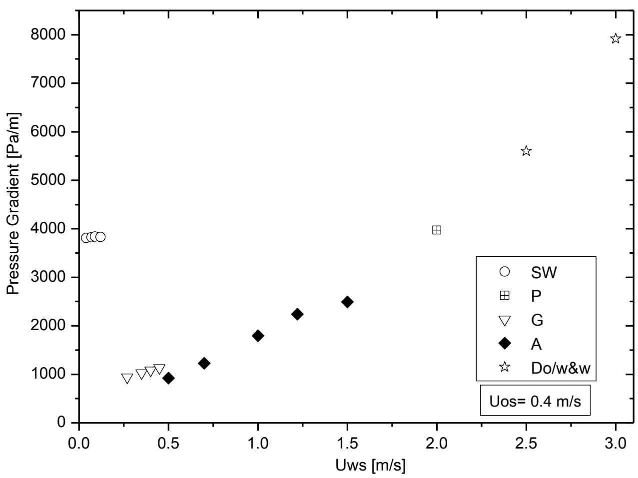

Figure 12 Experimental pressure drop variation for medium to high oil superficial velocities (0.31 m/s ≤ *Uos* ≤ 0.6 m/s).

Figure 13 shows the variation of the pressure gradient with water superficial velocity for high oil superficial velocities (0.7 to 1 m/s).

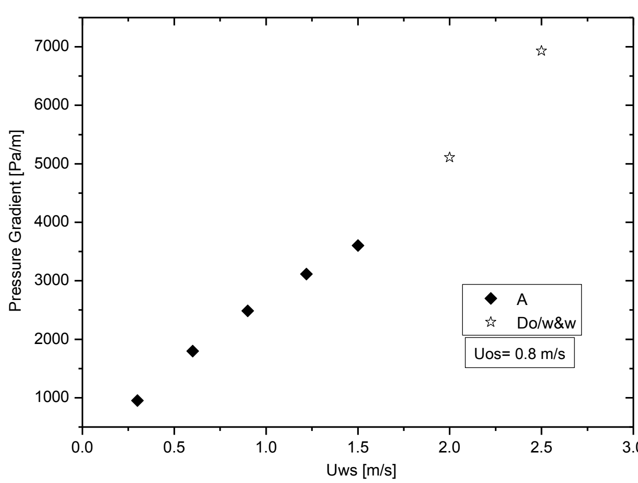

Figure 13 Experimental pressure drop variation for high oil superficial velocities (0.7 m/s ≤ *Uos* ≤ 1.0 m/s).

In this region two different trends are observed in the pressure gradient, with increasing the water superficial velocity. One related to the core-annular flow (A) with water superficial velocities between 0.2 and 1.5 m/s, and other to the dispersion of oil in water with water flow pattern (Do/w&w). The change in the derivative of the pressure gradient values is related to the flow pattern change from core-annular flow (A) to dispersed flow (Do/w&w).

Only these four figures were presented as they are representative of the pressure gradient variation of the entire range of oil superficial velocities to which they are linked.

From Figs. 10 to 13 some conclusions can be drawn about the regions of occurrence of each flow pattern as the water and oil superficial velocities vary. It is possible to compare the visual observation flow map with the pressure gradient data given. It is important to say that the transition between flow patterns occurs over a range of superficial velocities, not on a specific value. The next bullets are the delimitation of regions in which each flow pattern seems to occur. These regions are delimited by the water and oil superficial velocities as given below:

- Smooth stratified flow pattern (ST) (Fig. 2): The flow pattern occurs at extremely low water superficial velocities, below 0.03 m/s, and oil superficial velocities up to 0.18 m/s.
- Wavy stratified flow pattern (SW) (Fig. 3): The flow pattern occurs at oil superficial velocities up to 0.45 m/s and water superficial velocities between 0.03 m/s and 0.2 m/s.
- Stratified with mixture at the interface flow pattern (SW&MI) (Fig. 4): The flow pattern occurs at water superficial velocities between 0.1 and 0.3m/s and oil superficial velocities up to 0.3 m/s.
- Oils drops (G) (Figs. 5 and 6): The flow pattern occurs at oil superficial velocities up to 0.6 m/s and water superficial velocities between 0.1 m/s and 1.2 m/s.
- Oil plug flow (P) (Fig. 7): The flow pattern occurs for water superficial velocities above 0.25 m/s and oil superficial velocities between 0.08 m/s and 0.5 m/s.
- Core-annular flow (A) (Fig. 8): The flow pattern occurs at oil superficial velocities between 0.25 m/s and 1 m/s and water superficial velocities between 0.3 m/s and 2 m/s.
- Dispersion of oil in water and water layer (Do/w&w) (Fig. 9): the flow pattern occurs at high water superficial velocities, above 1.2 m/s, and oil superficial velocities up to 0.8 m/s.

Visual observations were used to build the experimental flow map presented in the next section, and the observed variation of the pressure gradient corroborates the regions of occurrence of each flow pattern.

Flow Maps

The experimental flow pattern map obtained in this work for heavy oil-water flow is presented in Fig. 14. A flow pattern map predicted by the model of Trallero [6] can be seen in Fig. 15 for comparison purposes, using the same pipe diameter, pipe inclination, and fluid properties of this work (figure 14). The symbols used in both flow maps are the same for the same flow patterns, to facilitate the comparison.

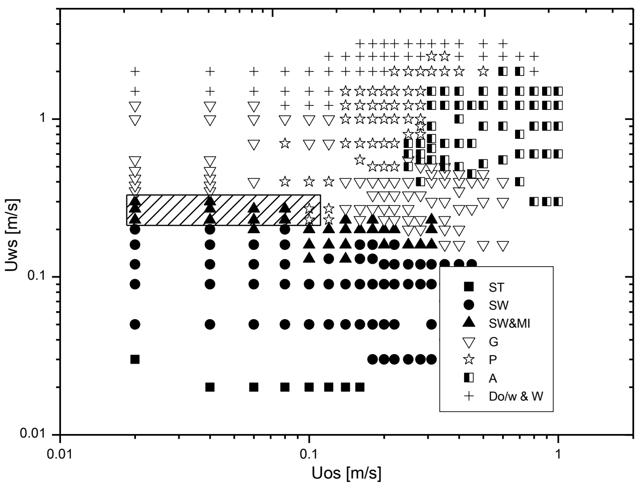

Figure 14 Experimental flow pattern map from visual observation and pressure gradient variation.

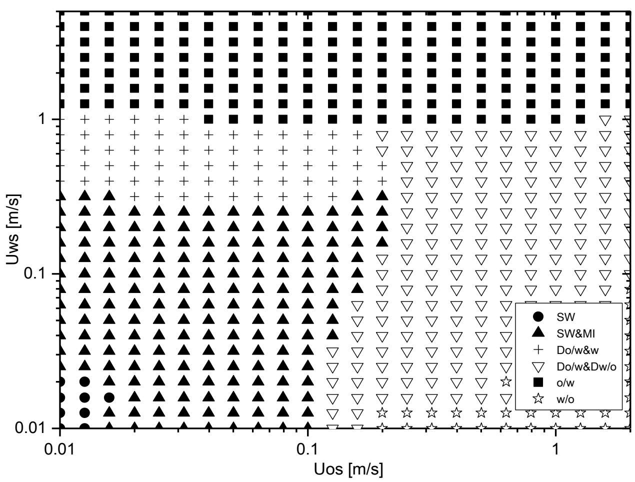

Figure 15 Flow pattern map predicted by Trallero's model [6].

The flow maps are, essentially, in complete disagreement (Figs. 14 and 15). It should be pointed out that Trallero [6] used light oil-water flow data to adjust his model. The region where stratified flow should occur is much smaller than the one observed in the experiments. The model does not predict the existence of core-annular flow, drops and oil-plug flow. On the other hand, it predicts emulsion of oil in water and emulsion of water in oil in regions where core-annular flow was experimentally observed. The authors believe that in light oil-water flow it is relatively easy for the turbulent dominant phase to break the continuous phase attached to the top pipe wall into drops; this phenomenon is quite harder to occur in heavy oil-water flow due to the oil viscosity, and so on the maintenance of a laminar flow of the oil phase for a wider range of superficial velocities.

Another observed phenomenon is the spatial transition of stratified flow patterns to drops and plug flow that occur in the hatched region of Fig. 14. In that region the initial stratified flow pattern breaks into other patterns along the pipeline, and the point in space where the transition occurs varies with the water superficial velocity. This phenomenon was already presented by [10], but now it is explained in details.

Spatial Transition of Stratified Flow

It is expected for a stratified flow pattern that each phases are attached to the pipe wall even for oil in oilphobic pipes. The wettability and contact angle effects of each phase depends on the pipe properties but only causes an increase or decrease in the wetted perimeter of the pipe by oil and water. In this case, for the same flow pattern and an oilphilic pipe the wetted perimeter by the oil should be greater.

It was observed, for several pairs of oil and water superficial velocities, that the initial configuration of wavy stratified or stratified with mixture at the interface is not maintained throughout the pipe line length. The adhesion of the oil with the pipe wall breaks and the flow pattern transits to oil plug flow or drops of oil, at some point in the line. It was also observed the same phenomenon occurring for in the transition from the wavy stratified flow to stratified with mixture at the interface.

One can see in Figs. 16 and 17 the development of the flow at water and oil superficial velocities of 0.2 m/s and 0.04 m/s, respectively. We see in Fig. 16 a stable wavy stratified flow at 2.8 m (107 pipe diameters) from the pipe inlet. At 7.3 m (280 pipe diameters) the break-up point is reached and oil-plug flow takes place (Fig. 17).

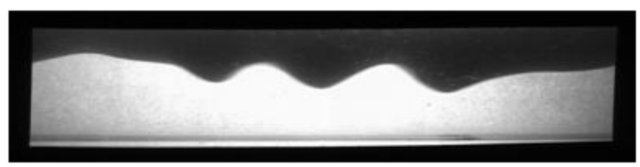

Figure 16 Wavy-stratified flow at 2.8 m from pipe inlet. (*Uws* = 0.2 m/s and *Uos* = 0.04 m/s).

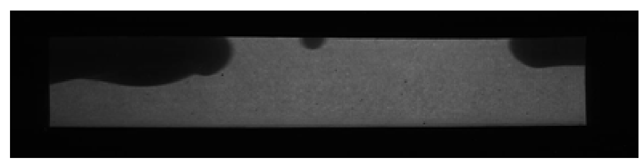

Figure 17 Break-up point, oil-plug flow takes place at 7.3 m from pipe inlet. (*Uws* = 0.2 m/s e *Uos* = 0.04 m/s).

The spatial transition described above was observed at several different positions from the pipe inlet depending on the pair of water and oil superficial velocities and the pipe inclination from horizontal. It was observed that transition takes place because of loss of adhesion of the oil phase from the top part of the pipe wall, which may have to do with hydrodynamics, wettability, interfacial tension and contact-angle effects. Some experimental point where the spatial transition occur are presented with the positions from the pipe inlet at which such transition was observed can be seen in Table 2 (SW-P) for horizontal flow. A more detailed observation revealed that the interfacial wave amplitude grows till a limit, which is geometrically given by the top part of the pipe wall, and then the oil adhesion is lost and plug flow occurs. It is a phenomenon similar to the setting up of slug flow in gas-liquid flow. Figure 18 shows a snapshot of the flow at the exact moment that the stratified flow breaks into the oil plug flow.

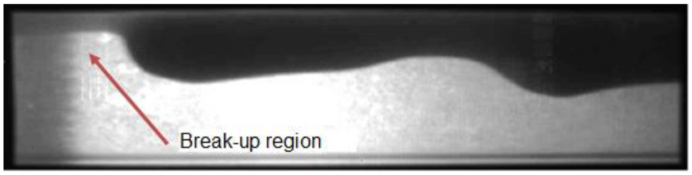

Figure 18 Break-up point, oil-plug flow takes place at 7.3 m from pipe inlet. (*Uws* = 0.2 m/s e *Uos* = 0.04 m/s).

The analysis of the interfacial wave before the break up shows that the wave amplitude, wavelength, and celerity increase along the pipeline.

A similar mechanism explains the transition from stratified with mixture at the interface to the drops flow pattern. The oil adhesion is lost and the drops of oil that are formed join those that were already flowing near the interface in the water layer. The point in space where that phenomenon occurs also seems to depend on the pair of water and oil superficial velocities (Table 2, SW&MI-G). Figure 19 shows a top view of the pipe where this phenomenon occurs.

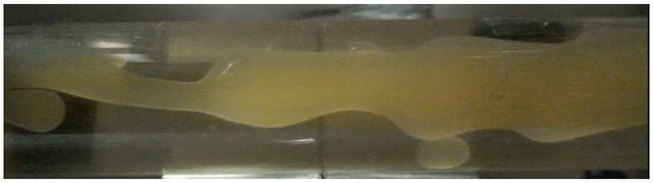

Figure 19 Transition from Stratified with mixture at the interface to drops flow pattern at 3.0 m from pipe inlet. (*Uws* = 0.27 m/s and *Uos* = 0.06 m/s).

One can see in Fig. 19, the oil attached to the pipe wall, and the droplets in the interface (SW&MI), and in the end of the image, the initiation of the formation of another drop, that will detach from the oil phase and becomes a new drop.

Artwork in Figs. 20 to 22 presents from the point of view of the observer the phenomenon of spatial transition of flow pattern occurring. In the drawings the flow occurs from right to left, and shows the front and top views of the flow. Figure 20 shows the stable wavy stratified flow seen at a distant point of the break up region.

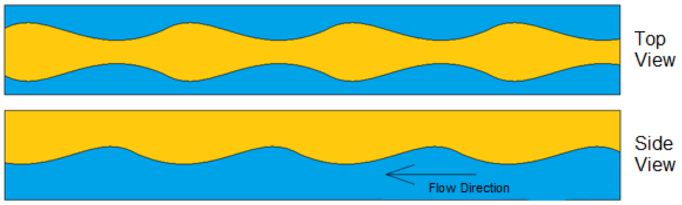

Figure 20 Scheme of the wavy stratified flow at a distant point of the break region.

Figure 21 shows the increase in amplitude and wavelength of the interfacial wave that occurs in a region near of the breaking point of the wavy stratified flow patter.

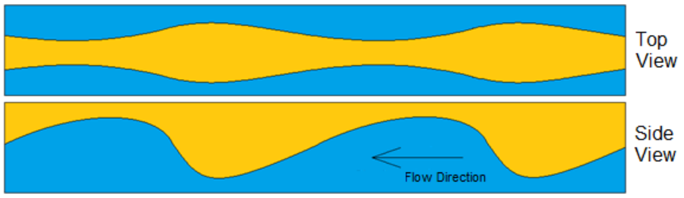

Figure 21 Scheme of the wavy stratified flow in the near point of break.

Finally, the wave amplitude increases such that the upper part of the flow becomes so thin that due to a similar phenomenon with tearing droplet from the interface that occurs in the stratified with mixture at the interface (SW & MI), the flow is divided and an oil piston is pulled out of the base oil wavy stratified flow (SW) (Fig. 22).

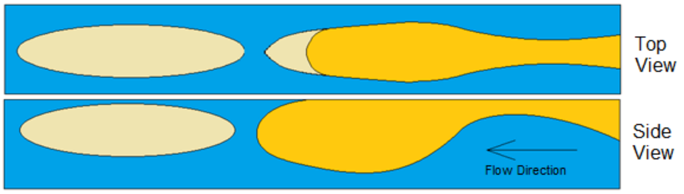

Figure 22 Scheme of the region where the break occurs.

Table 2: Flows where spatial break up was observed and the point in space from pipe inlet.

Uws [m/s]	Uos [m/s]	Pipe Inclination [°]	Flow pattern	Point in space [m]
0.18	0.02	0	SW-P	2.8
0.2	0.02	0	SW-P	7.3
0.23	0.02	0	SW-P	4.3
0.27	0.02	0	SW&MI-G	4.5
0.3	0.02	0	SW&MI-G	4.5
0.18	0.04	0	SW-P	2.8
0.2	0.04	0	SW-P	7.3
0.23	0.04	0	SW-P	4.3
0.27	0.04	0	SW&MI-G	4.5
0.3	0.04	0	SW&MI-G	3
0.2	0.06	0	SW-P	8.8
0.23	0.06	0	SW&MI-G	4.5
0.27	0.06	0	SW&MI-G	3
0.2	0.08	0	SW-SW&MI	5.8
0.23	0.08	0	SW&MI-G	8.8
0.27	0.08	0	SW&MI-G	3
0.2	0.1	0	SW&MI-G	5.8
0.23	0.1	0	SW&MI-G	8.8
0.27	0.1	0	SW&MI-G	4.3
0.3	0.1	0	SW&MI-G	1.3
0.2	0.12	0	SW&MI-G	2.8
0.23	0.12	0	SW&MI-G	8.8
0.27	0.12	0	SW&MI-G	2.8
0.3	0.12	0	SW&MI-G	1.3
0.23	0.14	0	SW&MI-G	4.5
0.27	0.14	0	SW&MI-G	3
0.23	0.16	0	SW&MI-G	3
0.23	0.18	0	SW&MI-G	4.5
0.02	0.18	5	SW-P	10.3

CONCLUSION

Although there is increasing interest in liquid-liquid flows due to the oil industry, works on viscous oil are still scanty. So, a classification of flow patterns for this kind of flow is still not well defined, and even there is no definition of flow patterns that would be observed. This work propose that in the observed region of viscous oil flows there are seven different flow patterns, which are: smooth stratified, wavy stratified, stratified with mixture at the interface, drops, oil plug flow, core-annular flow and dispersion of oil in water. Each observed flow pattern had their different characteristics analysed throughout the text. It was shown that the change or transition between flow patterns is responsible for changes in the behaviour of the trends observed in the pressure gradient.

It was observed that within the same flow pattern the pressure gradient stays constant or varies with the same rate (same derivative) as the superficial velocity of water increases for the same oil superficial velocity. The transition between flow patterns is characterized by an abrupt decrease of the pressure gradient as observed in the transition from stratified flows to drops flow, where the detachment of the oil from the pipe wall causes the decrease in the pressure gradient, or a change in the variation rate as observed in the transition from core-annular flow to dispersed flow pattern.

Finally, the last observed transition between flow patterns was due to spatial transition, which occurs along the pipeline at different points in space depending on the superficial velocities of the phases. The observed transitions are: wavy stratified to oil plug flow; stratified with mixture at the interface to drops and wavy stratified to stratified with mixture at the interface. The transition occurs due to an increase in the wave amplitude that occurs along the pipeline, till a moment that this wave touches the top of the pipe and plug is pulled from the flow. In the case of stratified with mixture at the interface, the wave length tends to decrease and increase the wave amplitude, so the wave becomes steeper leading to drop formation at the interface. It was observed that transition takes place because of loss of adhesion of the oil phase from the top part of the pipe wall, which may have to do with hydrodynamics, wettability, interfacial tension and contact-angle effects.

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