WIRE-MESH SENSOR APPLIED IN STRATIFIED LIQUID-LIQUID FLOW TO OBTAIN THE ENTRAINMENT FACTORS

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Abstract. *The frequent occurrence of multiphase flows in pipes has motivated a great interest in this research area. In addition, particular cases of liquid-liquid flows are usually found in petroleum industry. There is not a proper understanding for a significant number of phenomena observed in flows involving immiscible mixtures of oil and water, especially when oil is significantly viscous. This research aims to obtain detailed liquid-liquid flow data through a fast-response electrical-impedance wire-mesh sensor, using test facilities installed at the Thermal-fluids Engineering Laboratory of EESC-USP and data from the literature. The tomographic data obtained via wire-mesh sensor is useful for developing new models of transition and equations that can improve numerical codes applied in projects of directional oil well or wells equipped with gravitational gas separators. The study of the effect of the phases' volumetric-fraction distribution allows the adjustment of the existent mathematical models based on data from two-phase flows with oils of low viscosity. The analysis of the data gives not only the position of the interface, but it also gives which is the dominant phase. This information is useful for the experimental determination of entrainment factors in stratified flow. The obtained results are unprecedent in the literature, and, they will allow to make comparisons with existent data in order to evaluate whether some potential discrepancies detected in the phase fraction distributions have physical cause or occur due to limitation of the instrumentation.*

Keywords*: two-phase flow, stratified flow, oil-water flow, entrainment factors, wire-mesh sensor, petroleum industry.*

1. INTRODUCTION

Multiphase flows may have different flow patterns along the pipe. When fluids are segregated for certain conditions, the flow has a stratified pattern in which the fluids are separated from each other by an interface with each fluid occupying a continuous portion of the pipe, and therefore, a portion of the area for each one on the pipe's cross section. The condition of existence and stability of the interface is due to several factors such as density and viscosity, parietal and interfacial tensions, flow pressure conditions, superficial velocities, as well as the pipe characteristics, as internal pipe diameter, the material from which it is made, and hence its apparent and relative roughness. This interface can present both smooth and wavy, depending on flow parameters, and in this last case, it is said that the flow has an interfacial wave. For this reason, it is then called wavy stratified flow, SW.

In wavy stratified flow, the wavy interfacial phenomenon is related to the velocity between the phases. The increase in superficial velocities of the fluids, or also the increase of the difference between the superficial velocities of the phases, can produce changes related to stable values of amplitude and wavelength, and therefore, promoting shear between them. As the interfacial shear stress becomes sufficiently high to cause the drag between the fluid to overcome the restoring interfacial tension and gravity forces, droplets detach themselves from one phase dispersing into the opposite phase. This phenomenon is called droplet entrainment. When the drag between the phases increases quickly on the crests of the interfacial wave, high amplitudes provide conditions to occur the droplet entrainment (Al-Wahaibi et al., 2007). Thus, there is the breakup of the flow pattern, changing the wavy stratified pattern to stratified with mixing at the interface, ST&MI (Trallero, 1995; Al-Wahaibi and Angeli, 2009). This phenomenon can occur simultaneously for the two phases, providing up to four distinct regions in the pipe's cross section, two mixed regions near the interface and two continuous-phase regions, water at the bottom and oil at the top of the pipe.

As a result, these dispersed droplets of one phase into another exchange momentum with the fluid layers of the continuous phase in which they are inserted. The droplets coming from the slower phase start to slow down the fastest continuous phase, whereas the droplets coming from the fastest phase accelerate the slower phase. This exchange of momentum promotes loss of energy, quantified by pressure drop. Al-Wahaibi et al (2007) showed that the interfacial waves and the entrainment of drops may be responsible for increased wall shear stress of the oil-water flow. According to Lovick and Angeli (2004), the droplets tend to concentrate next to the interface when the fluids have low velocities. However, there is an increase of the dispersed phase for flows with higher velocities; these same dispersed droplets may even reach the pipe wall.

According Guzhov et al. (1973), the relative movement of the two liquid phases may develop vortices next to the interface that promote droplet formation. According Trallero (1995), the onset of formation of droplets can be explained by the Kelvin-Helmholtz instability that promotes the disturbance of the shape of the interface. The amplitude of the interfacial wave grows to the limit point of causing the disruption of the interface and, near the beginning of the formation of the droplet, and the wavelength is approximately twice the pipe's diameter. Al-Wahaibi and Angeli (2007) investigated experimentally the related drag, maintenance and breakup of the wavy structure at several velocities. According to Al-Wahaibi et al. (2007), the mechanism of droplets formation in liquid-liquid flow is not well known. However, the formation of droplets in stratified flow is related to a critical value of wavelength, a value below which the phenomenon does not occur.

The literature presents works on the entrainment phenomenon, including different suggestions for modeling this phenomenon, both for gas-liquid as well as for liquid-liquid flows. Among the objectives of these works are the quantification of the volume fractions of the phases and the pressure gradients (Pan and Hanratty, 2002; Al-Wahaibi and Angeli, 2007; Sawant et al, 2008; Al-Wahaibi and Angeli, 2009; al Sarkhi et al, 2012; Hadziabdic and Oliemans, 2007). Among the proposed models for the droplet entrainment in liquid-liquid flows, it is worth to mention the work of Hadziabdic and Oliemans (2007) and Al-Wahaibi and Angeli (2009), both featuring different models for entrainment factors as well as entrainment rates.

An important parameter of this phenomenon is the entrainment factor, also called by some entrainment fraction. According to Al-Sarkhi et al. (2012), the entrainment factor is a key parameter in many applications, including the design and development wells, flow lines and separators among others. It is important for the calculation of pressure drop, volume fractions, the dry-out in annular flow, as well as for the design and optimization of facilities for the phases' separation. In their work, Kataoka and Ishii (1982) state that the entrainment factor is a more stable parameter to measure and correlate as this represents the full effect of deposition and entrainment rate of the droplets. According to Al-Wahaibi and Angeli (2009), it is the main parameter for the prediction of the in-situ volume fraction and the pressure drop associated with stratified flow with mixing at the interface.

In a model proposed by Hadziabdic and Oliemans (2007), the entrainment factor E_k of the k phase is the ratio between the area occupied by the droplets entrained from k phase ($A_{k,droplets}$) and the total area occupied by the same phase (A_k) in the cross section of the pipe, to the subscript $k = w,o$ identifying the oil and water phases, respectively:

$$E_k = \frac{A_{k,droplets}}{A_k} \quad (1)$$

In their model, also called "Two-dispersion model" (TDM), it is assumed that entrained droplets forms a stable dispersion in each respective phase in which they are inserted. Such a condition can occur when the inertial forces of a continuous phase overcome the buoyancy force that tends to drive the entrained droplets back to their original phase. In this case, by hypothesis, it is assumed that entrained droplets have the same velocity of the continuous phase.

The model calculates the areas of the upper and lower layers of the flow. The upper layer comprises the continuous phase of oil, which includes a region of mixture of water droplets in oil. The lower layer is composed of a region formed by oil droplets in a continuous water phase and water at the bottom of the tube. The parameters of the flow are calculated for each phase and for each layer, top and bottom, weighted by the entrainment factors.

In their experimental work, Yusoff (2012) conducted studies of oil-water flow under mixing condition in horizontal, positive (+3° and +6°) and negative (-3° and -6°) inclinations. His work aimed to investigate the possibility of total downstream stratification of a dispersed oil-water flow coming from an abrupt diametrical expansion in the pipeline. To this end, the dispersed flow behavior was studied with the use of a Wire-mesh sensor installed at three different axial positions after the diametrical expansion of the tube, and by measuring the chordal diameter distribution of dispersed droplets via a FBRM probe (Focused Beam Reflectance Measurement) positioned at three different heights in the diametrical center line of the tube. Two of the observed flow patterns were stratified flow (ST and SW), and stratified with mixing (ST&MI) with regions of oil in water and water in oil across the interface.

2. METHODOLOGY

2.1 Description of the processing of the data of Yusoff (2012)

The objective was to analyze the experiments run by Yusoff (2012) using his own database. The identification of flow-patterns was made using graphs and images generated from specific MatLab® programs. It was done to oil-water flows in different conditions of velocity, inclination and void fractions. For each inclination (upward, downward, vertical and horizontal), flows of different oil volumetric fractions (0.2, 0.4, 0.6, and 0.8) were analyzed. It is important to notice that these oil fractions are injection oil volumetric fractions, which are given by oil flow rate over total flow rate at the pipe inlet. Graphs and images related to PDF (Probability Density Function), chordal phase fractions (horizontal and vertical) and flow tomography were generated. Different flow patterns were identified. The idea is to confront the results given by Yusoff (2012) with the results obtained in the present work, both obtained from the same databank, in order to understand potential contradictions.

Regarding the chordal fractions, which indicate the oil fraction in the mixture according to the linear position in the circular section of the pipe, it was chosen the horizontal chordal fraction for analysis. On these curves, the beginning of dispersion of oil in water was related to the first point of deflection from oil-fraction equals to zero. Then, to estimate the region of the interface, it was considered the next inflexion point on the curve, a curve with inclination nearer the horizontal position, until another point appears marking an inflection of opposite trend. Therefore, to identify the potential interval in which the interface is located, two parallel straight lines that intercept the points before described were drawn. If in between those two lines the curve appears to be a horizontal line, then the exact position of interface is found directly. However, if there is an inclined curve in the interval identified by these two points, the middle point of this curve was considered to determine the interface position. Finally, the end of dispersion of water in oil was related to the last point of deflection before oil-fraction equals to one. The flow pattern is given by the analysis of the obtained tomographies. The flow-pattern classification was done based on the criteria defined by Rodriguez and Oliemans (2006).

3.2 Description of methodology of data collection and treatment from experimental work of Yusoff (2012)

The experiments were conducted in the laboratory of the Department of Chemical Engineering and Environmental of the University of Nottingham, UK. The setup was a pipe through which water and oil were injected. The fluids passed through a device to promote mixing (flat plate with 18 holes, each one with 5 mm of diameter and located 250 mm from the expansion). The test section was made of acrylic and had abrupt expansion, from 38 mm to 68 mm of diameter. The total length of the pipe was of 3250 mm, 3000 mm length only the expanded section. At the end of the line, the fluids were separated by a horizontal gravitational separator for subsequent return to the test line.

In the experiment, with a 25°C of room temperature, deionized water was used with the following main properties: density ρ_w = 997 kg/m^3, viscosity μ_w = 0.0010 Pa.s, and surface tension σ_w = 0.0728 N/m. The used silicone-oil properties were: density ρ_o = 990 kg/m^3, viscosity μ_o = 0.0052 Pa.s, and, surface tension σ_o = 0.0240 N/m.

The mixtures were formed by droplets of a dispersed phase into the other. For obtaining data related to dispersed droplets and their respective diameters, one FBRM probe was used, with laser backscatter technique, directed to the central diametrical line of the cross section of the pipe, and in three different heights from the bottom to the top of the pipe, respectively in 17, 34 and 51 mm. For detection of spatial variation of flow properties in the cross section of the tube, i.e. for the identification of both continuous phases and mixtures, it was used a Wire-mesh sensor for obtaining tomographic images. Both devices, FBRM probe and Wire-mesh sensor, were arranged at three different positions of the section test, respectively 10*D*, 20*D* and 34*D* away from the expansion of the tube , where *D* is the diameter of the pipe.

Altogether three mixing velocities were used, J_m = 0.20 m/s, 0.30 m/s and 0.35 m/s, and four different input oil volume fractions (OVF or also C_o), C_o = 0.20, 0.40, 0.60 and 0.80. Therefore, Yusoff (2012) made several combinations of different pairs of input volume fractions and superficial velocity of mixture, positioning FBRM probe in relation to the heights in the central diametrical section and positioning the Wire-mesh sensor and FBRM probe in different distances from the diameter expansion, for the five different pipe inclinations.

Among all results obtained, some were of particular interest to this present study: the curves of the distribution of phases on the cross section of the pipe, in relation to the dimensionless height of the diameter (h/*D*), showing the layers and their spatial variations in the cross section, and the tomographic images of the phases and mixtures, all obtainable via Wire-mesh sensor.

The phase-distribution curves are presented in graphs where the phases are identified as continuous phases or mixtures according to the normalized height of the pipe by the diameter (h/*D*) in relation to the input oil volume fraction (OVF) for horizontal and small inclinations. The horizontal axis of the graphs identifies the in situ oil volume fraction from the 0 value at left to the maximum 1 value at right, while the vertical axis identifies the dimensionless height from the bottom (0) to top (1) of the pipe. The curves behavior corresponds to different flow patterns: stratified, stratified with mixing or dispersions. For stratified flows with mixing at the interface (ST&MI), the respective curves begin at the left hand side in the graph, corresponding to the height of the continuous water phase at the bottom of the tube. From this point, the oil volume fraction starts to be incremented due to the formation of the oil-in-water mixing region. A change of trend indicates the inversion to water-in-oil mixing, until the curve reaches the extreme right of the graph, when the in situ oil volume fraction reaches the maximum value, corresponding to the continuous oil phase at the top of the pipe.

Some simplifying assumptions were assumed for the development of a methodology for analyzing the data of Yusoff (2012), so that calculations could be performed. It was considered the hypothesis of plane interfaces between areas in the pipe cross section. Therefore, the possibility of having curved interface geometry (concave or convex) was not considered. In addition, the areas of the continuous phases and mixtures were calculated considering the symmetry of the flow through the cross section from the vertical diametrical line, i.e., the vertical center line.

For the curves of phases' distribution, in accordance with the in-situ oil volume fraction obtained through Wire-mesh sensor, it has been assumed that the height corresponding to the interfaces in the cross section of the pipe correspond to the mid-section of the oscillations of the curves. It is assumed that such inflections of the curves, or trend changes, correspond to spatial phase inversions, therefore locally the flow inverts from water-in-oil to oil-in-water dispersion.

The areas were calculated from equations deduced from the geometry of the cross section, always considering a planar interface and the symmetry of the flow. In the more general case, for which there are areas of mixture and areas of only the continuous phases, i.e., four distinct regions in the pipe' cross section, the θ angle is a function of three possible boundaries of separation: the interface between the two regions of mixture (Do/w and Dw/o) and two pseudo interfaces, separating each region of mixture from its respective continuous phase.

Finally, it has been proposed a method for estimating the two-dimensional packaging of droplets for the calculation of the entrainment factor. The "Droplets Packaging Factor in two-dimension" (DPF-2D) is used to estimate the areas occupied by the droplets over the cross section of the pipe from the curves of phase distribution presented by Yusoff (2012), which are shown in Fig. 1, by excluding the space between the droplets in the mixing area. By hypothesis, the droplets were assumed to be spherical, and the Sauter mean diameter d_{32} was used. It was also assumed non-coalescent droplets. These hypotheses are valid for quasi steady state flow conditions and for tiny droplets. The DPF-2D is used to correct the values obtained for the mixing areas. Therefore, the corrected areas tend to be more realistic since they consider that there is space between the droplets occupied by the phase in which the droplets are dispersed. A DPF-2D = 0.9070 was obtained. The dimensionless droplets areas, both normalized by the area of the pipe' cross section, $A_{w,droplets}/A$ and $A_{o,droplets}/A$, are presented in Table 1.

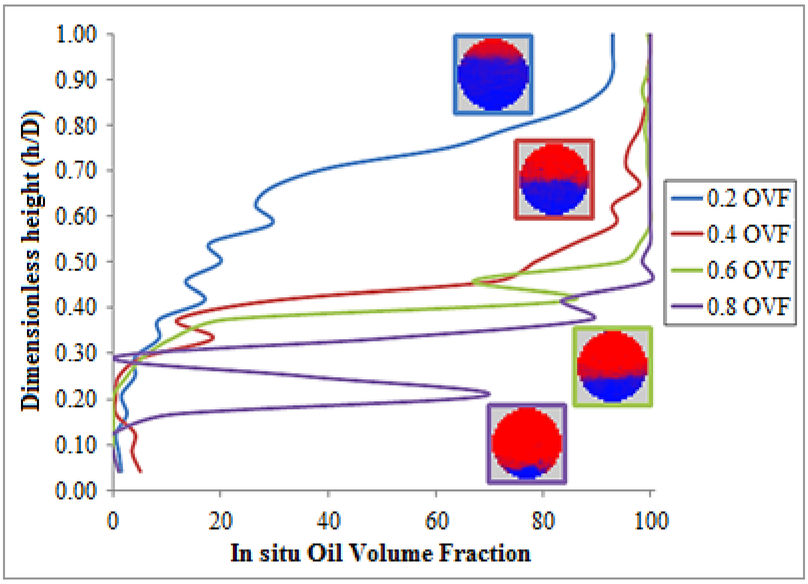

Figure 1 - Dimensionless height (h/*D*) as function of in situ oil volume fraction, and the phases distributions in the cross section of the pipe by tomographic images via Wire-mesh sensor at 10*D* from the pipe diameter expansion, *D* being the diameter of the pipe, to superficial velocity of mixture J_m = 0.20 m/s and different input oil volume fractions (OVF), horizontal flow. From Yusoff (2012).

3. RESULTS

3.1 Analysis of the data of Yusoff (2012)

3.1.1 Horizontal flow, inclination: 0°, OVF = 0.8

For each case analyzed, the mixture velocity is 0.20 m/s. In the Fig. 2, (a) is the PDF function, (b) is the longitudinal tomography, and (c) is the detailed horizontal chordal oil fraction with indication of the position of the interface. The Fig. 3 represents the vertical and horizontal chordal oil-phase fractions and transversal tomography. In horizontal flow the results are easier to explain due to the lack of gravity effects.

In this flow case, the flow pattern is ST&MI, the interface location is between -30 and -20 mm, arround -23 mm, given by the horizontal chordal oil fraction graph (Fig. 2c). However, when comparing the obtained results to the ones presented by Yusoff (2012), significant disagreement is identified. To Yusoff (2012), the chordal oil fraction graph for OVF = 0.8 (indicated in purple in Fig. 1) has approximately 5 points of trend changing. It does not happen in Fig. 2c. Instead of 5 strong changes, the chordal fraction graph in Fig. 2c presents 2 smooth transitions. In Yusoff (2012) analysis, the second point, the third point and the fourth point of changing, at in situ oil volume fraction of 0.10, 0.85 and 0.82, respectively, do not exist in Fig. 2c. If they were eliminated, both curves would be similar. In addition, Fig. 2c points the position -23 mm as the interface location. Because of those 'atypical changing points', if the same principle were applied in Yusoff (2012) curve, the most significant trend changing would be presented between 0.30 and 0.45 (h/*D*), where interface would be located. Moreover, according to the horizontal chordal oil fraction distribution (Fig. 2c), the interface is next to 0.32 (h/*D*). Therefore, for this flow, the found positions differ in 1.75 mm (5.2% of error), which is not a significant disagreement. The transversal tomography indicated in Fig. 3 strongly agrees with Yusoff (2012) tomography indicated in Fig. 4. Both images indicate the interface shape of the mixture and the proportions associated to each phase (in this case the oil fraction is predominant). In addition, the longitudinal tomography indicated in Fig. 2b is similar to spatial distribution presented by Yusoff (2012) presented in Fig. 5. Both images confirm the ST&MI flow pattern.

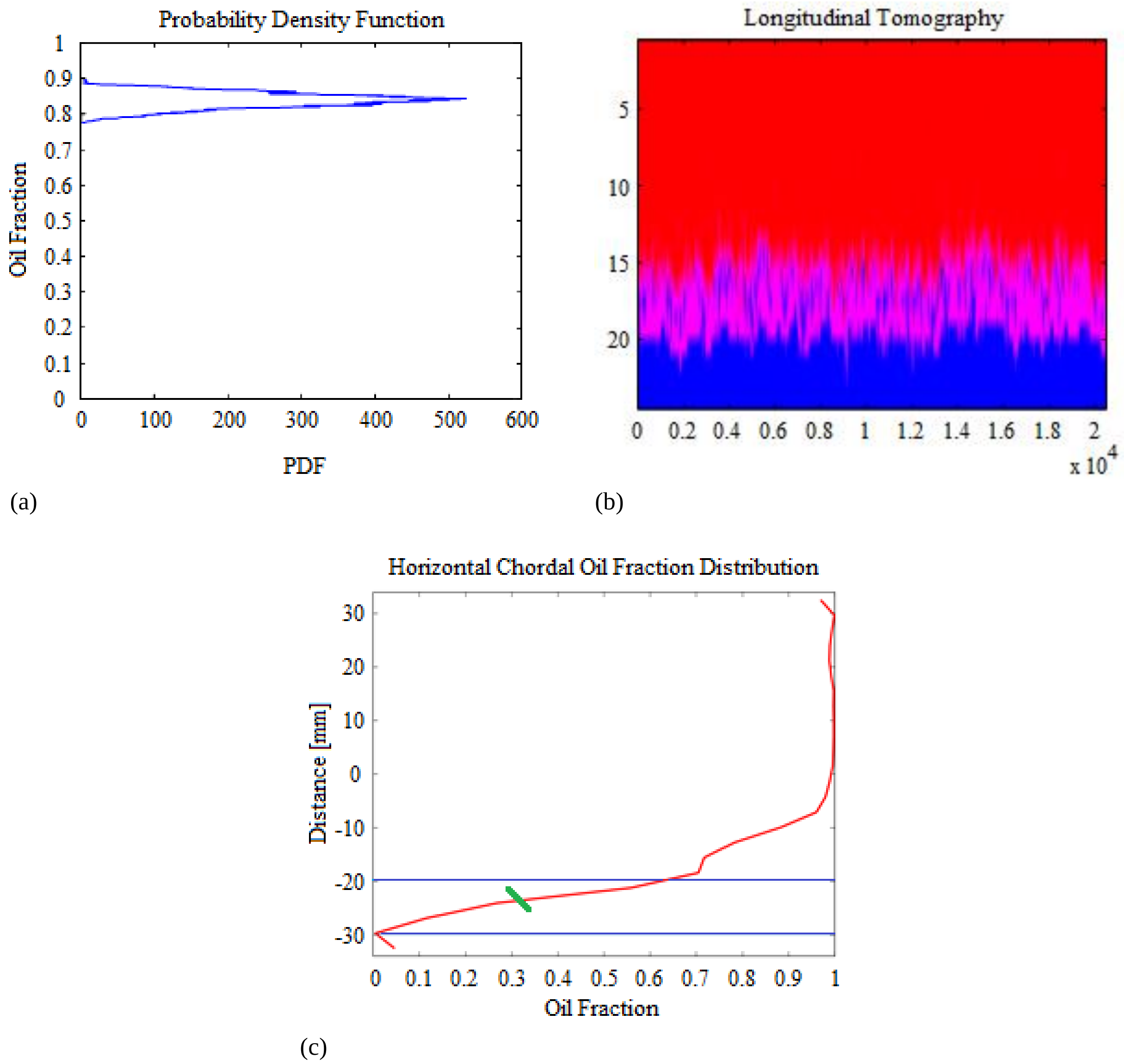

Figure 2 - Presents results: (a) PDF (Probability Density Function), (b) longitudinal tomography, and (c) horizontal chordal oil fraction with indication of the interface position (green trace), and horizontal flow at OVF = 0.8.

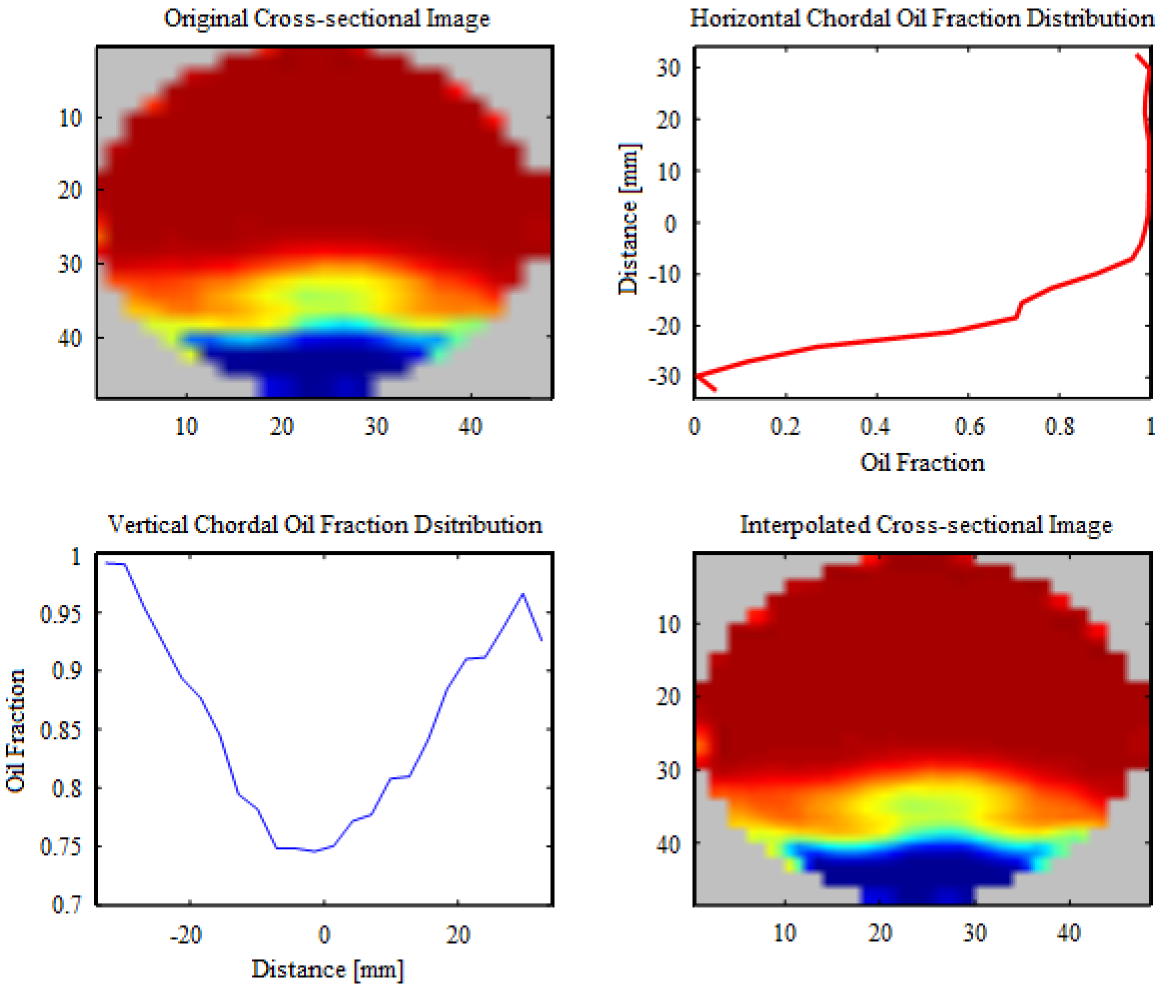

Figure 3 - Presents results: vertical and horizontal chordal oil-phase fractions and transversal tomography, horizontal flow at OVF = 0.8.

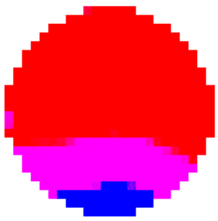

Figure 4 - Transversal tomography for superficial velocity of mixture J_m = 0.20 m/s and horizontal flow at OVF = 0.8. From Yusoff (2012)

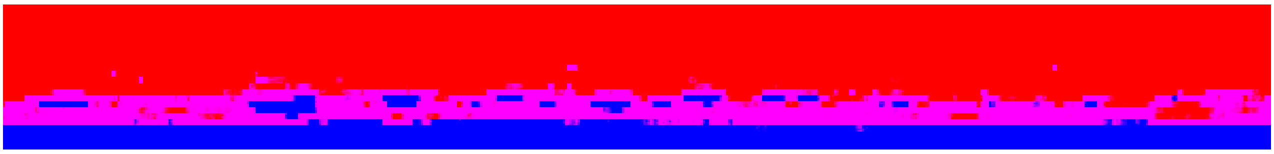

Figure 5 - Longitudinal tomography for superficial velocity of mixture J_m = 0.20 m/s and horizontal flow at OVF = 0.8. From Yusoff (2012)

3.2 Entrainment factors

Of all analyzed curves, 12 curves were identified corresponding to the flow pattern stratified with mixing at the interface (ST&MI), being 5 on horizontal. For these curves, the heights corresponding to the separation between the phases were identified as continuous or mixtures, described in sequence from bottom to top in the cross section of the tube: the height between the water continuous phase and oil in water mixture (Do/w), the interface height h_w/D between the oil in water mixture (Do/w) and water in oil mixture (Dw/o), and the height between the water in oil mixture (Dw/o) and the oil continuous phase.

For comparison with the results of h_w/D heights measured from the experimental curves of Yusoff (2012), it was used the two fluids model of Rodriguez and Baldani (2012), developed for liquid-liquid flows, in particular for wavy stratified oil-water flow. The model, identified as RB, was adjusted empirically for predicting the interfacial wave and possible curvilinear shapes of the interface in the pipe cross section (concave or convex), and as a function of contact angle, the in-situ oil volume fraction and the Eötvös number. For the present study, the model was implemented using the Mathematica® software, release 9.0, and the interface height h_w/D is found by an iterative numerical method, for each case. The results for the horizontal cases are shown in Table 1. The overall average error between the experimental and calculated h_w/D heights was of 10%, which shows that there is good agreement between the results from the proposed methodology and those calculated by Rodriguez and Baldani (2012) model.

The next step was calculating the corresponding areas of oil and water continuous phases and the mixture areas of dispersion of oil-in-water (Do/w) and water-in-oil (Dw/o), according to proposed methodology based on assumptions that consider the two-dimensional droplets packing factor, DPF-2D. The average values of droplet sizes for each flow condition described in Table 1 were obtained from Yusoff (2012). From the calculated areas, the entrainment factors of water and oil phases were then calculated. The dimensionless heights h_w/D of the interfaces as well as the dimensionless areas occupied by entrained droplets, $A_{w,droplets}/A$ and $A_{o,droplets}/A$, are presented in Table 1.

Table 1 - Interface heights h_w/D (dimensionless), areas of the mixing regions normalized by the pipe' cross section (dimensionless), and entrainment factors for horizontal cases of Yusoff (2012).

Inclin. [°]	J_w [m/s]	J_o [m/s]	h_w/D (exp.)	h_w/D (RB)	$A_{w,droplets}/A$	$A_{o,droplets}/A$	E_w	E_o
0	0.12	0.08	0.59	0.57	0.24	0.33	0.43	0.66
0	0.08	0.12	0.47	0.43	0.24	0.27	0.48	0.41
0	0.04	0.16	0.27	0.28	0.12	0.10	0.44	0.11
0	0.12	0.18	0.36	0.40	0.36	0.32	0.87	0.44
0	0.14	0.21	0.43	0.40	0.42	0.41	0.86	0.62

Regarding the entrainment factors, it is possible to observe in the data in Table 1 that the greatest values of entrainment factors corresponding to the cases where superficial velocities are the highest among all. Furthermore, in cases where there is a great difference between the water and oil superficial velocities, entrainment factors of the phases also exhibit significant differences in their values, higher entrainment factors for the higher superficial velocity of opposite phase. This is primarily due to the fact that the phase which is faster tends to be more turbulent, promoting a higher shears to the opposite phase. These results show that the entrainment factors are relevant parameters for understanding the behavior of fluids in stratified pattern flow with mixing (ST&MI), and they will allow studies on the modeling of entrainment factors in liquid-liquid flows for future, relating them to other flow parameters in each case to be studied. These results are unprecedented in the literature in the context of liquid-liquid flows, especially oil-water flows, what is relevant for the petroleum industry.

4. CONCLUSIONS

Based on what was presented in each flow situation and the comparisons made against Yusoff (2012) results, it can be concluded that some disagreements may have a reason on the data treatment. Since the same data was analyzed, it was expected same results and conclusions, or, at least, similar values for PDF functions, longitudinal and tomographies, horizontal/vertical chordal oil fractions, and interface position. It does not happen in some of the cases presented. Here, it is especially clear in horizontal flow conditions, when interface location differs significantly.

Most of the tomographies obtained matches the tomographies presented by Yusoff (2012). In mixtures classified as ST&MI, where interface position was similar when verifying tomographies, there was also a coincidence of interface location when applying the method of parallel lines in horizontal chordal oil fraction graphs. However, when there are differences, they are intense.

In some of horizontal chordal oil fraction graphs presented by Yusoff (2012), it is difficult to adopt the method of parallel lines. It happens because of the random behavior caused by some unexpected points of trend changing. Since boundary conditions and the analysis are the same, it is inferred that those differences are related to the programming involved in treating the data. It can be possible that the parameters used in the functions have come from a different weigh criterion. The weighing can change significantly the chordal fractions and the PDF functions, even if the boundary conditions are the same, which would directly affect the interface position.

Based on the methodology for the analysis of phases distribution curves obtained via Wire-mesh sensor in the work of Yusoff (2012), it was possible to calculate the entrainment factors of oil and water phases, relating them to the superficial velocities of the phases and consequently, to the formation of the flow pattern. It was possible to verify that the largest values for the entrainment factors are observed where the superficial velocity of opposite phase is much greater than the source phase of dispersed droplets, or when the superficial velocities of both phases are high. These results will allow future studies on the entrainment factors in liquid-liquid flows, relating them to other flow parameters in each case to be studied.

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