NUMERICAL SIMULATION OF OIL-WATER TWO-PHASE FLOW IN HORIZONTAL PIPES

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Abstract. *The numerical simulation of two phase flow through the CFD techniques have become of great interest due to the complexity of this type of flow. The present work aims to simulate the oil-water two-phase flow in horizontal pipes for stratification analysis of the mixture. In numerical simulations, incompressible flow, isothermal, steady state and laminar flow were considered. Numerical analysis of flow stratification was carried out for horizontal straight and curved pipe. FLUENT® was the commercial software employed in the simulation. Three-dimensional mesh generated by ICEM-CFD® program was used for numerical simulation. The numerical analysis flow pattern was carried out employing the Eulerian model, considering the drag and lift interphase forces. The simulation results for the horizontal straight pipe were qualitatively validated with experimental datas obtained in the Laboratory of Phase Separation of UNIFEI.*

Keywords: *Oil- water flow, Two-phase flow, CFD, Stratified flow, Model eulerian*.

1. INTRODUCTION

Two-phase flows are found in many industrial processes, as in petroleum, chemical, pharmaceutical, agricultural, etc.

The simultaneous flow of oil and water in pipelines commonly occurs in the petroleum industry, where crude oil and water are produced in wells, transported in pipelines and separate facilities of the process. Depending on the physical properties (density and viscosity), mixture velocities and the volume fraction, flows in pipes may acquire different flow patterns (Angeli and Hewitt, 2000). Different flow patterns were identified more accurately due to the advances in instrumentation techniques. The flow patterns and oil-water were examined more carefully as reported in the work of Trallero (1995), Nadler and Mewes (1997), Shi et al. (1999) Angeli and Hewitt (2000) and Elseth (2001). The Torres-Monzón (2006) work is one of the more recent studies in predicting the transition of flow patterns. Among the known patterns for oil-water flow in horizontal pipes, the goal of this present work was to analyze the stratified flow pattern. This flow pattern occurs at low mixture velocities (Lovick and Angeli, 2004).

Two-phase flow is governed by conservation laws such as conservation of mass, momentum and energy, expressed in terms of partial differential equations. The Computational Fluid Dynamics (CFD) is a numerical technique that searches through the numerical simulation to solve these equations (Hussain et al., 2007). CFD simulation is done by discretization of partial differential equations of conservation through numerical methods, such as the finite volume method (Lomax et al. Maliska 2000 and 2004).

In the works of Torres-Monzón (2006), Jun et al. (2006) and Damacena et al. (2009), the authors present a numerical study of oil-water flow in pipes through the techniques of CFD.

The numerical simulation of two-phase flow through the CFD tool have become of great interest due to the complexity of this flow type. With numerical simulation advancement it is currently possible to simulate a two-phase flow and obtain the global properties of the flow, like pressure rate and also details the flow field, such as shear stresses, velocity profile, pressure contour and streamline flow.

The aim of this work is to simulate the oil-water two-phase flow, in steady state, in pipes through the CFD tool for stratification analysis of the mixture. FLUENT® was the CFD software used to carry out the numerical simulations of two-phase flow. Three-dimensional mesh generated by ICEM-CFD® program was used for numerical simulation.

The numerical analysis flow pattern was carried out employing the Eulerian model. In this work is presented the fundamental equations that describe the stratification behavior.

2 EULERIAN MODEL

The numerical analysis flow pattern was carried out employing the Eulerian model considering the interphase forces such as drag and lift. The Eulerian model treats each phase as continuous medium occupying the entire domain of evaluation, where the amount of each phase present at each point of the domain is given by the volume fraction of phase (Drew, 1983 and Paladino, 2005). This model is the most complex multiphase models, because solves a set of equations including the equations of mass conservation, momentum and energy for each phase.

Isothermal flow was considered in the work, therefore the governing equations are expressed by the conservation of mass (or continuity) and momentum. Considering the steady flow and without mass transfer, governing equations are expressed as follows.

Continuity equation

The continuity equation for oil and water is given as

$$\nabla \cdot \left(\alpha_q \rho_q \vec{v}_q\right) = 0 \qquad (q = 1{,}2) \tag{1}$$

where α_q is the volume fraction of phase *q*, ρ_q the density of phase *q* and $\vec{v}_q$ the velocity of phase *q*.

Momentum equation

The momentum equation for phase *q* is

$$\nabla \cdot \left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right) = -\alpha_q \nabla p + \nabla \cdot \bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} + \sum_{p=1}^{n} K_{pq}\left(\vec{v}_p - \vec{v}_q\right) + \alpha_q \rho_q \left(\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{vm,q}\right) \tag{2}$$

where $\vec{F}_q$ is the external body force, $\vec{F}_{lift,q}$ is the lift force, $\vec{F}_{vm,q}$ is the virtual mass force and $\bar{\bar{\tau}}_q$ the shear stress tensor of phase *q*, defined as

$$\bar{\bar{\tau}}_q = \alpha_q \mu_q \left(\nabla \vec{v}_q + \nabla \vec{v}_q^{\,T}\right) + \alpha_q \left(\lambda_q - \frac{2}{3}\mu_q\right) \nabla \cdot \vec{v}_q \bar{\bar{I}} \tag{3}$$

and K_{pq} is the interphase momentum exchange coefficient. This coefficient was calculated using Schiller and Naumann model, for evaluating the drag force.

The coefficient K_{pq} can be calculated by the following form

$$K_{pq} = \frac{\alpha_q \alpha_p \rho_p f}{t_p} \tag{4}$$

where f is the friction factor, defined according to the drag coefficient (C_D)

$$f = \frac{C_D \,\mathrm{Re}}{24} \tag{5}$$

and

$$C_D = \begin{cases} 24\left(1 + 0{,}05\,\mathrm{Re}^{0{,}687} / \mathrm{Re}\right) & \mathrm{Re} \le 1000 \\ 0{,}44 & \mathrm{Re} > 1000 \end{cases} \tag{6}$$

where R_e is the relative Reynolds number, defined by

$$\mathrm{Re} = \frac{\rho_q \left|\vec{v}_p - \vec{v}_q\right| d_p}{\mu_q} \tag{7}$$

3. DETERMINATION OF THE OIL DROP DIAMETER

The oil drop diameter was obtained by an instrument that employs the laser diffraction principle to determine the distribution. Based on the experimental data, it was evaluated the drop averaged diameter in percentage of accumulated volume function (see Fig.1) to generate a polynomial function with the objective to determine the values of drop diameter for different percentages of accumulated volume. The Figure 1, shows the variation of the diameter of oil drop to 3% oil in water.

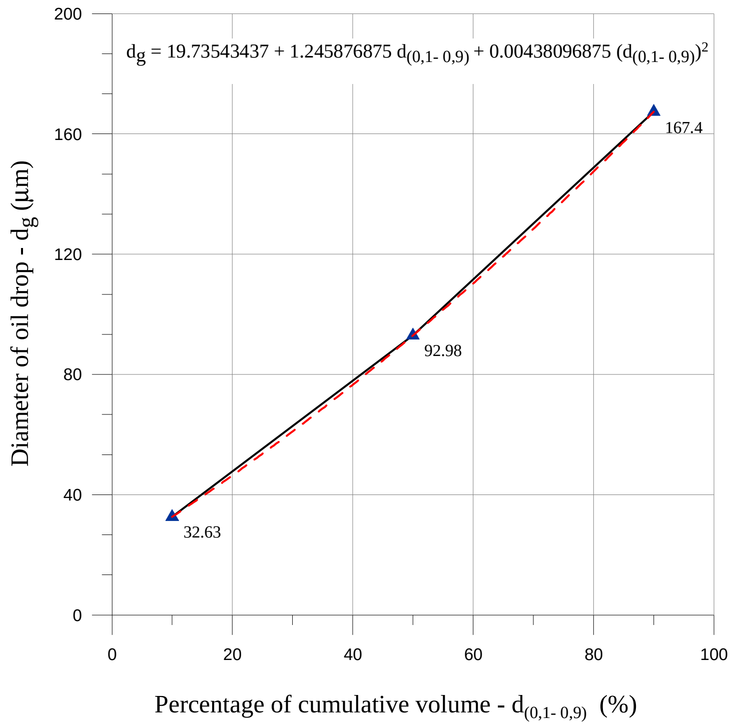


Figure 1 - Variation of the diameter of oil drop to 3% oil in water.

4. BOUNDARY CONDITIONS

The boundary conditions used in the simulations were: inlet velocity of oil and water, oil concentration, oil drop average diameter, reference pressure outlet and no slip at the wall condition.

5. RESULTS AND DISCUSSION

ICEM-CFD® software was employed to define the geometry and mesh. A structured mesh hexahedrical type "O-grid" was chosen. The mesh was refined (adapted) in the region of interphase to satisfy the condition of mass balance equation. For the numerical simulations, three-dimensional (3D) mesh was generated. The numerical simulations were carried out at the Hydrodynamics Virtual Laboratory (LHV), of the Mechanical Engineering Institute of Federal University of Itajubá.

The physical properties of oil and water used in the simulations are presented in Table 1.

Table 1 - Physical properties of water and oil.

Flow	Physical Properties	
	Density (kg/m^3)	Dynamic viscosity (kg/m-s)
Water	980	0,001003
Oil	880	0,02896

Laminar flow was considered for all numerical simulations, being Reynolds number Re = 1136 to 3% of oil and Re = 397.78 for 15% of oil.

5.1. Stratification analysis flow for a straight pipe

For the stratification analysis flow in a straight pipe (horizontal), a 3D mesh was generated for a pipe with length L = 13 m and internal diameter d = 0.0238 m. The data used in the simulation were: velocity of the oil and water u = 0.09 m / s, concentration oil $C_{óleo}$ = 3% and average diameter of oil drop d_g = 93 µm.

Figure 2 shows the contours of volume fraction oil in transverse planes of each 2 m of the pipe. The upper region (red) represents the major concentration of oil, the bottom region (blue) represents a minor concentration of oil and the middle region represents the interphase separating the two regions. It can be seen that from 2 m to 12 m pipe length, the flow pipe stratification becomes stable starting from 6 m.

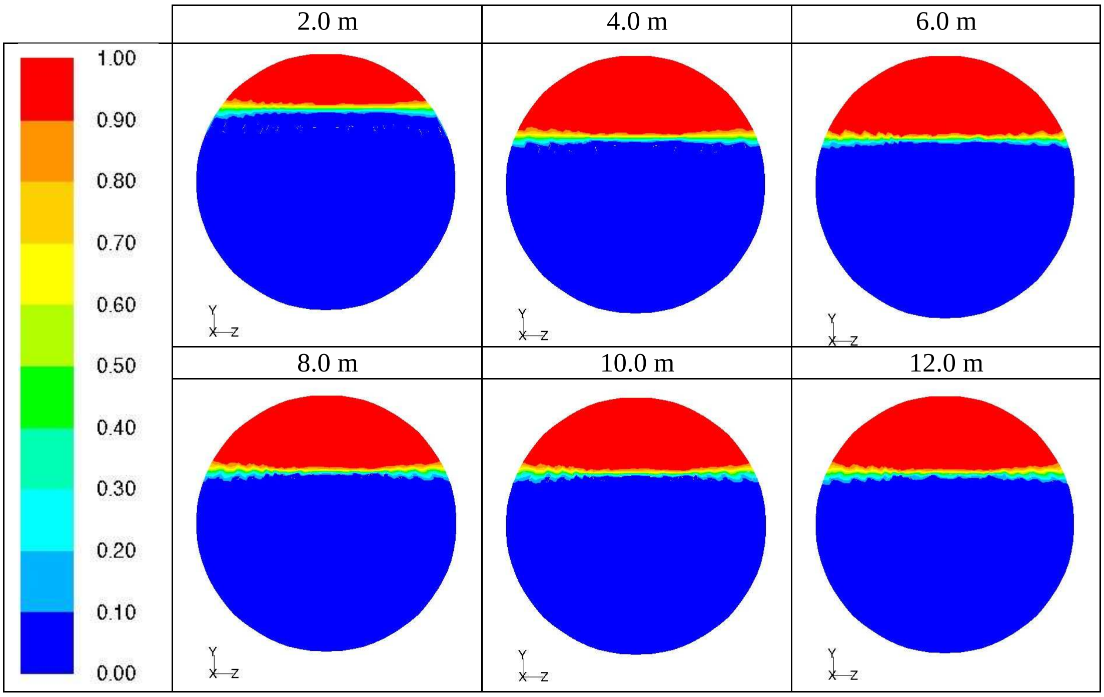


Figure 2 - Volume fraction contours of oil in different pipe transverse plans - 3% oil.

Figure 3 shows the behavior of the interphase of stratification for volume fractions in the interphase to 0.40, 0.65 and 0.90 for oil in the longitudinal plane. Note that the stratification occurs along the pipe. It is also observed that in the outlet region there is an instability at the interphase caused by reverse flow.

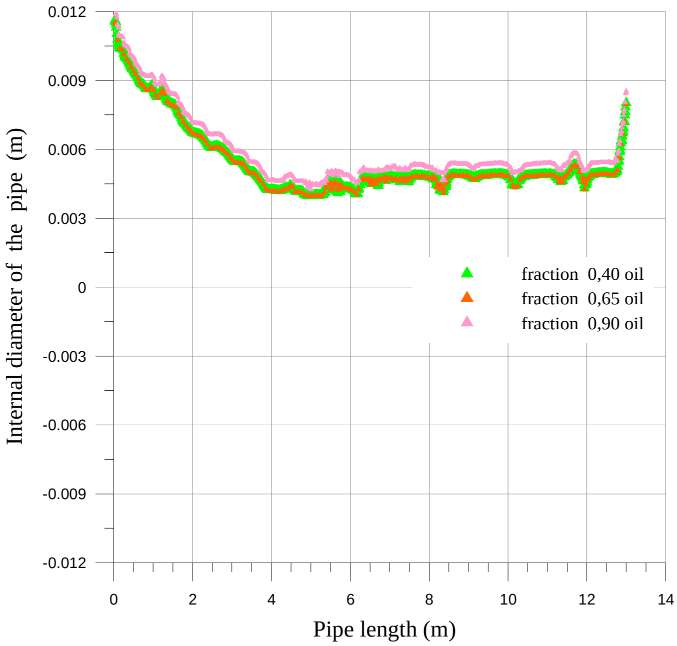


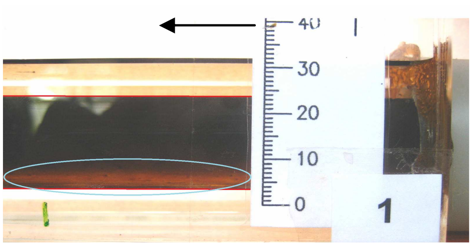
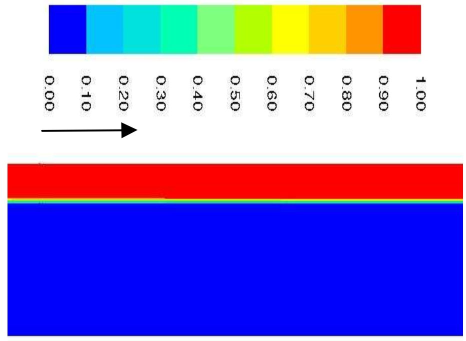
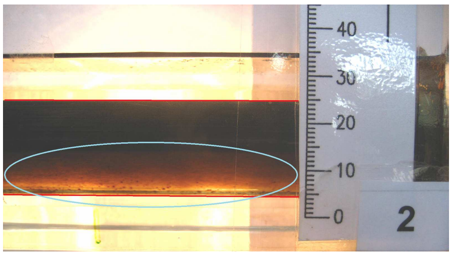
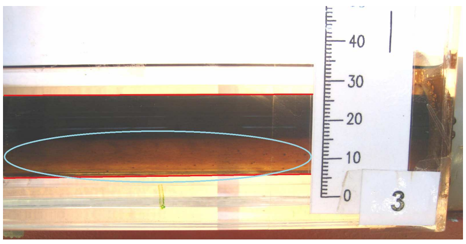
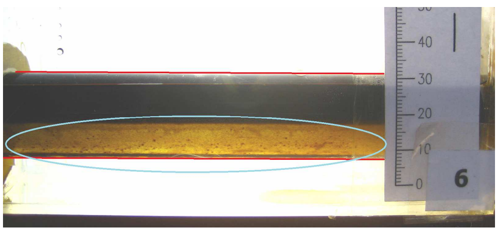
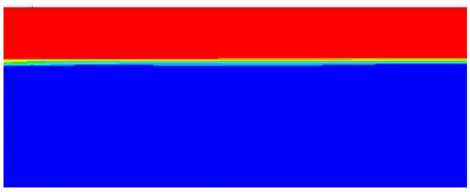
Figure 3 - Interphase of stratification for different volume fractions of the oil plane longitudinal - 3% of oil.

5.1.1 Validation of the oil-water flow

The simulation results for the horizontal straight pipe, were compared and validated with experimental data obtained in the Laboratory of Phase Separation of UNIFEI, as shown in Table 2.

Table 2 shows the flow visualization with 3% oil in water for experimental tests and simulations. The flow visualizations were made to sections of the pipe 2 m, 4 m, 6 m and 12m. It can be observed in both, the simulation and in experimental ,the stratification of the flow along the pipe.

Table 2 - Visualization of two phase oil-water flow to 3% oil - experimental and simulation.

3% de óleo	
Flow visualization - experimental	Flow visualization - numerical simulation
 Visualization 2.0 m.	 Section 2.0 m.
 Visualization 4.0 m.	 Section 4.0 m.
 Visualization 6.0 m.	 Section 6.0 m.
 Visualization 12.0 m.	 Section 12.0 m.

5. 2. Analysis of the curvature of the pipe in the stratification

To analyze the effect caused by the curvature of the pipe in stratification were considered curves with different radius. It generated a 3D mesh for a pipe with curve (horizontal) of length L = 6 m and internal diameter d = 0.0216 m. Different geometries were obtained for aspect ratios (r/d), as shown in Table 2.

The following parameters oil and water velocity u = 0.09 m/s, oil concentration $C_{óleo}$ = 3% and oil drop average diameter d_g = 35 μm were employed in the simulations.

Table 3 - Geometric relations for the pipe with the curve.

Case	Pipe internal diameter (m)	Curve radius (m)
1	0.0216	0.0216
2	0.0216	0.1400

The Figure 4 shows the contours of oil volume fraction with 3% oil in water, for a pipe with a curvature radius of r = 0.0216 for Case 1. It can be observed that stratification occurs before the curve and this has a mixture of flow due to centrifugal effect, and after the curve the flow becomes stratified.

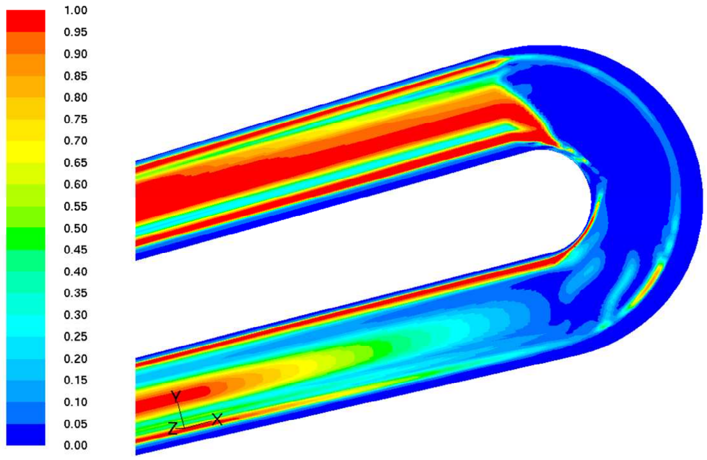


Figure 4 - Contours of volume fraction of oil to 3% oil in water - Case 1.

In Case 2 the results is shown in Figure 5. In this case it's considered the contours oil volume fraction with 3% oil in water, for a pipe with a radius of curvature r = 0.140 m. It can be observed that the stratification is maintained along the pipe, being little influenced by the curvature of the pipe.

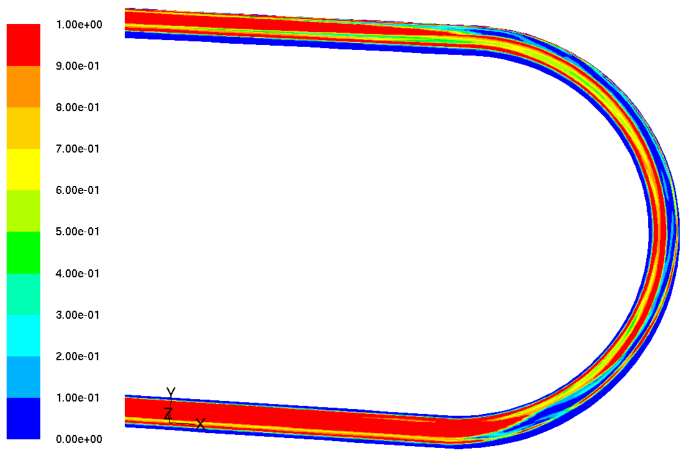


Figure 5 - Contours of volume fraction of oil to 3% oil in water - Case 2.

5. 3. Analysis of the diameter of oil drop in the stratification

To analyze the influence of the oil drop diameter in the flow stratification, a 3D mesh was generated for a horizontal straight pipe of length L = 2 m and internal diameter d = 0.025 m. The following parameter oil and water velocity u = 0.09 m/s, oil concentration of $C_{óleo}$ = 15% and oil drop average diameter d_g = 85 μm were employed in the simulations.

This analysis was carried out with different values of oil drop diameter in order to analyze the flow stratification along the pipe.

Figure 6, shows the behavior of the stratification interphase for 6 values of oil drop diameter (d_g) in the longitudinal plan. It can be seen variations in the interphase for the 6 drop diameters. For the diameter d_g = 20, 40, 85 and 170 μm was observed a stable stratification along the pipe. For the diameter d_g = 340 μm it can be noted the stratification at the beginning of the pipe and from 0.6 m is a mixture of the flow. For the diameter d_g = 680 μm is a mixture of 0.2 m from the pipe. A better view of the behavior of the interphase for d_g = 340 and 680 μm can be seen in Figure 7 (a-b).

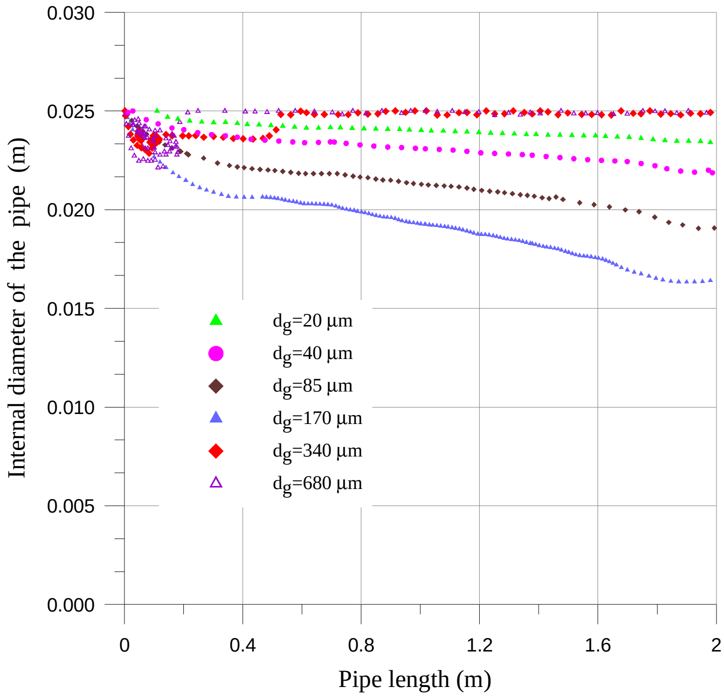


Figure 6 - Interphase of stratification for variation of the diameter of oil droplets.

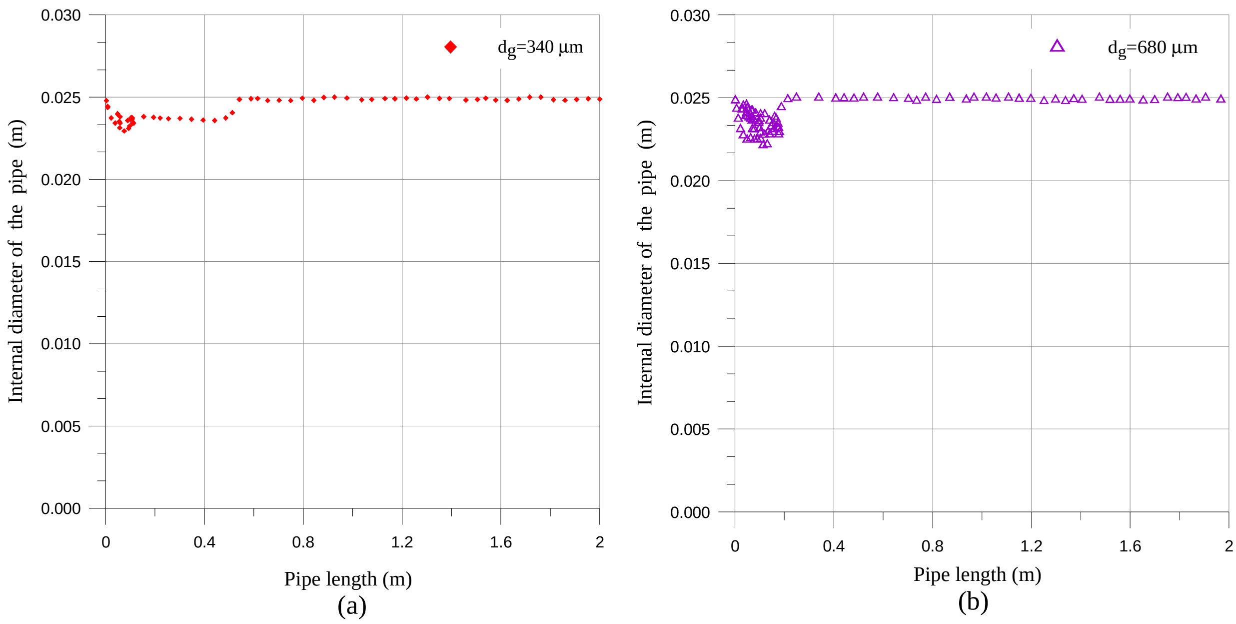


Figure 7- Interphase of stratification to drop diameter. a) d_g = 340 μm b) d_g = 680 µm.

6. CONCLUSIONS

For the analysis of straight pipe, it was observed the stratification of the oil-water flow along the pipe. The results of numerical simulation compared and validated with experimental results show a qualitative agreement between them.

For the analysis of the pipe with the curve, it was observed that the curve influence the stratification of the flow, and for smaller radius the mixture flow is more significant. For analysis of the oil drop diameter, it was observed that smaller diameter was obtained an interphase with more stable stratification in comparison to larger droplet diameters.

7. ACKNOWLEDGEMENTS

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