19th Brazilian Congress of Thermal Sciences and Engineering
November 6th–10th, 2022, Bento Gonçalves - RS - Brazil

ENCIT-2022-0290
DYNAMICS OF HORIZONTAL CORE-ANNULAR FLOW VIA PARTICLE IMAGE VELOCIMETRY (PIV)

Jorge E.Arrollo-Caballero
P. J. Miranda-Lugo
University of São Paulo (USP), São Carlos School of Engineering (EESC), Mechanical Engineering Department, Industrial Multiphase Flow Laboratory (LEMI), Av. Trab. São Carlense, 400 - Parque Arnold Schimidt, São Carlos - SP, 13566-590, Brazil.
jorgearrollo@usp.br*,pjosemiranda@usp.br,

Marlon M. Hernandez-Cely
Engineering Center, Federal University of Pelotas, Rua Benjamin Constant, n° 989, Porto, Pelotas 96010-020, RS, Brazil.
marlonhc@usp.br

O. M. H. Rodriguez
University of São Paulo (USP), São Carlos School of Engineering (EESC), Mechanical Engineering Department, Industrial Multiphase Flow Laboratory (LEMI), Av. Trab. São Carlense, 400 - Parque Arnold Schimidt, São Carlos - SP, 13566-590, Brazil.
oscarmhr@sc.usp.br

Abstract. *The interaction of non-miscible liquids is frequently encountered in the petroleum, food and chemical industry, where applications such as transportation of heavy oil with the injection of small amounts of water are found. When those fluids flow in a pipeline, they can take different spatial configurations called flow patterns, each with different hydrodynamic characteristics. One of those configurations is the core-annular flow pattern, in which the most viscous fluid is in the pipe's core, while the less viscous fluid forms a ring around the core and it is in contact with the pipe wall. That flow pattern is interesting because it can be used to reduce pressure losses in pipes in transport or production applications. Some theories on the hydrodynamic stability of the core-annular flow have been suggested in the literature. One of them is the lubrication model, which considers that the lubrication forces counterbalance the buoyance forces acting on the core, so that the interfacial waves are not symmetric and the interface must be wavy for the annular flow to be stable. The levitation model proposes that inertial forces on the core are responsible for the stability of the flow. Some authors state that both phenomena can coexist and promote the stability of that flow pattern. However, there is no agreement on which theory best describes the core-annular flow's hydrodynamic stability. In order to study the dynamics of a horizontal oil-water core-annular flow, we will obtain non-intrusive instantaneous local velocity measurements of cross-sectional and lateral flow fields and turbulence statistics at the water ring via PIV and high-speed video camera. New experimental data will be collected considering different flow regimes for the oil and water phases. Regions of high shear are expected to be close to the pipe wall and at the liquid-liquid interface. One can hope that such analysis shed some light on the core-annular flow dynamics and phenomena that may promote the stabilization of the oil core.*

Keywords: *Core-annular flow, Hydrodynamic stability, Oil-water flow, PIV, Velocity profiles.*

1. INTRODUCTION

Non-miscible liquid-liquid flows are present in nature and in much industrial equipment, such as air conditioning and refrigeration systems, nuclear and coal-fired power plants, and chemical processing systems. However, studying two-phase flows is not so easy to analyze due to the complexity of the interaction between phases, thus making the prediction of their behavior complicated by their different flow regimes, which are presented as: dispersed flows, separated flows and intermittent flows. The dispersed flow consists of water bubbles in the oil or vice versa, the intermittent flow consists of the separation that is generated between the continuity of the flow, such as oil generating large bubbles separated by water droplets. In the separated flows we find the core-annular and stratified pattern.(Brauner, 1991; Rodriguez and Bannwart, 2008; Rodriguez and Castro, 2014). For some years now the transport of highly viscous fluids in industrial and commercial processes has been attractively implemented, One of the flow patterns, which seems most attractive from the point of view of reducing the pressure loss in liquid transport lines, is that of the central core flow of highly viscous fluid, while the less viscous fluid (water) forms a uniform ring in the high shear rate region next to the pipe wall.

In order to observe these flow patterns, we must take into account the properties of the fluid, the geometry and the size of the pipe. In the literature, we can find studies that contribute greatly to the compression of these. Angeli and Hewitt (2000) conducted experiments to show other properties that affect fluid behavior, such as working with steel ducts, showing that the differences due to the wall are significant. Brauner (1991) states that theoretical studies of annular flow can be divided into two main groups: the first includes those studies that use the general concept of encapsulation of solids or viscous liquids that are displaced by less viscous liquids; in the second group, direct solutions of the hydrodynamic or fluid instability equations are more common (Brauner, 1991; Angeli and Hewitt, 2000; Shi and Yeung, 2017).

Over the years efforts have been made to capture the local velocity needed to guide the development of fluid flow models, for annular core flow, many of these studies have focused on the thin film generated by the less viscous fluid, some of these studies have generated an amalgam of techniques to capture the nature of the velocity field such asHewitt *et al.* (1990) who used photochromatic dye as a tracer, obtaining these velocity profiles of an axial flow and other authors such as: B. (1995) who applied this technique of photochromatic dye activation in horizontal annular flows and with their study of the behavior of the fluid contributed to the analysis of the upward transport of liquids.

Actually, the study of velocity profiles by means of optical techniques has increased the compression of these flow patterns. This experimental campaign is focused on the study of the dynamics of core-annular liquid-liquid flow, which is carried out with the optical technique particle image velocimetry (PIV). The velocity vector fields This technique mentioned above takes some techniques to improve the visualization of the fluid because the thickness of the liquid is of millimeter order, among these techniques we find the use of tracer particles, fluorescent dyes, image processing techniques, among others. Some researchers adopted several techniques and made a combination of these, Ashwood *et al.* (2014) used a technique described Shedd (2001) as thin film particle imaging velocimetry (TF-PIV), this technique is a combination of typical micro-piv seeding and imaging with a unique approach to illumination and image processing to cope with the challenges of a constantly varying liquid layer and interface, they were able to obtain detailed velocity profiles in a vertically rising annular liquid film.

In the following work we will use some of these techniques found in the literature for the application of PIV-2D in the study of flow dynamics, we will also use theoretical models and methods for image processing, seeking to extract velocity profiles and contribute to improve the compression of this pattern.

2. EXPERIMENTAL WORK

2.1 Experimental setup

One can see in Fig. 1 a schematic view of the new test facility designed and built up to study the dynamics of stratified liquid-liquid flow. Water (ρ_w = 995 kg/m^3, μ_w = 1.0 mPa.s) and oil (ρ_o = 820 kg/m^3, μ_o = 1.64 mPa.s) were adopted as working fluids. There are two independent supply lines, one for water and another for oil, and two test sections (F and K), made of borosilicate-glass pipes with lengths (L_p) of 4.5 and 7.5 m and internal diameters (i.d.) of 9.7 and 20.5 mm, respectively. Each test section has a rectangular transparent acrylic viewing section (G and L), where the PIV system and a high-speed video camera will be installed. The fluid distribution system is driven by gravity from two reservoirs (A and B). The liquids are injected into the test section through a set of flow straighteners (C, D, H, and I) and a specially designed inlet section (E and J). The former aims to reduce large-scale flow structures at the test section inlet, while the latter prevents the fluids from mixing inside it and promotes stratified flow once the liquids get together in the test section. Both flow lines have an array of liquid flowmeters (1, 2, 4, 5), thermocouples type K (3, 6, 7, 8), and differential pressure transducers (9, 10). The two-phase mixture that comes from the test section is transferred to an oil-water separator (M). From this separator, each fluid is driven to tanks (N and Q) and then pumped by positive displacement pumps (P and S), controlled by variable-frequency drivers (O and R), to their respective reservoirs (A and B), completing the test loop. The liquids' columns in reservoirs A and B are controlled through gauge pressure sensors installed in each tank. A control system based on LabVIEW® will allow setting the water and oil flow rates, selecting the appropriate pumps and flowmeters, and checking in real-time the experimental conditions. Images of the oil-water stratified flow in the lateral and cross-section views will be taken separately using a high-speed video camera. Image processing algorithms will be applied to the collected images to obtain two-phase velocity profiles, turbulence statistics, and the interface's longitudinal (R_1) and cross-section (R_2) curvature.

2.2 Experimental procedure

This experimental campaign is based on the study of annular flow dynamics in horizontal pipes in the film section generated by the water and in the upper and lower part of the pipe by means of PIV. Once the liquid distribution is stabilized by the viscous forces, where the more viscous fluid stays in the center and the less viscous fluid in this case water forms the ring around the oil, the surface velocities Jo and Jw will be established by a flow pattern map in our annular flow condition

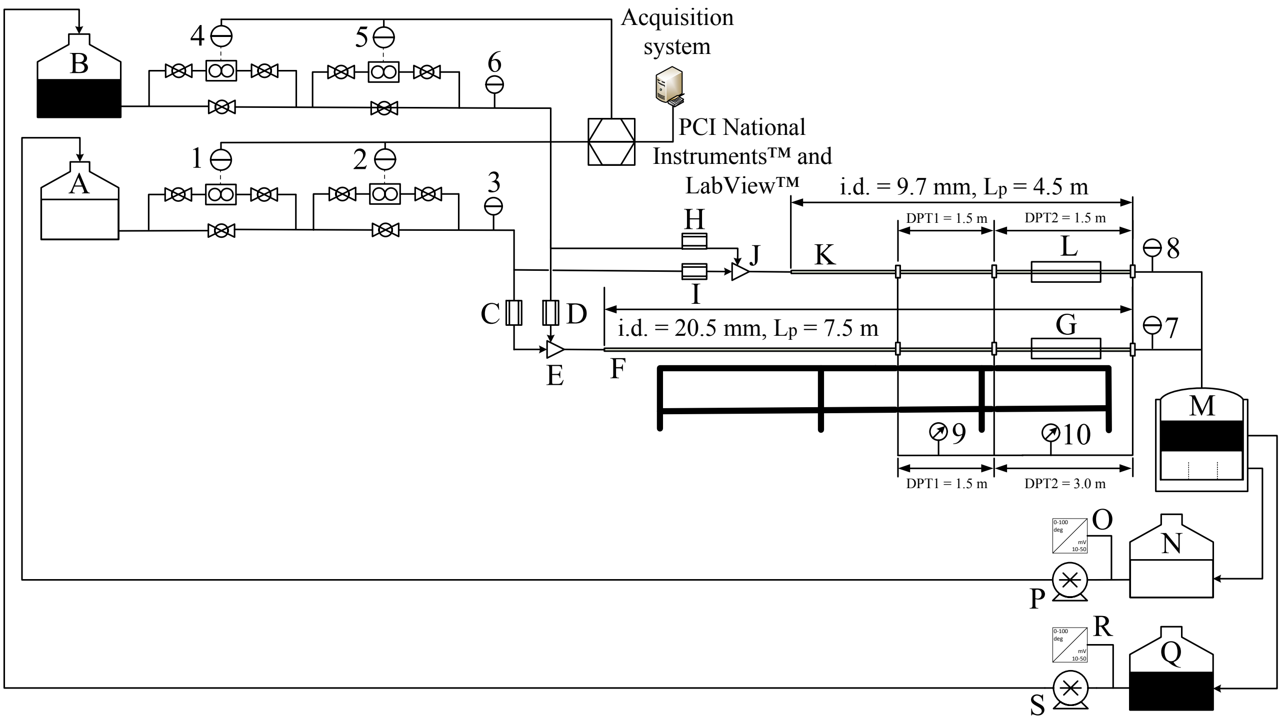


Figure 1. Schematic representation of the liquid-liquid test facility installed at the Industrial Multiphase Flow Laboratory (LEMI) of the University of São Paulo (USP) at the São Carlos campus.

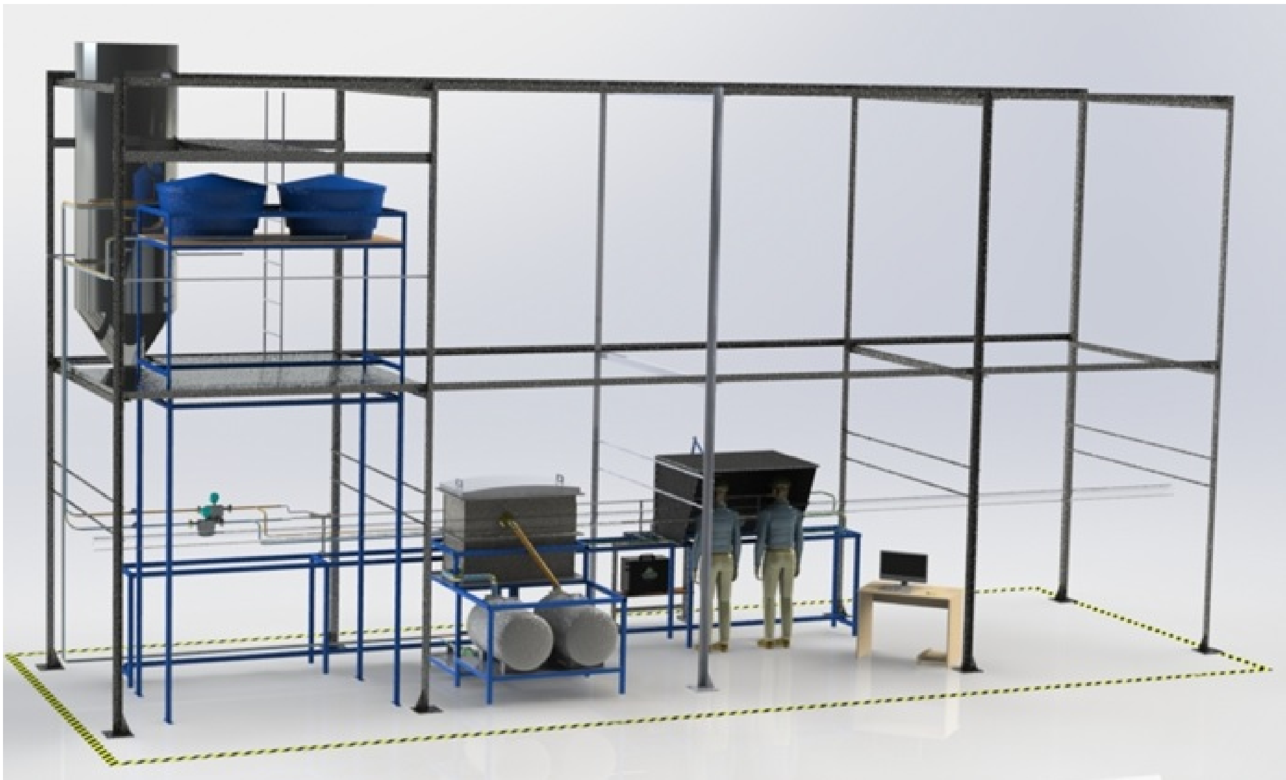


Figure 2. 3D experimental installation

corresponding to this experiment. This flow pattern map in horizontal liquid-liquid pipes for a 20.5 mm pipe was drawn using the one-dimensional liquid-liquid flow model proposed by Rodriguez and Castro (2014) and can be seen in fig. 3. That model takes into account a wavy, concave or convex interface depending on the Eötvös number, the interface height and the contact angle is used to calculate the in situ mean flow magnitudes such as phase Reynolds numbers and liquid holdups. Since the liquid-liquid interface scatters the laser sheet (Nd:YAG laser with wavelength of 532 nm) of the PIV system and the laser direction changes due to the mismatch of the refractive index of the fluids (Snell's law), the evaluation of the stratified flow dynamics using the PIV technique will be performed separately for each fluid, i.e., the oil and water phases will be studied non-simultaneously. The PLIF and TF-PIV technique will be used to identify the velocity profiles formed at the top and bottom longitudinally To combine the two techniques, hollow glass spheres with an average diameter of 10 µm will be used.

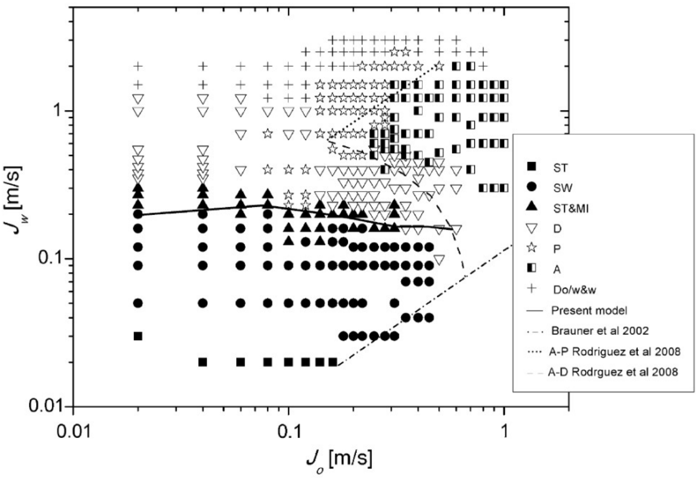


Figure 3. Flow-pattern map of the superficial velocities; ST – stratified smooth, SW – wavy stratified, STMI – stratified with mixing, D – oil drops, P – plug, A – core-annular,Do/ww – oil-in-water dispersion with water layer. The test section inclination is measured from the horizontal.Extracted from Rodriguez and Castro (2014)

Since the liquid-liquid interface scatters the laser sheet (Nd:YAG laser with wavelength of 532 nm) of the PIV system and the laser's direction change due to the mismatch of the fluids' refractive index (Snell's law), the assessment of the dynamic of the stratified flow via PIV technique will be carried out separately for each fluid, i.e., the oil and water phases will be studied non-simultaneously. The PLIF technique will be used to identify the liquid-liquid interface's shape and its longitudinal curvature radius. To combine the two techniques, hollow glass–spheres with a mean diameter of 10 μm and a density of 1,100 kg/m^3, and silver coated glass spheres with a mean diameter of 50 μm and a density of 800 kg/m^3, will be seeded into the water and oil phases, respectively. In addition, rhodamine 6G will be added to the water phase to obtain a clear distinction between the phases and, therefore, to identify clearly the liquid–liquid interface. The choice of the fluorescent dye for the PLIF technique was based on the excitation and emission spectra. We found that rhodamine 6G has an excitation peak at a wavelength of 530 nm (green light) and an emission peak at 552 nm (yellow light). Figure 4 described the setup for data collection procedure. To study the water phase's dynamic, the laser sheet will be located under the viewing section towards the bottom up, while for the oil phase the laser will be installed above the viewing section towards top to bottom. An array of high-speed video camera Olympus i-Speed3, suitable lens, and a high-pass filter with cut frequency of 550 nm will be used to block the scattered light from the liquid-liquid interface and the hollow glass–spheres at 532 nm (green light). In addition, pressure drop data for single-phase and two-phase flows will also be collected during the experiments.

2.3 Processing and data analysis

The instantaneous velocity data obtained by the PIV technique will be analyzed in order to assess the hydrodynamic of the stratified flow. Since the oil and water phases will be studied separately, the experimental data processing will be also evaluated independently for each phase. The time-mean local axial $\langle u \rangle$ and radial $\langle v \rangle$ velocity components are calculated by Eq. 1.

$$\langle u \rangle = \frac{1}{n}\sum_{i=1}^{n} u_i \qquad \text{and} \qquad \langle v \rangle = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{1}$$

where n represents the number of instantaneous velocity data (number of images), u_i and v_i are the instantaneous and local axial and radial velocity components, respectively. On the other hand, the standard deviation of the local velocity components, or velocity fluctuation rms (root mean squared) are estimated by Eq. 2.

$$u_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (u_i - \langle u \rangle)^2} \qquad \text{and} \qquad v_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (v_i - \langle v \rangle)^2} \tag{2}$$

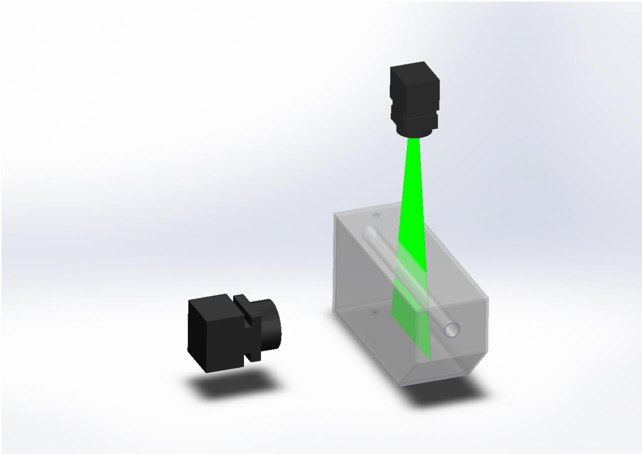


Figure 4. fig: Data collection methodology

The cross-moments are defined by Eq. 3. Here, $u\prime$ and $v\prime$ represent the velocity fluctuation components in streamwise and wall normal directions. The Reynolds shear stress is obtained by multiplying the cross-moments and the liquid density ($\rho \langle u\prime v\prime \rangle$).

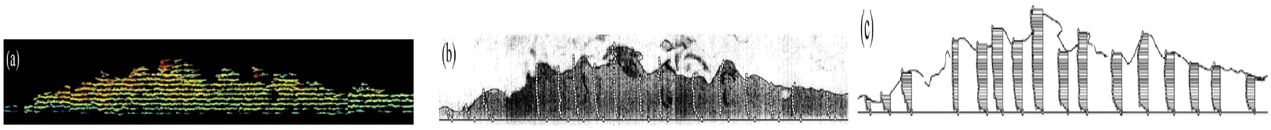
$$\langle u\prime v\prime \rangle = \langle uv \rangle - \langle u \rangle \langle v \rangle = \frac{1}{n}\sum_{i=1}^{n} (u_i - \langle u \rangle)(v_i - \langle v \rangle) \tag{3}$$

3. EXPECTED RESULTS

This section presents the obtaining of longitudinal velocity profiles in the water film generated around the oil in a liquid-liquid annular flow for the study of fluid dynamics with similar techniques and theoretical models to those reported in the literature.

3.1 Longitudinal velocity profile acquisition via PIV

In fig 5(a) showing us also some velocity fields that are presented along the longitudinal section, and film thickness, all this is obtained after capturing the images of the particles in a time interval (t), these images are processed and thus achieving general velocity profile and velocity fields as shown in fig 5.

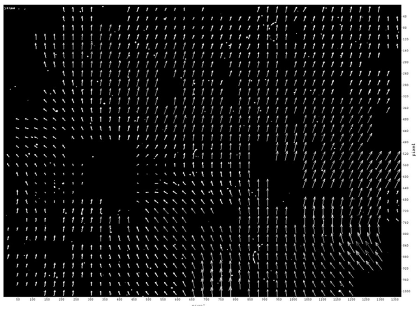


(a) (b) (c)

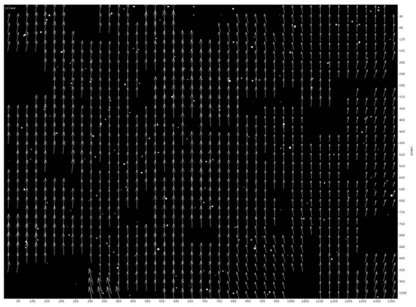
Figure 5. (a) PIV velocity vector-map, (b) instantaneous velocity profiles superimposed on an instantaneous raw image with highlighted two-phase interface and the wall position, and (c) resulting instantaneous velocity profiles. Extracted from Zadrazil and Markides (2014)

3.2 Dynamics of core-annular liquid-liquid horizontal pipe flow via PIV

The PIV technique has some sources of measurement uncertainties, these include statistical, calibration, data filtering and resolution sources. Two of these are produced by random errors such as statistical and resolution uncertainties, which are corrected with a large number of samples. The Davis software used for PIV data processing has an accuracy of ± 0.05 pixels for images per interrogation region with at least 7 particles, which must be taken into account since these regions must have 6 or more particles to be valid vectors. Ashwood *et al.* (2014) and Zadrazil and Markides (2014) have obtained some interesting velocity profiles in annular flow, which they managed to obtain with different techniques as in the case of Ashwood *et al.* (2014) who used TF-PIV, managing to obtain vector maps in a radial position, also being able to observe pressure gradients and film thicknesses. What is really interesting is that they have managed to capture these velocity profiles in the regions close to the wall, being a region where data are scarce or sometimes unreliable in the literature. Fig 6 shows some velocity vector profiles obtained by Ashwood *et al.* (2014) in which shows that the technique has great utility for regions where we have film thicknesses in ranges of a few millimeters or less than 1 mm, this being the biggest challenge of the current experiment, which is performed in a 20.5 mm pipe and where that water film can be in a range of 1 mm. These data that will be extracted from the experiments will be compared with those found in the literature and studied with the models proposed by some authors in the literature.



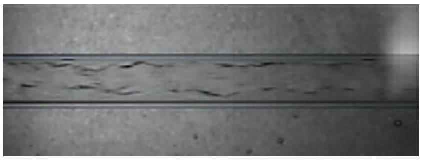
(a)



(b)

Figure 6. two additional instantaneous vector maps randomly selected from data at 90 um from the wall. The scales are in pixels with a scale factor of 0.8 um/pixel. Extracted from Ashwood *et al.* (2014)

The following images were obtained in the industrial flow laboratory of USP with a high-speed camera recording in a 9.7 mm tube, showing the annular flow pattern and the interaction of oil (medium) with the water layer close to the tube walls Fig 7.

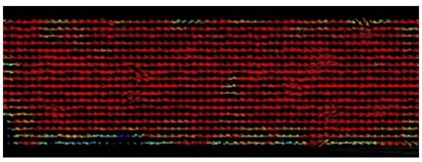


(a)

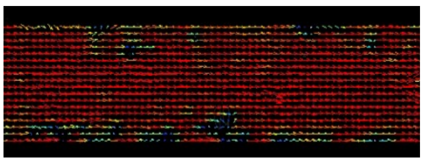
(b)

Figure 7. (a) and (b) core-annular flow pattern captured with high-speed camera in 9.7 mm glass tube.

One of the challenges is to obtain data near the wall, initially the study would only be performed with particles dispersed in water, but we wanted to present a work done with particles in both fluids from which interesting data were obtained and yes, it is notorious that the data near the wall are difficult to obtain, with the above said we managed to obtain a complete velocity profile of the entire two-phase flow Fig 8, it is expected to be able to study both phenomena simultaneously. The method uses a calibration pattern and a polynomial function to correct the images. In addition, image processing algorithms incorporating Gaussian and Laplacian filters and a cross-correlation method with multi-pass and decreasing window sizes from 64x64 to 32x32 pixels will be applied to the corrected images to obtain the velocity profiles in the pipe's, and an acquisition frequency of 15Hz.



(a)



(b)

Figure 8. (a) and (b) core-annular flow velocity profile.

4. CONCLUSIONS

The understanding of the dynamics of a liquid-liquid core-annular flow is interesting from the dynamic analysis of this, this allows us to take a step further to the knowledge of the behavior of the flow patterns. This work is based on the study of the core-annular flow dynamics in horizontal oil and water pipes, by means of the PIV-2D technique and high speed camera recording, data were collected from the literature containing the final product of the processing of these images, being this of great help for the validation of the information obtained by this analysis. These contain the axial velocity profiles and their velocity fields generated along the pipe, finding also some theoretical similarities, where gravitational and viscous forces have a great impact in the generation of this flow pattern. In this ongoing experiment, image processing algorithms will be used to statistically predict the shape of these profiles and their velocity fields, it is also expected that by obtaining these average velocity profiles some hydrodynamic phenomena between two-phase fluids such as interfacial interactions between oil and water will be shown.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge National Council for Scientific and Technological (CNPq) for the grants of Jorge E. Arrollo-Caballero (proc. 131659/2021-9) and Oscar M. H. Rodriguez's (proc. 311057/2020-9) and CAPES (Coordination of the Improvement in Higher Level Personnel of Brazil) for Pedro J. Miranda-Lugo (proc. 88882.379164/2019-01). Sincere thanks are extended to Gabriel Jacobina and Gustavo Braga for their help during the experimental campaign. The technical support for the built-up of the experimental rig given by Mr. Pedro Donizete, Mr. Lazaro, and Mr. Jorge N. dos Santos is also appreciated and recognized.

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