25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-690
PARTICLE IMAGE VELOCIMETRY APPLIED TO THE FLOW IN PORE DOUBLETS

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Abstract. *In order to advance the knowledge of the flow of biphasic fluids in porous media, an experimental technique that has been gaining considerable space in several research areas is used, due to its great versatility in terms of the generated data. The technique called Particle Image Velocimetry (PIV) is very interesting for the study of geometries that present uncertainties regarding the behavior of fluid flow, as is the case of the doublet-pore model. This is due to the fact that it is a non-intrusive optical technique that allows simultaneous monitoring of the entire velocity field of the region of interest. In this work, PIV recordings were performed for a single-phase water flow in both a rectangular channel and doublet-pore geometry. The data resulting from the experiment were compared to those obtained by the analytical solution for a rectangular channel and those generated by a reliable numerical simulation for the doublet-pore model, in order to validate the adopted experimental procedure. Recordings were then made on a double-pore flow in which the oil was trapped in the smaller channel while the water was drained by the larger one. The results showed that for a two phase flow in which the wetting fluid is more viscous than the non-wetting fluid, there will be no way to remove the trapped fluid in the minor channel just by raising the flow rate.*

Keywords: *PIV, Porous Media, Microchannels, Doublet pore model.*

1. INTRODUCTION

Understanding the physical phenomena that occur when two phases flow through micrometric channels is of great interest to the oil industry, since the reservoirs are formed by porous media impregnated with oil, water and gas. The physical concepts developed for normal scale flow do not apply precisely to micrometric scales, since fluid properties such as viscosity, interfacial tension and solubility exert a strong influence on the flow, as well as with factors pertinent to the porous medium where the fluid is drained, such as permeability and wettability, which are very relevant in micrometric flow (Wolf, 2006).

The technological advance contributed significantly to the development of numerical methods for the fluid flow simulation. However, as stated by Roman et al. (2016), due to the specificities of the microscale flow, conventional algorithms to simulate macroscale flows become inadequate. Thus, it is desirable to perform experimental work for providing data on the actual conditions found in the microscale fluid flow. Miranda (2004) states that, under this analysis, the PIV technique is one of the most suitable because it allows the field of velocities to be obtained with high spatial resolution, even in difficult access regions, such as near-wall flow and where vortices occur.

Particle image velocimetry is an experimental technique coupled with data processing that intends to find the velocity field of a given flow within a region of interest. The experimental procedure is summarized in capturing images of the fluid flow, to which tracer particles were previously added, and later perform the processing of these images by the cross correlation technique (Thielicke and Stamhuis, 2014) that defines the position of the particles at specific times for the sequence of images, finding the distance and direction traveled by the particles, enabling the calculation of velocity vectors, assuming that the particle motion behaves like that of the fluid (Raffel et al., 2007).

The use of the PIV technique to investigate the interface movement of two immiscible fluids flowing inside microchannels is very interesting and has been studied in several studies (Kazemifar et al., 2016, Li et al., 2017, Ashwood et al., 2015, Kim et al., 2004) due to the great contributions that quantitative data collection in this area can bring. However, caution should be taken in evaluating the results, since errors in such small dimensions may be high and data processing in the PIV technique may present incorrect results if the procedure is not predefined by reliable data. Therefore, the experimental results must be validated by comparing the results with numerically modeled flow data or analytical solutions.

In this work, experiments were performed with rectangular cross-section channels with the aim of comparing the results of the μ-PIV technique with the Poiseuille solution (Mortensen, 2005). Also, velocity field measurements in a doublet-pore model were carried out for the single-phase fluid flow. These obtained data were compared to the results of numerical simulations using the Lattice Boltzmann method (Venturoli and Boek, 2006), thus validating the experimental technique and defining the appropriate procedure for that experimental setup. Finally, the velocity field was determined for an experiment in which oil was trapped in the smaller pore of the model, while water with particles flowed through the larger pore.

2. MATERIALS AND METHODS

2.1 Micro channels fabrication

The micro channels fabrication was made by demolding of the micromodel material (Polydimethylsiloxane, PDMS) from a 30 um trick SU-8 master with the micro channel geometry. SU-8 is a negative photoresist (from MicroChem Corp) and the SU-8 master is fabricated on 50 mm x 50 mm photomask glass plate covered with a 100 nm Cr layer. The Cr layer is for adhesion reasons. The microfluidic device fabricated in this work is composed, basically, by two pieces. A PDMS lid with the micro channels itself and a glass plate with a thin spin coated PDMS film, that works as a micro channels cover. In this work the PDMS micro channels were fabricated in a laminar flow bench, utilizing Sylgard 184 PDMS from DOW CORNING Company in a (10:1) elastomer to cure agent ratio.

The PDMS is slowly poured over the SU-8 master placed on a metallic template that define the total volume and thickness of PDMS. The filled template is placed on hotplate by 30 minutes at 80ºC for PDMS cure. After the cure, the PDMS is demolded with the aid of a surgical scalpel and a plastic tweezer. The PDMS should be carefully and slowly pulled from master to avoid tearing the silicone rubber and also destroying the SU-8. After demolding, the inlet and outlet holes are made with a 2 mm diameter biopsy puncher aided by a digital camera.

The micro channels sealing is made by means of a glass base with partially cured PDMS place in contact with the PDMS lid. Alter contact, the device is cure at 80ºC for another 30 minutes to complete the PDMS cure.

2.2 Experimental procedure

A workstation specially designed for experiments with μ-PIV under low flow rates was assembled. It is composed of a Zeiss trinocular inverted model Axio Observer III, which has a reflected light system with a 120 watt halide metal lamp for fluorescence. The optical path has lenses with apochromatic correction and two filters, one for yellow/green (525-575 nm) and one for Nile red (535-590 nm). The digital camera has sensitivity for all microscopy techniques, has 2.8 MP resolution, CCD sensor, USB 3.0 interface and can capture up to 90 frames per second.

The experimental bench, as seen in Figure 1, also has a syringe pump (Harvard Apparatus, Pico Plus Elite, ± 0.5% accuracy) that is used to inject fluid into the micromodel. The pump has an integrated operating system that supports the use of various syringes, which allows varying the volumetric flow rate in a wide range of values.

The objective of the setup is to provide μ-PIV recordings in two-phase flows in a well-studied doublet-pore channel model (Chatzis and Dullien, 1983, Sorbie et al., 1995, Lundström et al., 2008, Nabizadeh et al., 2018), but that still presents uncertainties. As Chatzis and Dullien (1983) explain, when there is displacement from one phase to another in porous media, the competition between capillary and viscous forces causes more influence than the injection flow rate and gravitational forces themselves, which leads to anomalous behavior, being the doublet pore configuration widely used to investigate the entrapment of the displaced phase during the flow of immiscible fluids in porous media. Qualitative studies performed with micromodels simulating the flow in doublet pores presented insufficient results for flow modeling, and quantitative data will contribute to a better understanding of the trapping phenomenon.

To perform experiments with μ-PIV in liquid flows, the addition of tracer particles to the fluid is required. Lindken et al. (2009) argue that these particles need to be chosen judiciously because various details must be evaluated to obtain reliable data as a result of the experiments. As in the present work the objective is to perform experiments with water, tracer particles suitable for this type of fluid were selected.

Figure 1. Experimental setup for use of the μ-PIV technique.

The carboxylate modified microspheres (FluoSpheres) were chosen because such surface modification generates affinity for water, thereby enhancing their distribution within the fluid and avoiding agglomeration between particles or the walls of the micromodel. These microparticles have a density of 1,050 kg/m^3 which is relatively close to that of the water, this ensures that they will be transported with the flow without disturbing the same. The particle diameter was chosen based on the smaller channel of the micromodel, according to Raffel et al. (2007), it is convenient that the particle size are two orders of magnitude smaller than the channels through which the fluid will flow, thus with particles of 1 μm, it will be possible to perform experiments with micromodels having channels of at least 100 μm.

In order to perform PIV recordings, the micromodel must be pre-filled with water, since the objective of the experiment is to evaluate the single-phase fluid flow, which does not occur if there is air inside the channel and how the air is a wetting fluid for the PDMS compared to water, it is not possible to fill just by injecting water. In this way, isopropyl alcohol is injected, since it is a wetting fluid for PDMS compared to air, which allows the complete filling of the micromodel. As alcohol is soluble in water, after injecting 5 ml of ultrapure water the entire geometry gets filled with only water.

After filling, a solution of water and particle tracer in the ratio of 0.06% particle to water, based on volume, was injected into the micromodel. The water was injected using a Hamilton 1700 series precision syringe with 500 μl. The flow rate was adjusted according to the frame rate and particle size. According to Roman et al. (2016) it is advisable for the particles to move up to three diameters between the images of the pair, which results in a speed of 1008 μm/s, considering for the calculation that the image of the particle in the magnification used is 4 μm in diameter and that the camera has been set to capture 84 frames per second. Knowing the fluid velocity and the smallest channel dimension, which is approximately 250 μm wide and 30 μm deep, the water injection flow rate can be calculated, resulting in 7.56×10^{-12} m^3/s. However, a somewhat smaller volumetric flow was used, since with the increase of the displacement velocity of the particles, the luminous noise was also increased, making the particles images difficult to be followed by the software. The flow rate used was 6.11×10^{-12} m^3/s, which allowed capturing better defined images and, consequently, more reliable results.

To eliminate luminous noise, an induced fluorescence system is used. The light source emits light at high intensity, exciting the particles in the water. These particles after excited emit light at a wavelength greater than that emitted by the light source. An optical filter placed between the observed region and the objective lenses allows only light passing with a wavelength between 525 and 575 nm, which corresponds to the range of light emitted by the particles. In addition to the optical features, the ZEN 2.6 Blue Edition software allows a very specific configuration for the light spectrum presented in the images, generating a high contrast between the particles in the water and the rest of the observed region, as observed in Figure 2.

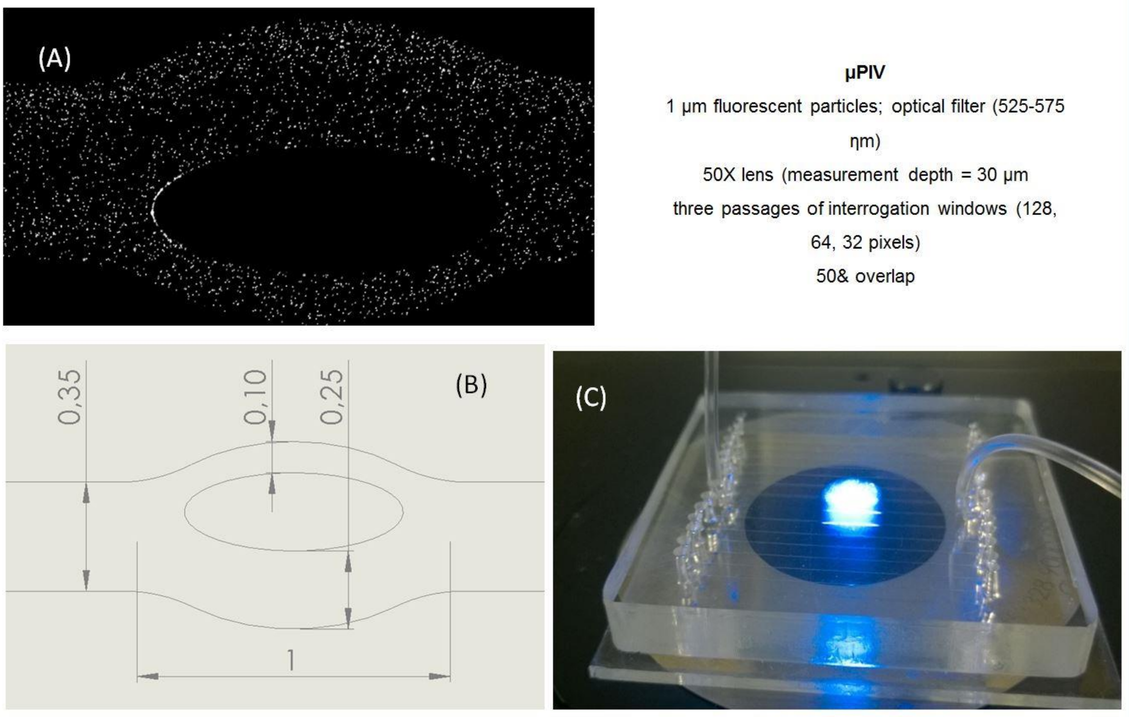

Figure 2. (A) The particles within the channel, (B) the geometry design in mm and (C) the micromodel.

The micromodel must be placed under the microscope and positioned precisely in the region where the images will be captured. After filling with ultrapure water, the injection of the water/particles solution was started, so when the steady-state condition is reached, the camera is triggered to start capturing the images.

The software used to perform the image processing was PIVLab, a MATLAB® tool developed by Thielicke and Stamhuis (2014). In order to improve the contrast between the particles and the water, a limited contrast adaptive histogram equalization of 20 pixels was applied and an adaptive wiener denoise filter with three pixels was applied to prevent out-of-plane particles from being part of the velocity vector calculations.This pre-processing options are available in the PIVLab tool.

Due to the optical filter used in the microscope, only the light emitted by the particles is captured by the camera, being necessary to create a mask to identify the position of the channel in the images. This mask was made by adding all captured images using a MATLAB® script and applying a reversal of color so that the region of the channel becomes black and the rest white. When making the sum of the images, the entire region through which particles have passed will become white and the rest will turn black, thereby creating a perfect mask of the region to be evaluated.

To determine the velocity vectors between the pairs of images a discrete Fourier transform correlation with several passages was used and a window overlay algorithm was then used for cross-correlation of the image data. Despite the higher computational cost, four passages with interrogation windows that differ by a factor of two were used whenever possible. Larger interrogation windows have a better signal-to-noise ratio, but lead to very low vector resolution. For this reason, the first pass is made with relatively large windows and in subsequent passages the size of the interrogation window is halved. However, there is a minimum threshold for the size of the interrogation window, according to Roman et al. (2016), it is interesting that the smaller window is at least three times larger than the particle image diameter. Thus, windows of 128, 64, 32 and 16 pixels were used, since the particle diameter in the image magnification was four pixels.

PIV recordings were performed at a 50-fold magnification and the images captured for the rectangular cross-section channel are 600 x 400 pixels in size, whereas for the doublet-pore model the images have 1500 x 800 pixels. Under these conditions, although the particles are only 4 μm in diameter in the obtained images, they become relatively large, this induces the experiments to be performed with a relatively low density of particles. This led to the need to use a high number of pairs of images to obtain reliable results, despite the computational cost, this guarantees more accurate data, since the fluid flow is under steady-state condition and the experiment is intended to find the speeds for the streamlines. For each experiment more than two thousand images were captured, what allowed the software generates an image with the averaged vectors of the calculated image pairs, as shown in Figure 3.

3. RESULTS AND DISCUSSION

3.1 Fluid flow in a rectangular channel

It is of great importance to validate the data obtained as a result of the PIV technique, because although it is an experimental technique, both the experiment and the image processing can lead to significant errors. Thus, image recordings were done in an experimental setup in which the water/particle solution was injected through a rectangular cross-section channel. The experimental data were then compared to the analytical solution obtained by solving the Poiseuille equation (Mortensen, 2005) to verify the proximity of the results. Figure 3 shows the channel with the field of velocity vectors and in Figure 4 the profile generated by the analytical solution is compared with the results obtained with the experiment.

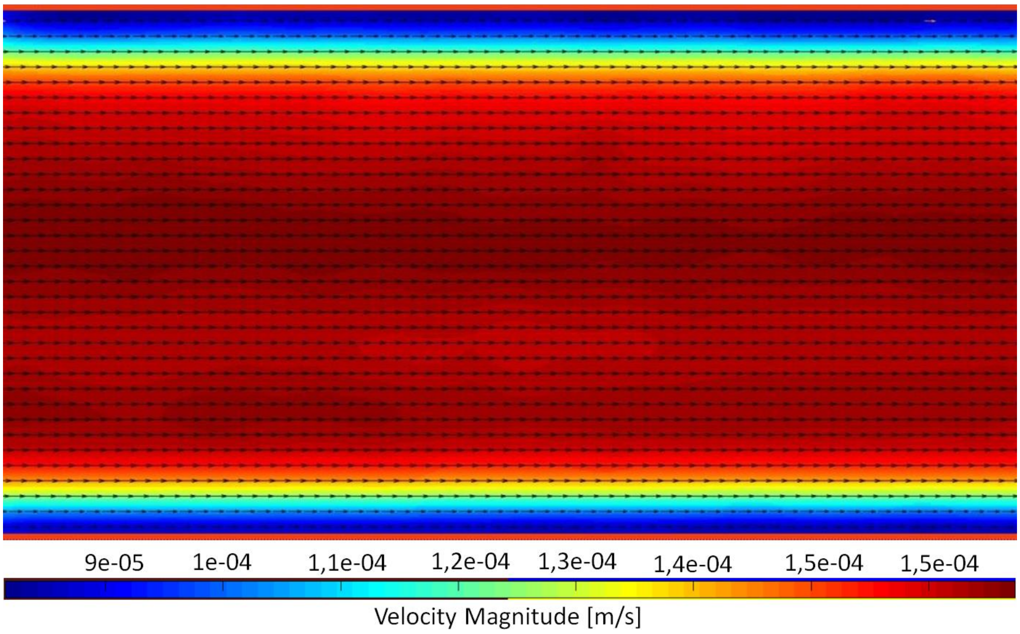

Figure 3. Average vector field for rectangular section channel.

There were significant errors between the obtained velocities for the regions near the channel walls. This was already expected since the analytical profile considers the non-slip condition of the fluid close to the channel wall, whereas in the experimental analysis the particles slide (or roll) on the wall when they are dragged by the fluid that is in the vicinity of them (Gutiérrez, 2013, Silva, 2008). However, this error occurs approximately only around 6 µm far from both walls, considering that the particle diameter is 1 µm, we conclude that this condition approaches the limits of the experimental bench. For the central region of the channel, the velocity field obtained by the analytical and experimental analyzes was very close, with a maximum difference of 7.93% between the values, remaining within the uncertainty calculated from the experimental data.

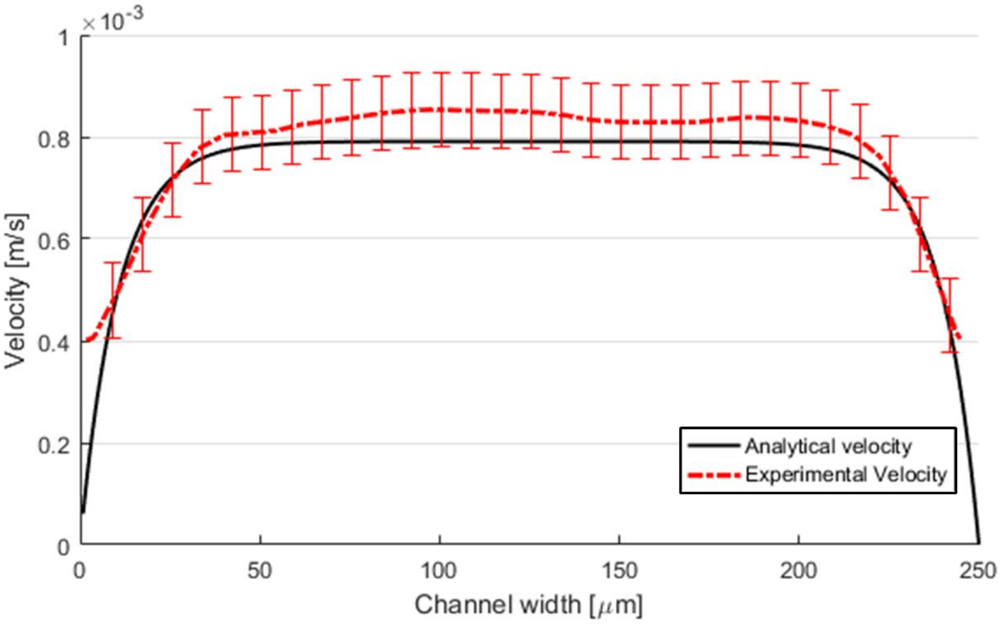

Figure 4. Comparison between the field of analytical and experimental velocities

In addition to the comparison between the experimental and analytical values, calculations were made for the uncertainties associated with channel width and depth measurements, as well as for the flow rate imposed by the pump. The magnitude of the mean velocity is found by dividing the volumetric flow rate by the area of the cross-section channel. The pump used to inject the fluid in the micromodel has an uncertainty of 0.5% provided by the manufacturer, and for the uncertainty calculation of the area, the depth values reported by the manufacturer of the micromodel and the values measured in the microscope for the width of the channel used. With the values in Table 1 the uncertainty was calculated for the velocity that results in ± 7.27x10^{-5} m/s, according to error bars shown in Figure 4.

Table 1. Values and uncertainties related to the experiment.

Quantity	**Value**
Volumetric flow rate	(6.1111 ± 0.035) x 10^{-12} m^3/s
Channel depth	(3.37 ± 0.32) x 10^{-5} m
Channel width	(2.468 ± 0.056) x 10^{-4} m

In addition to the uncertainties with respect to the input data provided by PIVLab, presented in Table 1, other quantities were also calculated to serve as a guide to understand if the experimental analysis was generating reliable data. The response time (τ),

$$\tau = \sqrt{\frac{\rho_p}{\rho_f}\frac{d_p^2}{18v}} \tag{1}$$

in which ρ_p is the density of the particle, ρ_f is the fluid density, d_p is the pore diameter and v is the kinematic viscosity of the fluid (Lindken et al., 2009), refers to the behavior of the particles in the fluid, whether or not they are following the fluid and what confidence can be attributed to the data found by comparing the response time with the higher magnitudes of velocities present in the flow. From Equation (1) it was verified that the response time for the conditions of the experiment was 5.83x10^{-8} s.

From the knowledge of the highest speed achieved by the fluid and the response time, it was possible to calculate the Stokes number as given by

$$Stk = \frac{tu_0}{l_0} \tag{2}$$

being u_0 the highest flow velocity and l_0 the channel dimension, in order to understand if with the proposed experimental setup, there would be a very large error due to the drag of the particles by the fluid. Solving Equation (2), we obtain the Stokes number of 1.99x10^{-7}, showing that the error due to the drag on the particles by the fluid is quite small, less than 1%, according to Raffel et al. (2007).

Another characteristic of the flow that has been evaluated is the error related to the Brownian motion,

$$\varepsilon = \sqrt{\frac{2}{\Delta t}\frac{k_B T}{3\pi \mu d_p}} \tag{3}$$

in which Δt is the time between the successive images, k_B is the Boltzmann constant, T is the temperature, μ the dynamic viscosity of the fluid and d_p the particle diameter, because the particles that are used in the experiment have a diameter of 1 μm, and according to (Lindken et al., 2009), particles with diameter less than or equal to 1 μm may exhibit non-standard behavior due to Brownian motion, leading to errors in the results obtained with the experiment. Using Equation (3), we obtain the value of ε = 9,13x10^{-6} m/s, which divided by the mean speed of 7.76x10^{-4} m/s, results in 1.18% error. However, as already commented, the uncertainty analysis was done based on the average of the vectors generated by more than 2,000 pairs of images, which makes this error negligible.

3.2 The Pore-doublet model

Other validation step of the PIV technique was done comparing the results obtained from a single-phase fluid flow experiment with the numerical simulation using the Lattice-Boltzmann method (LBM) (Sukop and Thorne, 2007). The CFD model used in this work is based on the Boltzmann conceptual view but substantially simplified by reducing possible positions and microscopic momenta from a continuum to a discretized problem. Basically, the particle positions are confined to the lattice nodes, and their variations in momenta are reduced to a determined number of directions. It was used the BGK (Bhatnagar-Gross-Krook) collision operator, which is commonly used for the simplest LBM. The method was applied based on D3Q19 scheme, which implements the variation in momenta within 18 directions (plus one for the rest particles), represented in a three-dimensional space. At the solid-fluid interface, it was implemented the bounce-back boundary condition. The entry condition was established from the analytical solution for a rectangular cross-section channel. For the exit, it was chosen the Von Neumann boundary condition for incompressible fluid flow, which had shown good performance during the tests with no noticeable disturbance upstream.

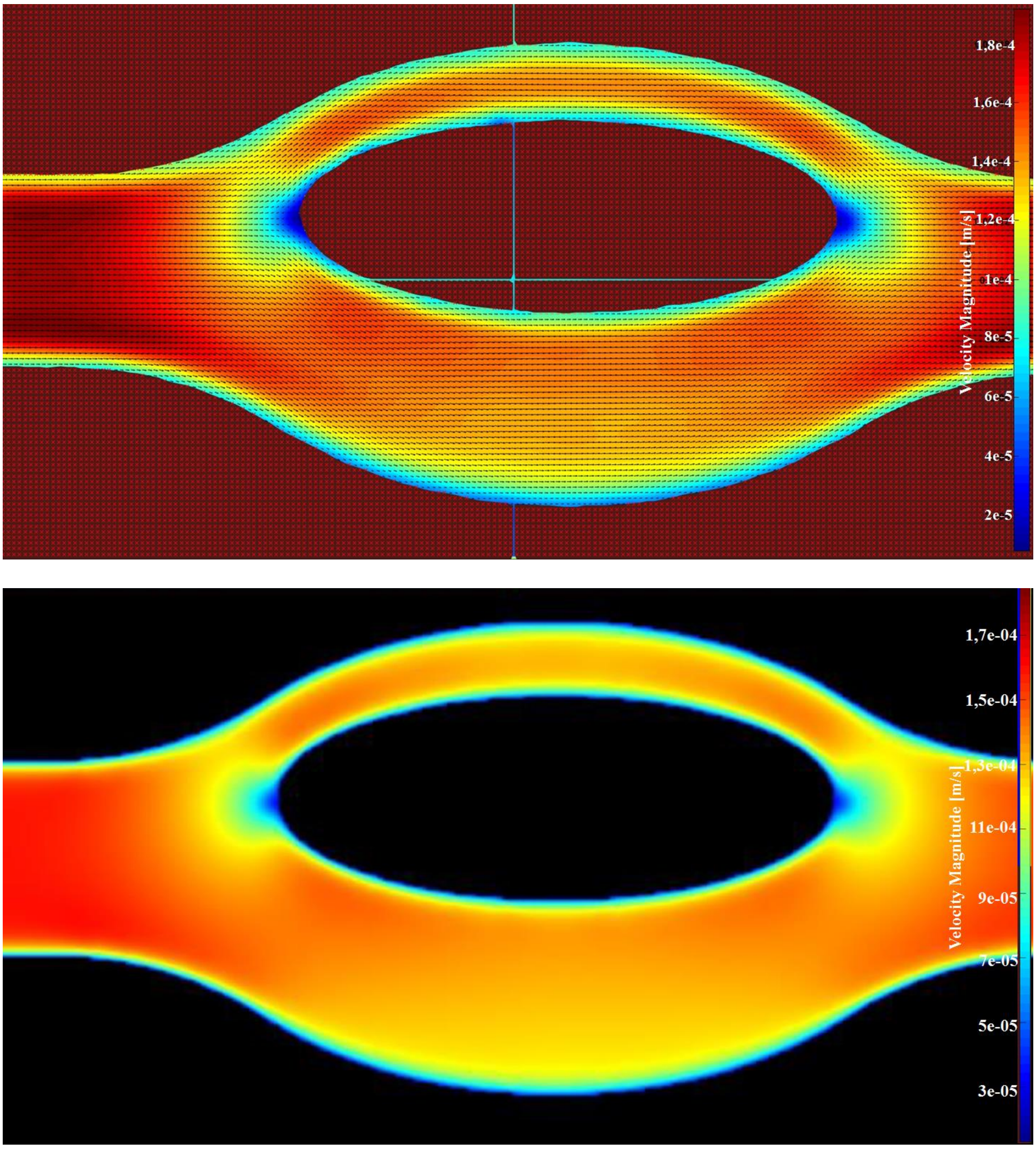

Figure 5. Water flow in doublet-pore model.

It can be observed, in figure 5 that obtained results were qualitatively very similar and are in agreement with what was already expected for this geometry. In Figure 6 we present the quantitative results for the velocity magnitude from baseline drawn across the center of the channel comparing analytical and experimental results. As can be seen, the μ-PIV velocities were slightly higher, which probably was caused by imperfections in the internal structure of the channels (particularly due to the variability of the channel depth), resulting in a local increase in velocity, but the difference between the experimental and simulation velocities is within the uncertainties of the experiment.

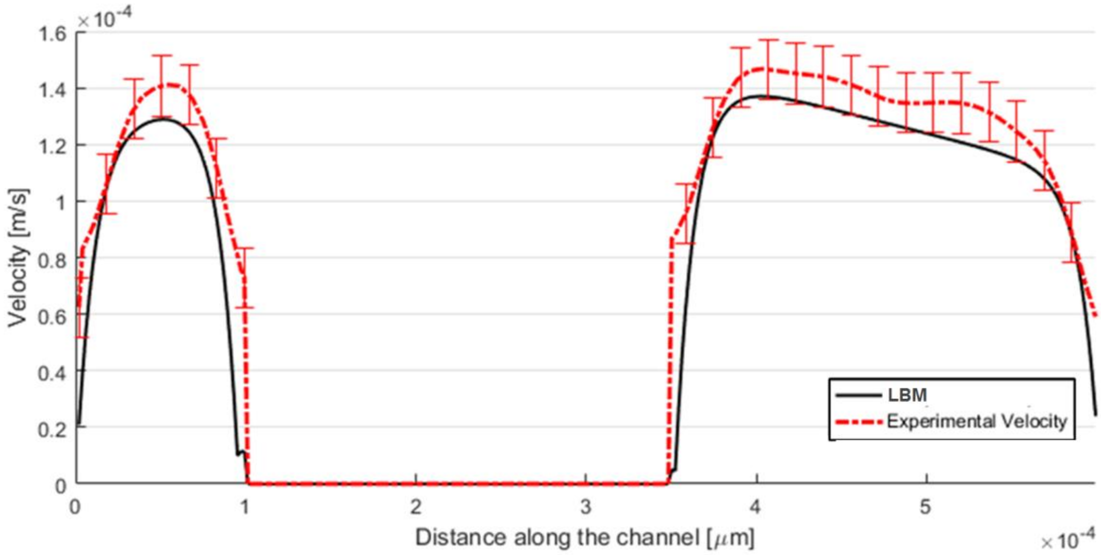

Figure 6. Comparison between the analytical and experimental results for the double-pore model.

After verifying the correctness of the results obtained by the PIV technique, some experiments were performed with two immiscible fluids in order to identify the interface dynamics during the flow, as shown in Figure 7. The fluids used were water and Heptacosafluorotributylamine (FC-43). However, as the particles did not show affinity with this fluid, being agglomerated between them and even attached to the glass of the Becker where the solution was made, experiments were carried out in which only the water received the tracer particles, thus preventing the visualization of the phase during the experiment.

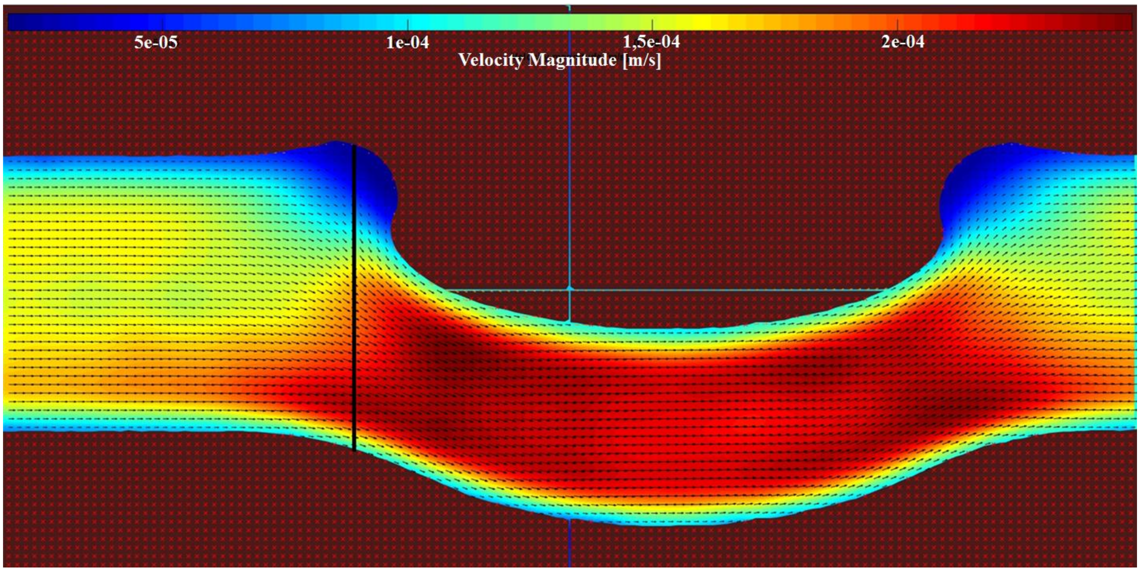

Figure 7. Velocity field in the two-phase fluid flow.

For this experiment, $2.0\text{x}10^{-11}$ m^3 of FC-43 was injected into the channel, enough to fill the tube connecting the syringe to the micromodel and the channel analyzed. Then, the water solution with tracer particles, in the same proportion as in the previous experiment, was injected at a flow rate of $1.72\text{x}10^{-12}$ m^3/s which resulted in the vector field of Figure 7. The injection rate imposed for this experiment was calculated according to the capillary number (C_a),

$$C_a = \frac{\mu u}{\sigma} \tag{4}$$

where μ is the dynamic viscosity of the injected fluid and σ and the interfacial tension between the fluids, since according to Chatzis and Morrow (1984) in the oil recovery process the values found for the capillary number vary between 10^{-5} and 10^{-7}. The capillary number for this condition is $2.73\text{x}10^{-6}$ which is among the values found in the oil recovery process.

As shown in Figure 8, which shows the velocity profile of the black line drawn in Figure 7, the velocity vectors field is completely in agreement with what was expected. Even before the fluid reaches the bifurcation region, there is an increase in fluid velocity at the bottom of the channel of about 20% relative to the mean, this is because the hydraulic resistance of the upper region of the channel increases when fluid approaches the central obstacle. This condition causes the wetting fluid, which remains trapped in the minor channel as mentioned above, not to be disturbed by the flow of water in the larger channel under the flow conditions which have been imposed. However, even raising the flow rate up to 2.78×10^{-10} m^3/s, which generates a capillary number of 4.42×10^{-4}, there were no changes in the fraction of the trapped phase.

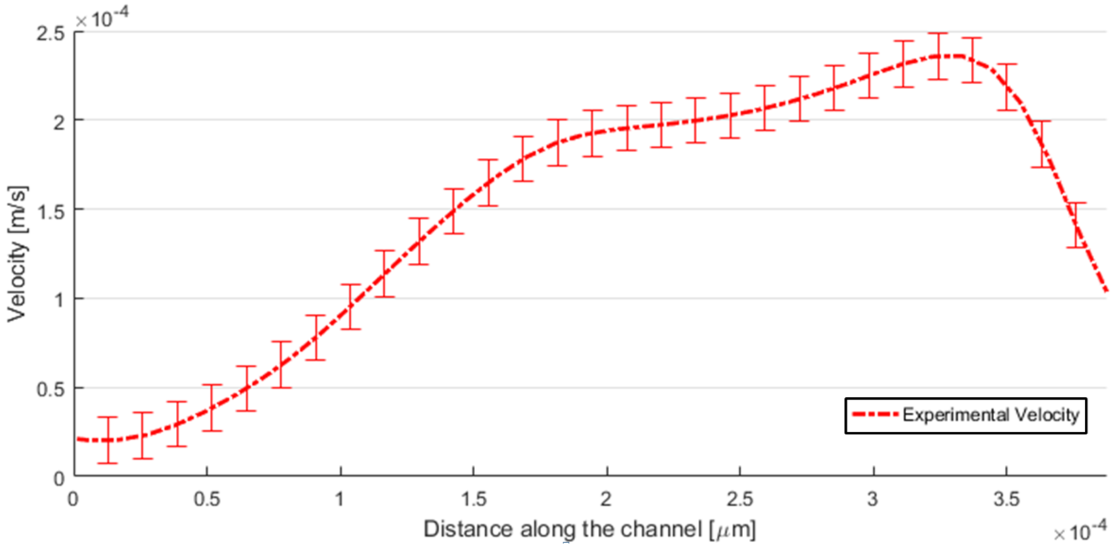

Figure 8. Profile of the vector field in the two-phase fluid flow.

4. CONCLUSION

With the development of this work it became clear how the PIV technique can contribute to research involving micrometric fluid flow, both by understanding the physical phenomena involved, and by obtaining quantitative data that can later be used for flow modeling. It is noted that a great effort is still needed so that the experimental results can contribute significantly to the research, since the tests performed were in only one geometry and the uncertainties found were relatively large for the employed dimensions. In order to obtain reliable data and in a wider range of conditions, regarding the geometries used and the combination of fluids to be tested, it will be necessary to expand the limits of the bench, equipping it with more advanced devices and defining for each type of experiment a proper procedure. However, this work showed that the effort is viable due to the excellent results obtained, among them the confirmation of some theories, such as the slipping of a wet phase liquid film during the drainage process and the imprisonment of the non-wet phase in low capillary numbers, and unpublished results such as the relationship between the velocities of the fluid injection and the interface between the fluids in the trapping region.

5. ACKNOWLEDGEMENTS

Thanks to Petrobras for the financial support provided.

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