μ-PIV STUDY OF OIL-IN-WATER EMULSION FLOW THROUGH CONSTRICTED MICRO-CAPILLARIES

Oswaldo Robles Castillo, oroblesc@yahoo.com
Marcio da Silveira Carvalho, msc@puc-rio.br
Pontificia Universidade Catolica do Rio de Janeiro (PUC-Rio). Department of Mechanical Engineering.
Rua Marques de Sao Vicente 225. Gavea, Rio de Janeiro, RJ, 22453-900. Brasil.

Abstract. *A micron-resolution particle image velocimetry (μ-PIV) system was used to measure velocity field of the flow through a constricted micro-capillary and the dispersed phase drop velocity as a function of the imposed flow rate and drop diameter. The system consists of a motorized reflected fluorescence microscope, 1.0μm uniform polystyrene fluorescent microspheres, a pulsed Nd: YAG laser and an intensified CCD camera to record high-resolution particle-image fields. The capillary and constriction diameters were 200 μm and 50 μm respectively. Ensemble-average was used to obtain small resolution. In the analysis presented the resolution was of the order of 18 μm.*
The accuracy of the μ-PIV system was demonstrated by measuring the well-known velocity field of the flow through the straight cross section of the capillary and let develop a good approximation on the study of the less well-known flow through the converging geometry of the capillary constriction.

Keywords*: μ-PIV, emulsion, constricted micro-capillary, enhanced oil recovery.*

1. INTRODUCTION

During water injection, oil is swept through the reservoir to production wells by non-uniform displacement fronts originating entrapped oil in the smallest porous space. Uniform displacement fronts and better reservoir sweep can be achieved by improving the mobility ratio between water and oil, as a result of reducing the viscosity ratio between both phases.

Polymer solution injection is one of the most used mobility control agent, however, the large volume of polymer needed to increase the viscosity of the injected water turns it into a high-cost oil recovery method. A non high-cost alternative to polymer injection is dispersion injection, in particular emulsions, that let use produced water as injection fluid.

When injecting emulsions, mobility control is achieved by blocking water paths with the dispersed phase drops, which have a diameter of the same order of magnitude of the pore size. Then the water injected may be diverted to non swept pores improving the reservoir sweep efficiency.

The role of emulsions as mobility control agents and the pore blocking effect may be developed by analyzing different flow regimes of emulsions inside porous media.

Despite emulsion injection is not a mature technology it has been used successfully in some field trails.

McAuliffe (1973) remarked the idea of flooding pore space with dispersed phase drop with a diameter similar to rock pore-throat size, also he studied the oil in water emulsion flow though porous media as blocking agent. Experimental results indicate improvements in reservoir sweep efficiency with lower water-oil ratio in production wells by using oil in water emulsions instead of water injection.

By inserting tightly Ottawa sand between glass plates, Soo and Radke (1984) developed micro model experiments to prove permeability decreasing due to capture mechanism. This mechanism was analyzed as a filtration process. The variation of the drop size distribution, measured at the inlet and outlet of the porous sample, let account this mechanism and confirmed oil drops captured inside the sample with permeability decrease.

Bragg (1999) studied the advantage of emulsion injection instead of polymer technique in heavy oil recovery. In his analysis effective mobility control was achieved by injecting emulsion to displace heavy oil through porous media.

Janssen (2000) studied the flow of immersed drops in liquid continuous phase through capillaries to understand the flow of emulsions through porous media and also remarked the strong influence of the interface between the continuous and dispersed phase in multiphase flow.

Guillen (2007) carried out alternating injection of oil in water emulsions and water in an Arkosic sandstone sample improving significantly the oil recovery factor. Experimental data showed pressure drop increase due to pore throat blocking.

Cobos (2009) remarked that macroscopic properties do not plenty describe the flow behavior of oil in water emulsions at the pore scale. Blockage of porous media throats was modeled by emulsion flow through constricted capillaries. A constricted quartz capillary was used to represent a pore throat that connects two adjacent pore bodies. The results indicated that pressure drop fluctuation increased for large drop size emulsions and mobility decreased as emulsion drops flowed through the capillary constriction.

In this work, the analysis of the emulsion flow through a constricted micro-capillary was developed by using the microscopic particle image velocimetry (μ-PIV) system to measure velocity field of this flow.

In the last years, μ-PIV system has been used as a diagnostic tool for microscopic flow fields. It is based on the simple idea of using an optical microscope for the imaging of a particle seeded flow in micro-scale instead of photographic lenses in macro PIV.

Santiago (1998) developed a micro PIV system using an epi-fluorescent microscope with a high numerical aperture objective lens and an intensified CCD camera to measure the low-speed Hele-Shaw flow with a velocity of approximately 50μm/s.

Meinhart (1999) carried out a particle image velocimetry system to measure velocity fields with order 1-μm spatial resolution. The accuracy of this μPIV system was demonstrated by measuring the known flow field in a 30 μm x 300 μm micro-channel.

Wereley (2002) remarked the utility of combining advanced imaging and processing techniques to achieve spatial resolutions on the order of single microns. A μPIV system was used to measure the flow through a micro-nozzle with a 15° half angle and a 28 μm throat.

Brown (2005) developed micron resolution particle image velocimetry experiments to predict velocities from computational fluid dynamics (CFD) flow simulations. Two complex micro-channel geometries were used to define the depth of correlation and the optical properties of infinity corrected lens systems to produce the required weighted average across interrogation volumes within the CFD solution.

Van Steijn (2007) used μ-PIV system to analyze transient measurements of the continuous phase flow field during the bubbles formation in a micro-fluidic T-junction. A high speed camera let measure the shape and movement of the interface between the two immiscible phases.

The goal of this work was to measure the velocity field of the continuous phase through the straight section and constriction of the micro-capillary and to determine the dispersed phase drop velocity, as a function of the imposed flow rate and drop diameter, in the two-phase flow.

2. EXPERIMENTAL SETUP

The flow was analyzed using μ-PIV system built on an OLYMPUS® manual/motorized reflected fluorescence microscope, equipped with a 10x0.30 OLYMPUS® UPlanFLN objective and a filter cube, connected to a PowerView 1.4MP CCD camera. The illumination was provided by a 532nm SOLO PIV Nd:YAG pulsed laser (NEW WAVE RESEARCH) with a repetition rate of 15Hz. All the devices were connected to a LASERPULSE synchronizer, which is the imaging system´s timing and control module and it was controlled through the INSIGHT 3G software developed by TSI to acquire and process the images. The schematic of the experimental setup is shown in Fig. 1

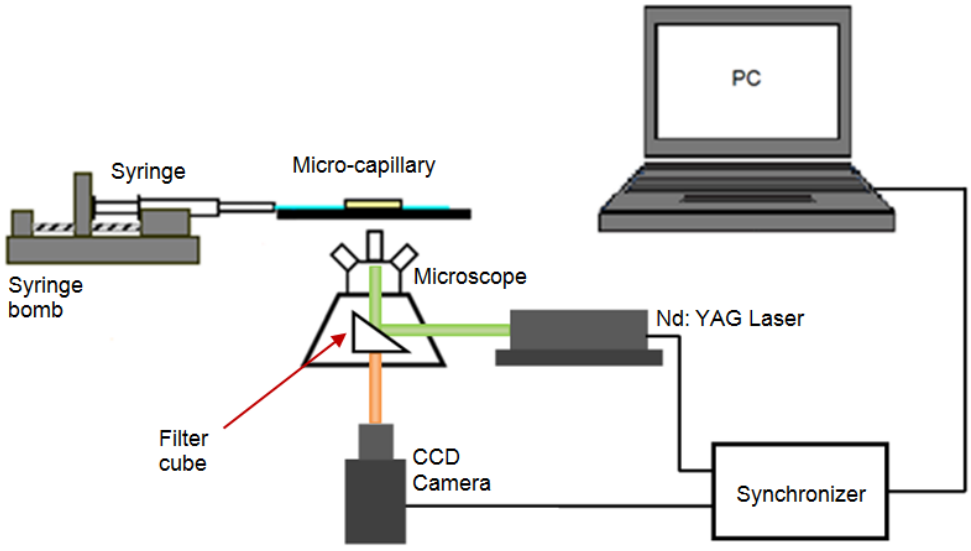

Figure 1. Experimental setup used to measure the velocity field of the flow through the micro-capillary.

The μ-PIV measurements were performed by seeding the carrier fluid (continuous phase) with 1 μm diameter polystyrene fluorescent microspheres (FluoSpheres® produced by INVITROGEN®).

The continuous phase was formulated as a solution of 85% of glycerin and 15% of distillated water in order to increase its viscosity and to avoid segregation of phases caused by density differences. After the filtration of the distilled water, both water and glycerin were mixed by using a magnetic stirrer, FISATOM, Model 754A in order to homogenize the mixture. The continuous phase (ρ=1222.2 kg/m^3 and μ= 0.11 Pa.s at 23°C) was injected by using a 3ml

luer lock syringe (BD-MULTIFIT) mounted in a syringe pump (COLE-PALMER) and connected to the capillary by a three way ball valve (EMBRAMED). The entrapped air from the syringe, valve and connectors was expelled before injecting the aqueous phase. The fluorescent particle concentrations used for seeding the continuous phase were 10:2 and 10:3 for the imaging of the flow through the straight section and through the constriction respectively.

SHELL Tivela S460 Oil was used as dispersed phase, with density and viscosity equal to ρ=997.1 kg/m^3 and μ= 1.19 Pa.s at 23°C, respectively. The dispersed phase was injected manually by using a 100 µl gastight luer lock syringe (HAMILTON). To control the dispersed phase drop diameter it was necessary to inject the dispersed phase as an emulsion of 50% of oil and 50% of seeded continuous phase. Both phases were emulsified using a six rotational rate mixer, ULTRA TURRAX T-25. The interfacial tension of both phases was σ=4.4mN/m.

The constricted quartz capillary, used to measure the velocity fields, was fabricated by HILGENBERG® and is shown in Fig. 2. The straight section and constriction diameters and the length of the capillary were 200µm, 50µm and 800mm respectively.

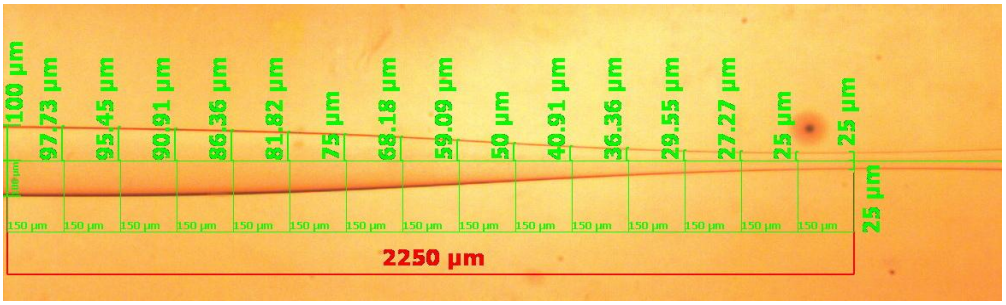

Figure 2. Photograph of the 200/50µm constricted micro-capillary.

3. RESULTS AND DISCUSSION

The velocity field of the continuous phase flow and the dispersed phase drop velocity was measured using the INSIGHT 3G software developed by TSI Inc, at a constant flow rate of injection of 0.02ml/hr.

3.1. Velocity field of the continuous phase flow through the straight section of a micro-capillary

The current experiment was developed using a visualization field of 1376 x 532 pixel (517 x 200 µm). The time spacing between laser pulses was 4400 µs and the exposure time of the CCD camera was 2400 µs. The spatial resolution, defined by the size of the first interrogation window was 64 x 48 pixel, which corresponds to 24 x 18 µm. Fifty image pairs were processed using the ensemble average method. Fig. 3 and Fig. 4 show the velocity field produced by the INSIGHT 3G and TECPLOT software respectively.

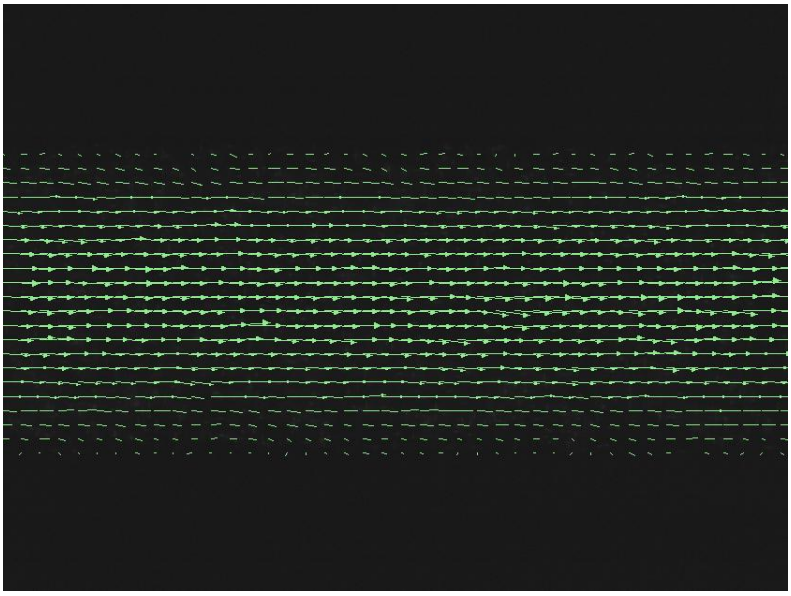

Figure 3. Velocity field of the continuous phase flow through the straight section of the micro-capillary – INSIGHT 3G.

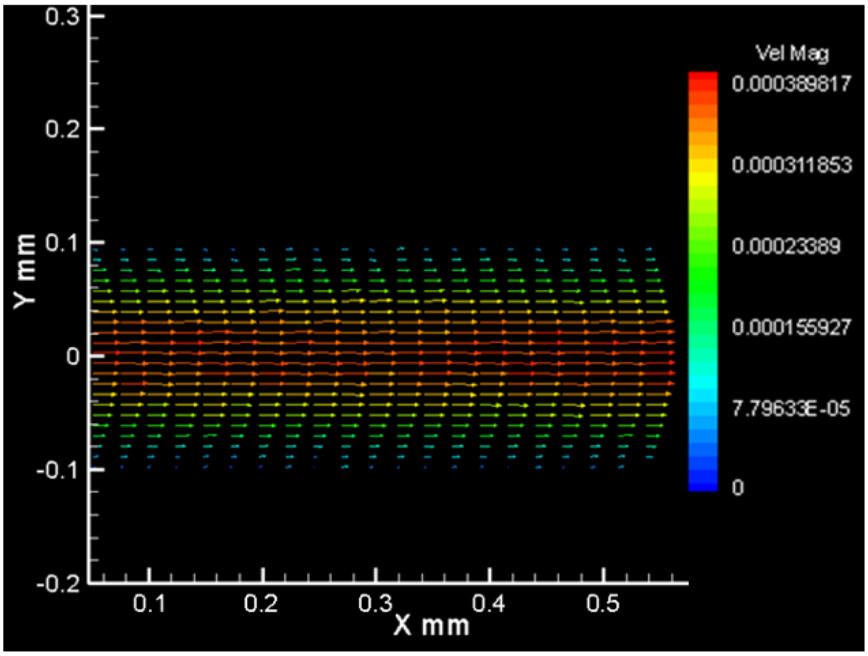

Figure 4. Velocity field of the continuous phase flow through the straight section of the micro-capillary - TECPLOT.

The experimental velocity profile is analyzed by comparing it with the parabolic analytical solution for steady flow in a straight channel of circular section. The comparison is shown in Fig. 5. The experimental flow rate was calculated for the 42 velocity fields. The average experimental flow rate was 0.02041 ml/hr. The discrepancy between the experimental flow rate and the analytical solution was almost 2.0%.

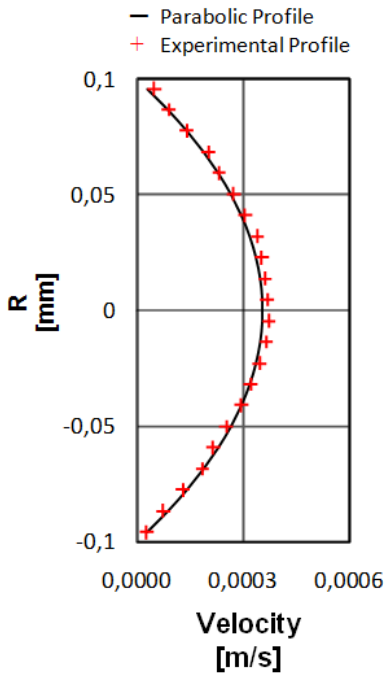

Figure 5. Comparison between experimental profile and analytical solution for the flow through the straight section of the micro-capillary.

3.2. Velocity field of the continuous phase flow through the convergent section of a constricted micro-capillary

Figure 6 shows the ensemble-average velocity-vector field of the convergent section of the capillary constriction obtained from processing 50 image pairs with the INSIGHT 3G software. The length of the visualization area was 517 μm and the height for large and small diameter sections were 82 and 64 μm, respectively. The time spacing between laser pulses was 1500 μs and the exposure time of the CCD camera was 950 μs. The spatial resolution of the interrogation window was 48 x 32 pixel, which corresponds to 18 x 12 μm. Figure 7 shows the velocity field measured by TECPLOT software.

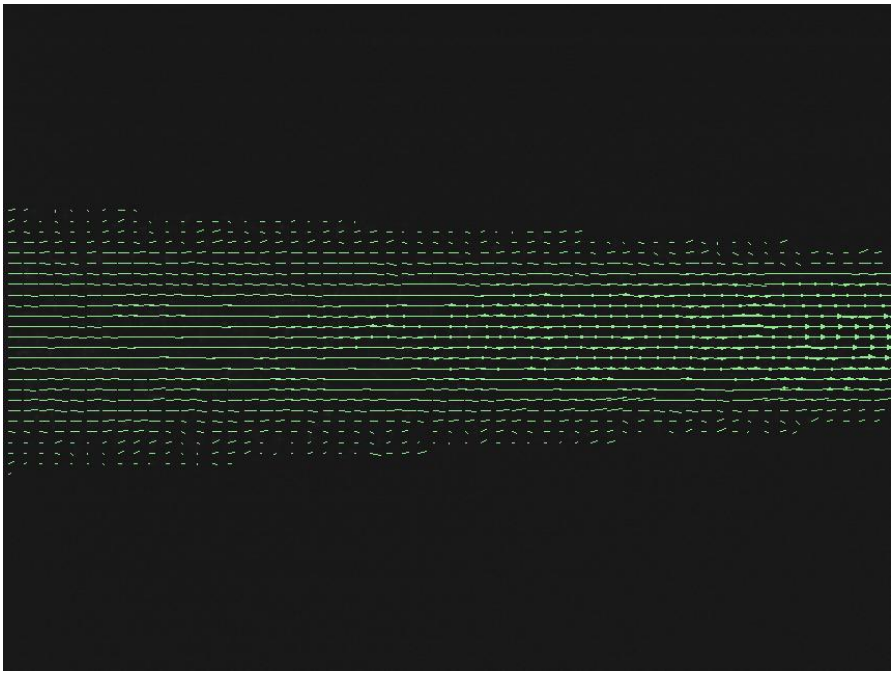

Figure 6. Velocity field of the continuous phase flow through the convergent section of the constricted micro-capillary – INSIGHT 3G.

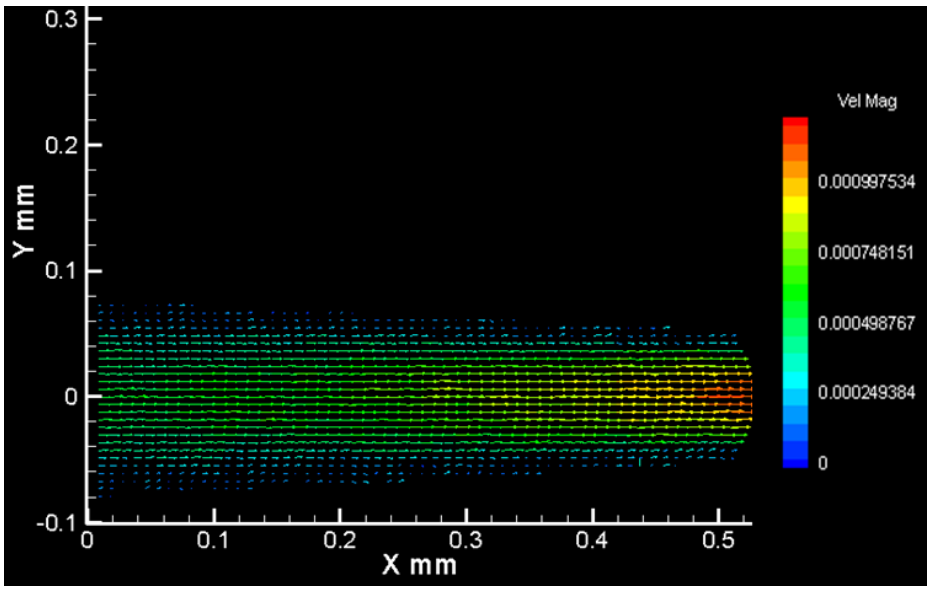

Figure 7. Velocity field of the continuous phase flow through the convergent section of the constricted micro-capillary – TECPLOT.

The velocity profiles in the convergent section approximate to the parabolic analytical profile, as remarked by Wereley (2002) in the study of the flow in a micro-nozzle. As done in the straight section analysis, the velocity profile at the large diameter section and the one at the small diameter section were compared to the parabolic profile (Fig. 8). The experimental flow rates calculated for each velocity profile were 0.01938 ml/hr and 0.01912 ml/hr, respectively. In both cases the discrepancy between the experimental flow rate and the analytical solution was less than 4.5%.

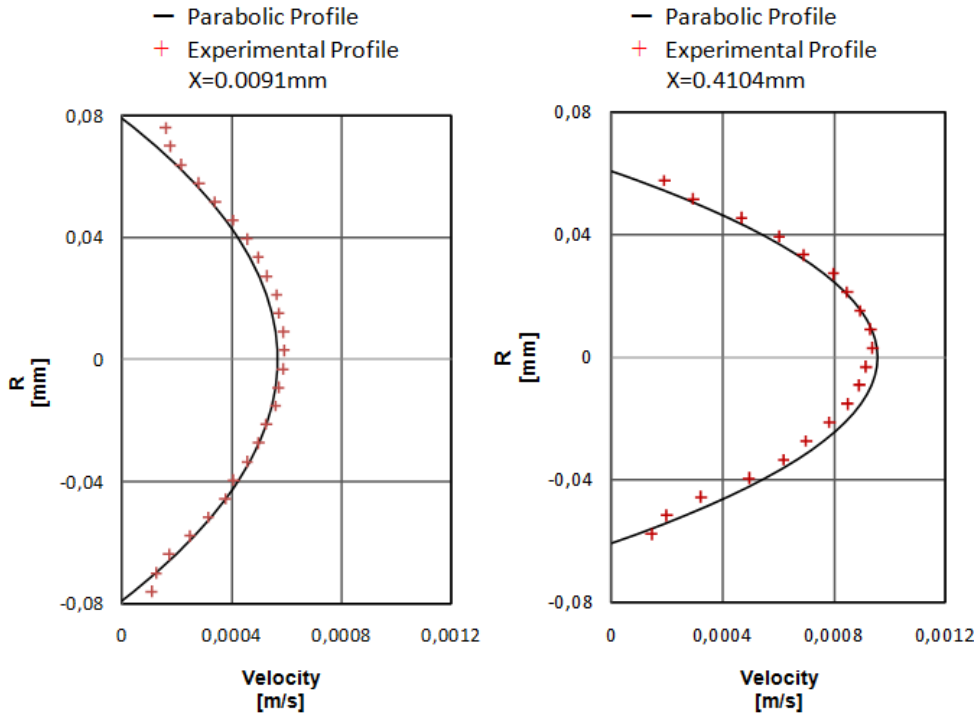

Figure 8. Comparison between experimental profile and analytical solution for the flow through the convergent section of the constricted micro-capillary.

The maximum velocity variation through the convergent section for ten velocity profiles is shown in figure 9.

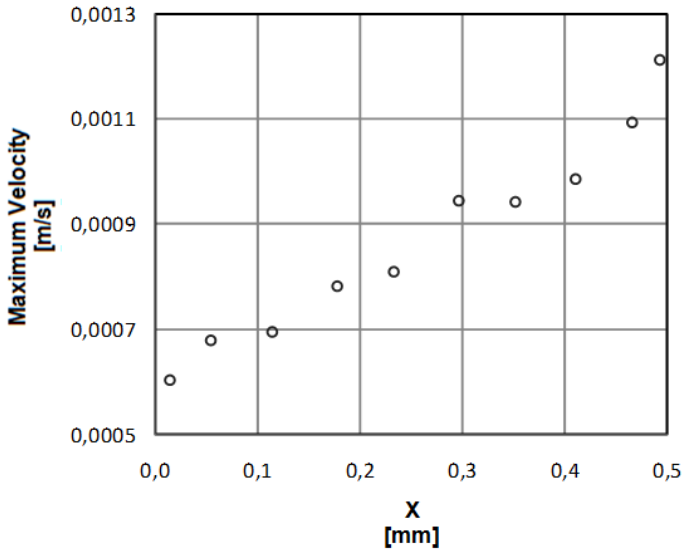

Figure 9. Variation of the maximum velocity through the convergent section of the constricted micro-capillary.

3.3. Velocity field of the two phase flow through the straight section of a micro-capillary

The current experiment was developed using a visualization field of 1376 x 532 pixel and the time spacing between laser pulses was set to 4400 μs and the exposure time of the CCD camera to 2400 μs. The spatial resolution of the interrogation window was 32 x 32 pixel (12 x 12 μm). The processing method used was the classic PIV and two post-processing methods were used to produce an 84 velocity profile field from just one instantaneous image pair.

By considering that only the continuous phase was seeded with fluorescent particles, the circular black hole in the flow- upstream represents one 160 μm diameter dispersed phase drop approximately. Figure 10 shows the two phase flow velocity field measured by TECPLOT software.

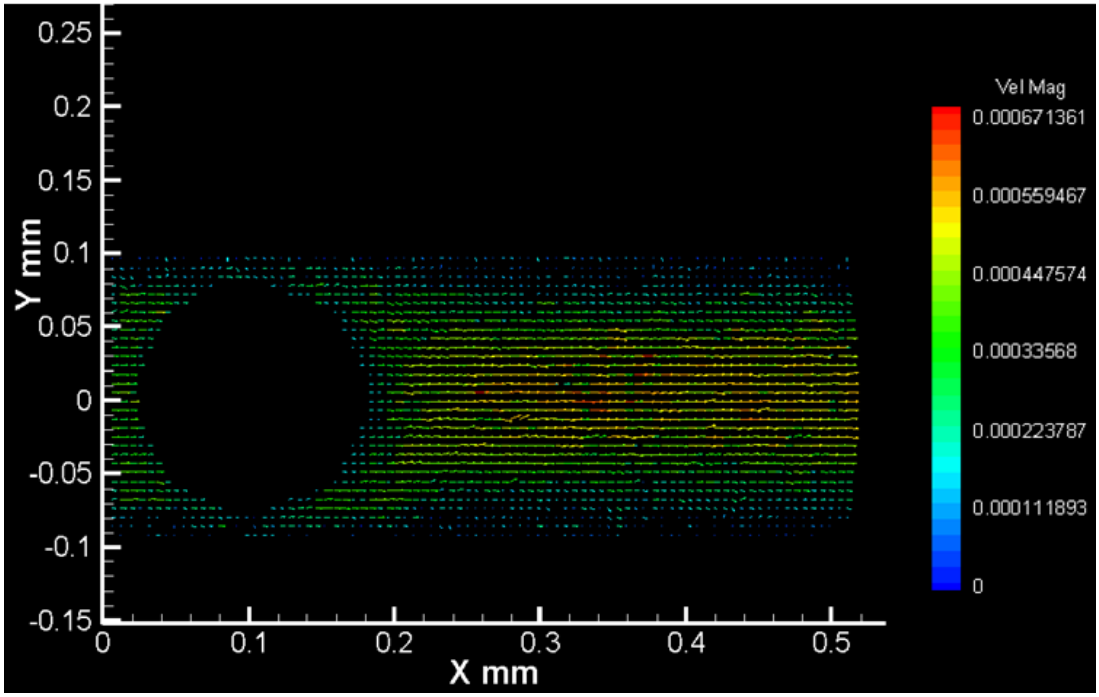

Figure 10. Velocity field of the two phase flow through the straight section of a micro-capillary.

Finally, the velocity of the dispersed phase drop can be determined by measuring the velocity of the continuous phase surrounding it. In this analysis the velocity was calculated as the average of the velocity values in the frontal region of the oil-continuous phase interface. The velocity of the drop was 0.000158 m/s. This value is less than the average velocity (0.000177 m/s) estimated for the 0.02 ml/hr injection flow.

4. CONCLUSIONS

A micro particle image velocimetry system has been developed and applied to measurements of velocity fields of the continuous phase flow through a constricted quartz micro-capillary by using the ensemble average method to process fifty image pairs. The resolution obtained was in the order of 18μm.

The accuracy of the measurements was analyzed by comparing the experimental velocity profile with the analytical solution for flow in a straight channel with circular cross section.

In the analysis of the two phase flow, it was possible to determine the dispersed phase drop velocity by measuring the velocity of the continuous phase surrounding it.

This analysis represents invaluable information that can be used in the development of a capillary network model to study the flow of emulsions through porous media.

5. ACKNOWLEDGEMENTS

O. Robles was supported by CNPq agency and PUC-Rio through a scholarship. This research was funded by PETROBRAS.

6. REFERENCES

Bragg, J. R., 1999, "Oil recovery method using an emulsion". United States Patent. No. 5855243.

Brown, M. R., Macinnes, J. M. and Allen, R. W. K., 2005, "Micro-PIV simulation and measurement in complex microchannel geometries". Measurement Science and Technology 16, pp. 619-626.

Cobos, S., 2009, "Flow of oil-in-water emulsions through a constricted capillary". International Journal of Multiphase Flow, 35, pp. 507-515.

Guillen, R., 2007, "Deslocamento de óleo em um meio poroso através de injeção de emulsões óleo-em-água: Análise de fluxo linear". Master´s thesis. Mechanical Engineering Department, PUC-Rio.

Janssen, P., 2000, "Characterization of oil in water mixtures produced in high-watercuts oil wells". Ph.D Thesis, Delf University of Technology.

McAuliffe, C.D., 1973, "Oil-in-water emulsions and their flow properties in porous media". Journal of Petroleum Technology, 25, pp. 727-733.

Meinhart, C. D., Wereley, S. T. and Santiago, J. G., 1999, "PIV measurements of a microchannel flow". Experiments in Fluids 27, pp. 414-419. Springer-Verlag.

Santiago, J. G., Wereley, S. T., Meinhart, C. D., Beebe, D. J. and Adrian, R. J., 1998, "A particle image velocimetry system for microfluidics". Experiments in Fluids 25, pp. 316-319. Springer-Verlag.

Soo, H. and Radke, C., 1984, "The flow mechanism of dilute, stable emulsions in porous media". Ind. Eng. Chem. Fundamentals, 23, pp. 342-347.

Van Steijn, V., Kreutzer, M. T. and Kleijn, C. R., 2007, "μ-PIV study of the formation of segmented flow in microfluidic T-junctions". Chemical Engineering Science 62, pp. 7505-7514.

Wereley, S. T., Gui, L. and Meinhart, C. D., 2002, "Advanced algorithms for microscale particle image velocimetry". AIAA Journal, Vol 40, pp. 1047-1055.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.