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COMPLEX FLUID FLOW THROUGH A CONSTRICTED MICROCHANNEL

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Abstract. *This work presents a study of the flow of a viscoelastic solution of PEO (0.1 wt% Polyethylene Oxide solution) through a constricted glass microchannel, used as model for a pore-throat geometry of a porous media. Pressure drop measurements are performed and flow velocity fields are obtained using the micro particle image velocimetry (micro-PIV) technique. Experiments with a viscous solution of glycerin (61 wt% glycerin in water), of similar shear viscosity to the PEO solution, were also performed to investigate elastic effects of the PEO solution. Non-linear pressure drop behavior due to extensional effects of the PEO solution were observed. The velocity fields of the glycerin solution showed a permanent regime for the entire flow rate range explored, while the PEO solution shows changes in the direction of the flow and velocity fluctuations over time for high flow rates. In addition, the presence and growth of vortices (upstream of the constriction) were observed for the PEO solution. This study provides important information on how viscoelastic polymer solutions behave in a porous media and can impact their use in Enhanced Oil Recovery.*

Keywords: *Microfluidics, Viscoelasticity, Elastic turbulence, PEO Polymeric solution, Micro-PIV*

1. INTRODUCTION

Polymeric solutions are used to modify flow in various applications, the most common being enhanced oil recovery. The sweep efficient of water injection in an oil reservoir (secondary oil recovery) is limited due to a high mobility ratio between the water and oil. This promotes a non-ideal displacement behavior called fingering. Polymeric solutions are used to improve oil recovery due to their higher viscosity when compared to water. Viscoelastic properties of the polymeric solutions may also change the pore-scale flow behavior and reduce the residual oil saturation. However, polymer injections are still not well understood. Microfluidic devices can be used to represent porous media and study the effects of viscoelasticity at the micro-scale.

"Recently, Miranda (2015)" performed injection tests of three different fluids - water, a viscous solution of glycerin, and a viscoelastic polymeric solution of PEO - in an oil saturated glass microfluidic device (pore network and channels). They observed that the PEO injection produced a greater displacement of oil ganglia and a lower residual oil saturation than the glycerin and the water injections, as shown in "Fig. 1". The higher mobilization of oil ganglia observed with the injection of the PEO solution was associated with the lower water mobility at the pore scale and the extensional behavior of the PEO solution. As a consequence, a lower residual oil saturation was obtained.

Recent studies have shown pressure drop increase in the flow of viscoelastic liquids through constrictions. "Clarke, *et al.*, 2015" used particle tracking velocimetry (PTV) to visualize the injection of HPAM viscoelastic solutions in a microfluidic device (pore network and channels) and observed velocity fluctuations associated to pressure drop increase. "Boek, *et al.*, 2006" analysed the behavior of EHAC polymeric solutions flowing through a microchannel with expansion-contraction geometry using micro-PIV. They showed that the water flow is stable, but the EHAC solution exhibits velocity fluctuations in the contraction region. These velocity fluctuations were linked to the phenomena called elastic turbulence (transition from steady laminar flow to a strongly fluctuating flow).

Here a study of the flow of a viscoelastic solution of PEO and a viscous solution of glycerin through a constricted microchannel is presented, measuring pressure drop along with velocity fields. Solutions with similar shear viscosity were chosen to explore elastic effects, such as velocity fluctuations, flow thickening and extra pressure drop, among others.

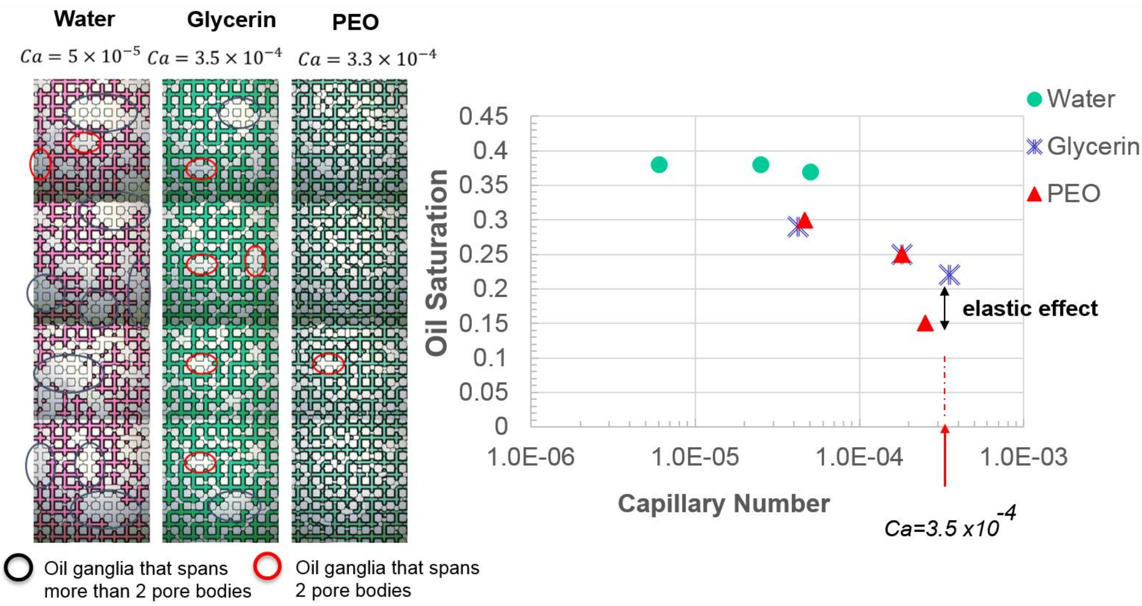


Figure 1. Experiments by "Miranda (2015)" of the injection of: water (colored pink), a viscous solution of glycerin (colored light green), and a viscoelastic polymeric solution of PEO (colored dark green). On the left: oil ganglia remaining after injection. On the right: residual oil saturation.

2. EXPERIMENTAL PROCEDURE

2.1 Experimental Set-up

The experimental set-up used for the pressure drop and velocity field measurements is shown schematically in "Fig. 2". The pressure measurement system is composed of the Validyne pressure sensor (Model DP-15, range: 0-1.25psi), an interface board and the data acquisition system (Easy Sense 2100 software). The Micro-PIV (TSI Inc.) system was used to measure the flow velocity fields with micron spatial resolution. In this system the Nd:YAG laser (Model Solo, 532 nm, 15 Hz) light is filtered by a filter cube (optical filters inside the Olympus® inverted microscope) and transmitted through the objective (Olympus® 10x/30) to illuminate the fluorescent particles seeded in the fluid flow. The scattered light by the particles reaches the CCD camera (Sensicam Mod-630066, 1.4MP), in synchronicity with the laser pulse. Consecutive images (frames) are recorded by the camera. These images are divided into small areas, called interrogation windows, and the average displacement of particles is calculated using cross-correlation statistical methods. Each interrogation window generates a vector and gives the local velocities in the bulk fluid. The Micro-PIV system is controlled by a computer using the Insight 4G™ (TSI®) software.

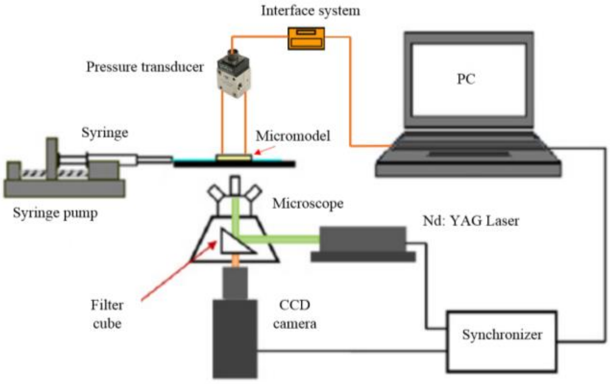


Figure 2. Experimental set-up.

2.2 Working fluids

The viscoelastic solution used was composed of polyethylene oxide (PEO, M_w=8x10^6 g/mol) at concentration of 0.1% by weight. The viscoelastic solution (PEO in deionized water) was mixed using a digital mechanical stirrer (Model RW-20, IKA®) at 200 rpm for 24h. It was then characterized rheologically using the rotation rheometer (Physica MCR 301-Anton Paar). The solution showed a shear thinning behavior (the viscosity decreases with increasing shear rate). The range of shear viscosity was 3 to 5 cP at 23°C (shear rates used in the experiments).

The viscous solution used was composed of glycerin ($C_3H_8O_3$, M_w=92.09 g/mol) at concentration of 61% by weight. The viscous solution (glycerin in deionized water) was homogenized using a digital magnetic stirrer (Model Corning PC-240) at 500 rpm for 1h. It was then characterized rheologically using the rotation rheometer. The shear viscosity of the solution was of 4.0 cP at 23°C, close to the PEO solution viscosity.

2.3 Methodology

"Figure 3" shows: a) the glass micromodel (Dolomite Microfluidics Center Ltd.) used as pore space model, and b) the geometry of the elliptical cross section and details of the constriction.

For each experiment, the solution was loaded into the glass syringe (Hamilton Gastight®, 2.5 ml) and pumped through the micromodel using the syringe pump (Harvard Apparatus Elite 11). The solution enters in the opening 2 of the glass micromodel and exits through 3 (see Fig. 3). The openings 1, 6, and 7 are closed during the experiments.

To measure the pressure drop of the solutions across the constriction the openings 4 and 5 were connected to the chamber of the pressure transducer. The data acquisition was performed every 0.25 seconds for a total time interval of 10 minutes, using the Easy Sense 2100 software.

To measure the velocity field near the constriction, each solution was seeded with polystyrene microspheres (1.0 µm, orange fluorescent, Thermo Fisher Scientific) to follow the flow, without interfering with it. The images were processed using the Insight 4G™ software to obtain the velocity vectors.

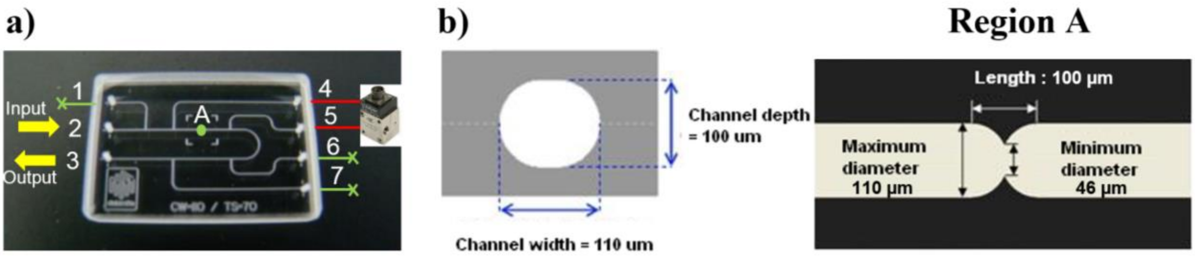


Figure 3. Micromodel, cross-section, and constriction geometry.

3. RESULTS AND DISCUSSION

3.1 Measurements of pressure drop

Pressure drop measurements across the constriction were performed for the PEO solution and for the glycerin solution. The goal of performing measurements with a viscoelastic fluid and a viscous fluid with similar shear viscosity was to explore extensional thickening of the PEO solution that can lead to additional pressure drop.

"Figure 4" shows the pressure drop as a function of the flow rate for the glycerin solution and for the PEO solution. The contraction ratio is $\beta \approx 2.5$ (110 µm/46 µm). The glycerin solution presented a linear behavior (Newtonian fluid) for the entire flow rate range explored. The PEO solution exhibited a linear response up to a critical flow rate of Q_C~0.08 ml/h. Above this critical flow rate the pressure drop showed a non-Newtonian behavior. This occurs due to elastic effects of the polymer.

To show the pressure increase associated with the elastic effects a plot of the ratio of the pressure drop of the PEO solution to the pressure drop of the glycerin solution is presented in "Fig. 5". In the Newtonian region, flow rates up to ~0.08 ml/h, the ratio is close to 1, therefore no extensional effect are observed. In the non-Newtonian region the ratio increases with the flow rate (elastic effects). For the flow rate of 0.18 ml/h the ratio is ≈ 4 and for 0.28 ml/h the ratio is ≈ 6.7.

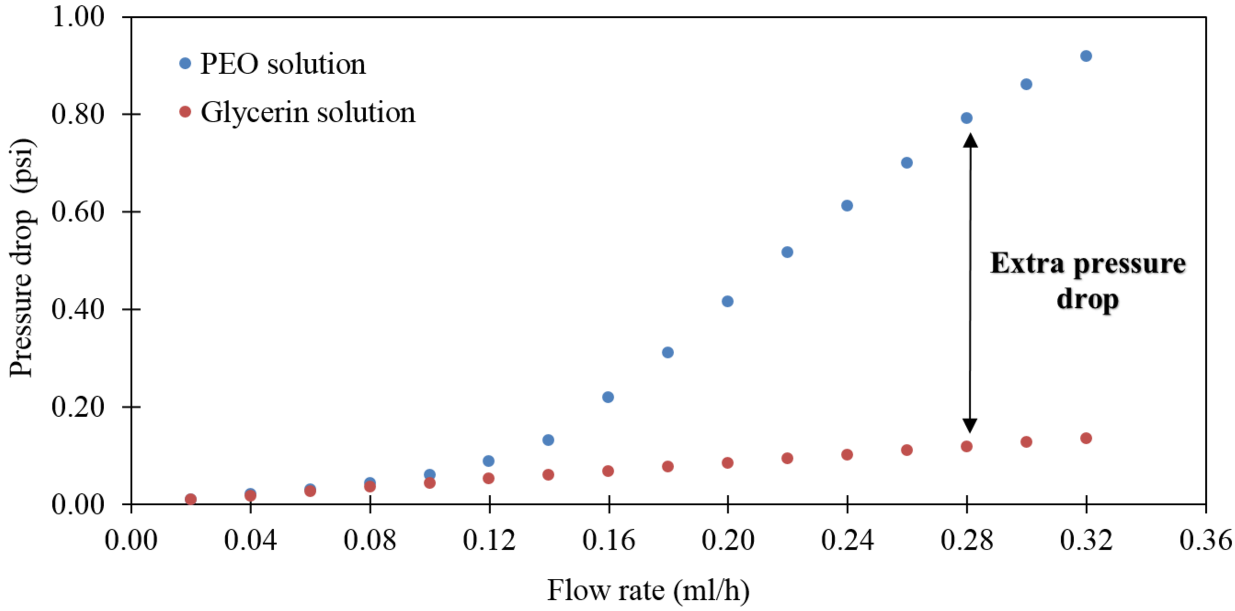


Figure 4. Pressure drop of the viscoelastic solution of PEO and the viscous solution of glycerin vs. flow rate.

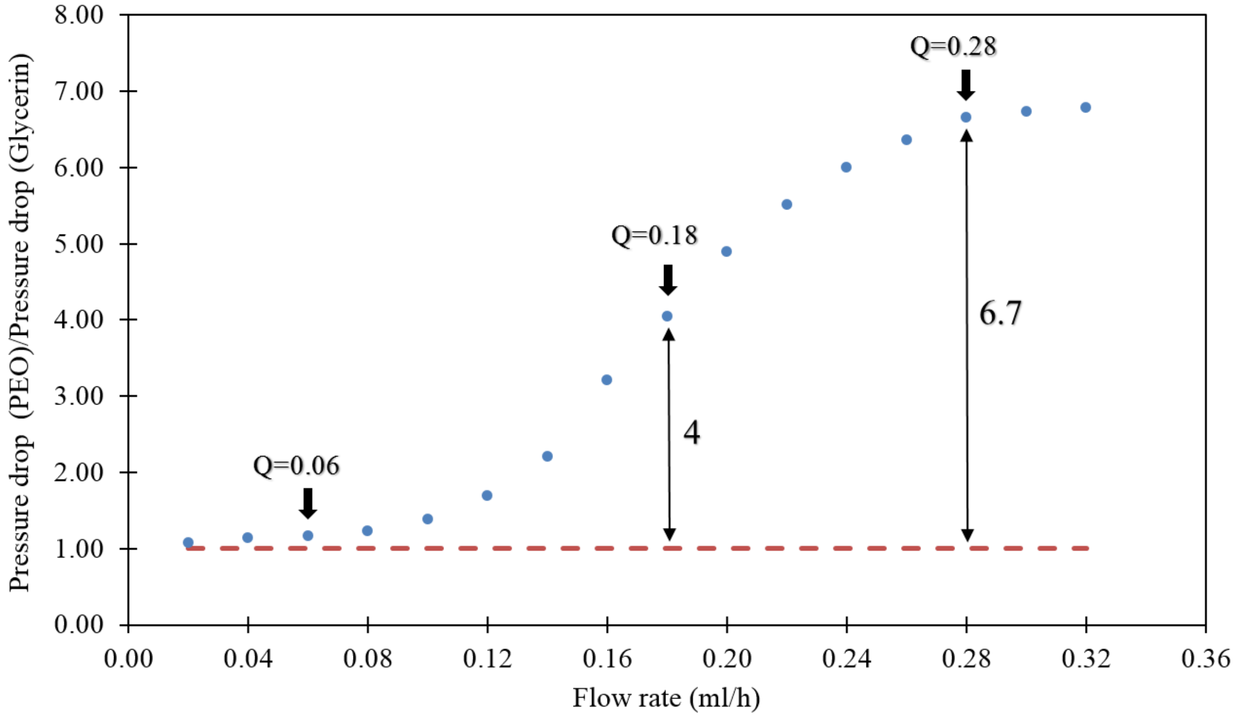
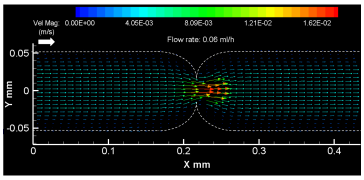
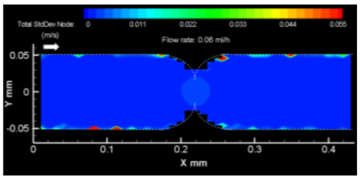
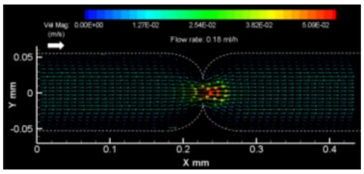
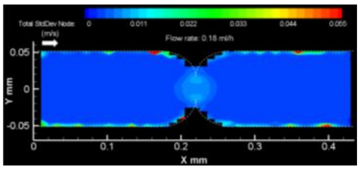
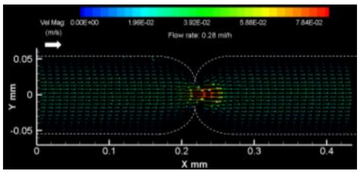
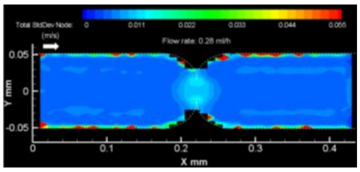
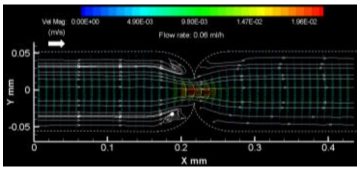
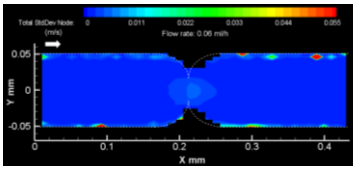
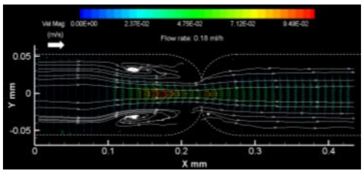
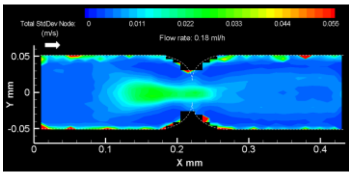
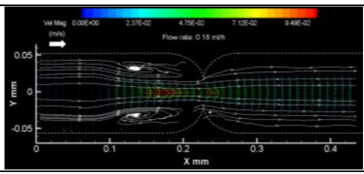
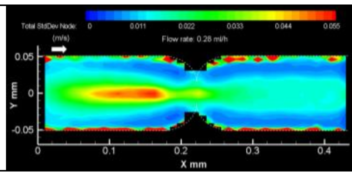


Figure 5. Ratio of the pressure drop of the PEO solution to the pressure drop of the glycerin solution as a function of the flow rate.

3.2 Measurements of velocity field

Micro Particle Image Velocimetry (micro-PIV) was used to study the different flow patterns in the region of the constriction (pore-throat model). Flow experiments were carried out for the viscous solution of glycerin (Newtonian fluid) and for the viscoelastic solution of PEO. The velocity fields studied for the different flow rates are shown in Tab. 1.

Table 1. Scheme of the velocity field study performed.

Solution	Flow rate (ml/h)	Average velocity field	Standard deviation velocity field
Glycerin	0.06		
	0.18		
	0.28		
PEO	0.06		
	0.18		
	0.28		

The average velocity field consists of creating a field vector from the sample mean of several instantaneous fields. This process minimizes problems of insufficient number of particles inside each interrogation area, reduces the percentage error due to Brownian motion of the particles, and increases the signal to noise ratio in the correlation peak. The spatial resolution used was 32x16 pixel^2 (1 pixel = 0.32 μm). To determine the velocity fields 500 consecutives image pairs obtained at a frequency of 4.83 Hz were used.

The results for the viscous solution of glycerin are shown in “Fig. 6”. As expected for a Newtonian fluid, the flow field is symmetric and the Poiseuille profiles can be seen along the microchannel.

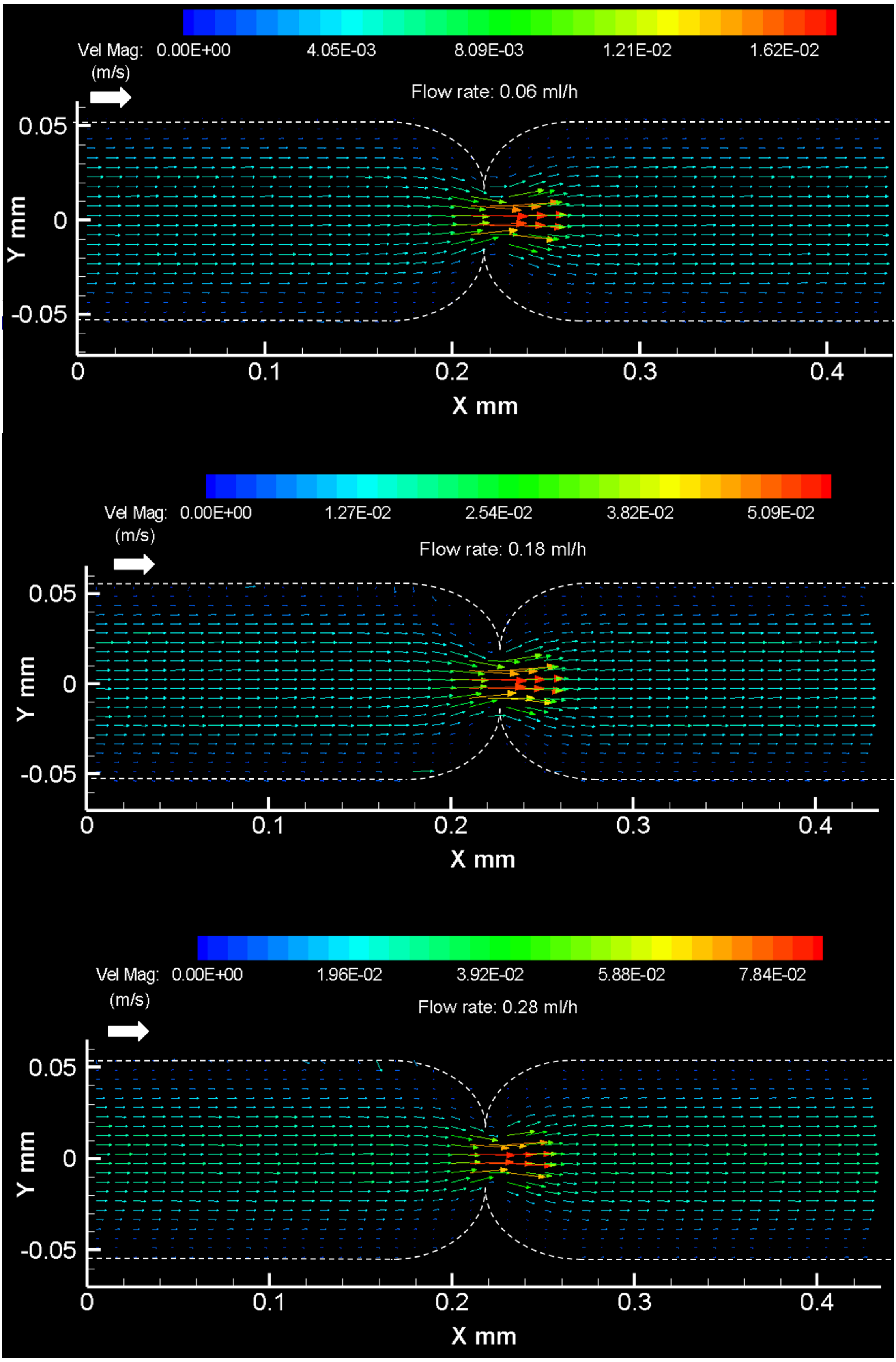


Figure 6. Glycerin solution - average velocity field for the flow rates of: 0.06, 0.18, and 0.28 ml/h, respectively.

The results for the viscoelastic solution of PEO are shown in "Fig. 7". A significant change in the velocity profiles is observed with the increase of the flow rate. The streamlines showed the presence of vortices. The size of the vortices increased with the flow rate.

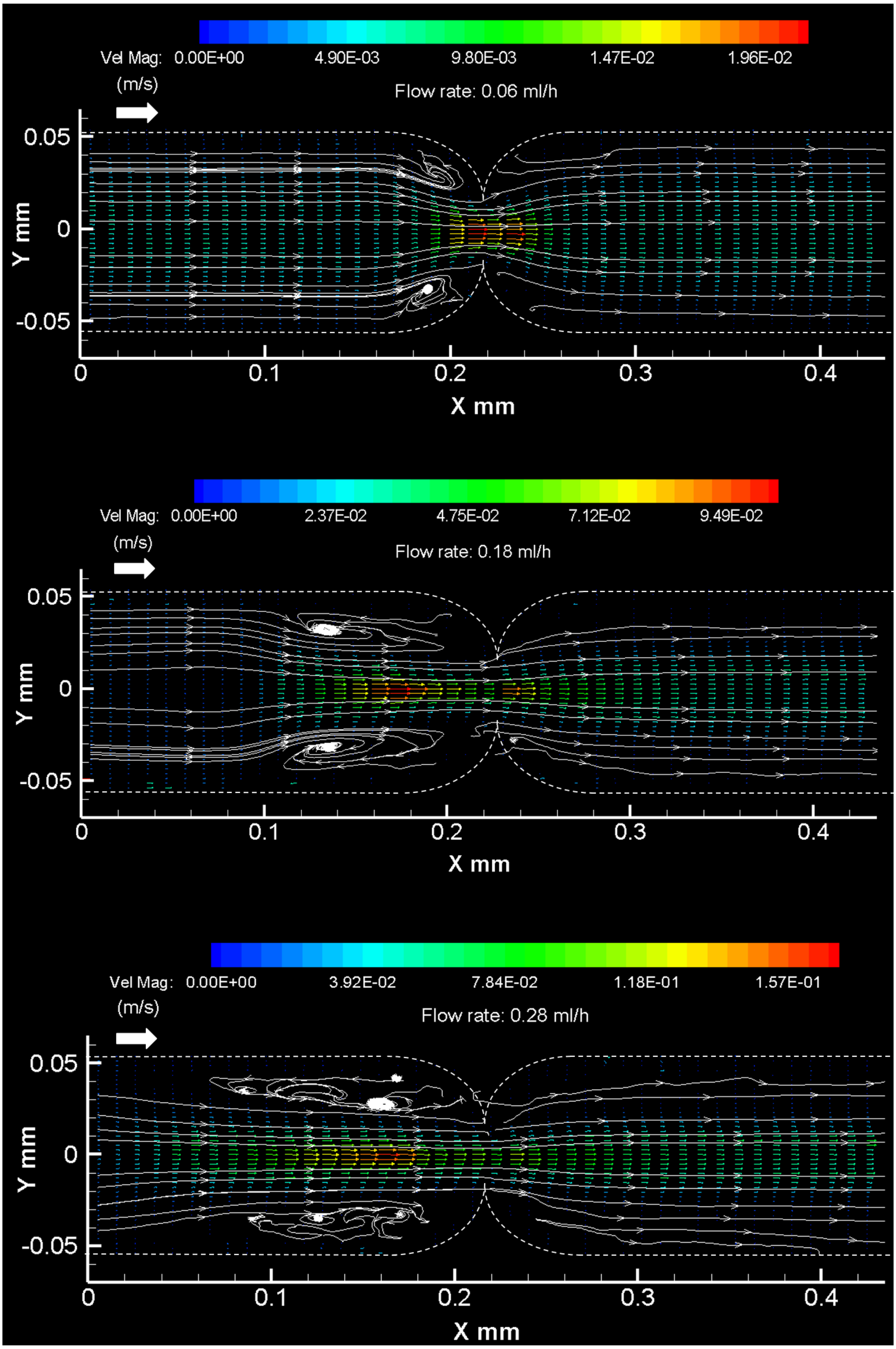


Figure 7. PEO solution - average velocity field for the flow rates of: 0.06, 0.18, and 0.28 ml/h, respectively.

Instantaneous velocity fields (single image pair) of the PEO solution showed changes in the direction of the flow and velocity fluctuations over time for high flow rates. To quantify this effect standard deviation velocity fields were produced. The spatial resolution used in this case was 64x32 pixel^2, higher than the previous case to minimize statistical noise.

The results for glycerin solution are shown in "Fig. 8". As expected the standard deviation velocity field is approximately zero for the entire region (no associated elasticity). The standard deviation variation close to the channel walls and to the center of the constriction is just an artifact due to low particle statistics.

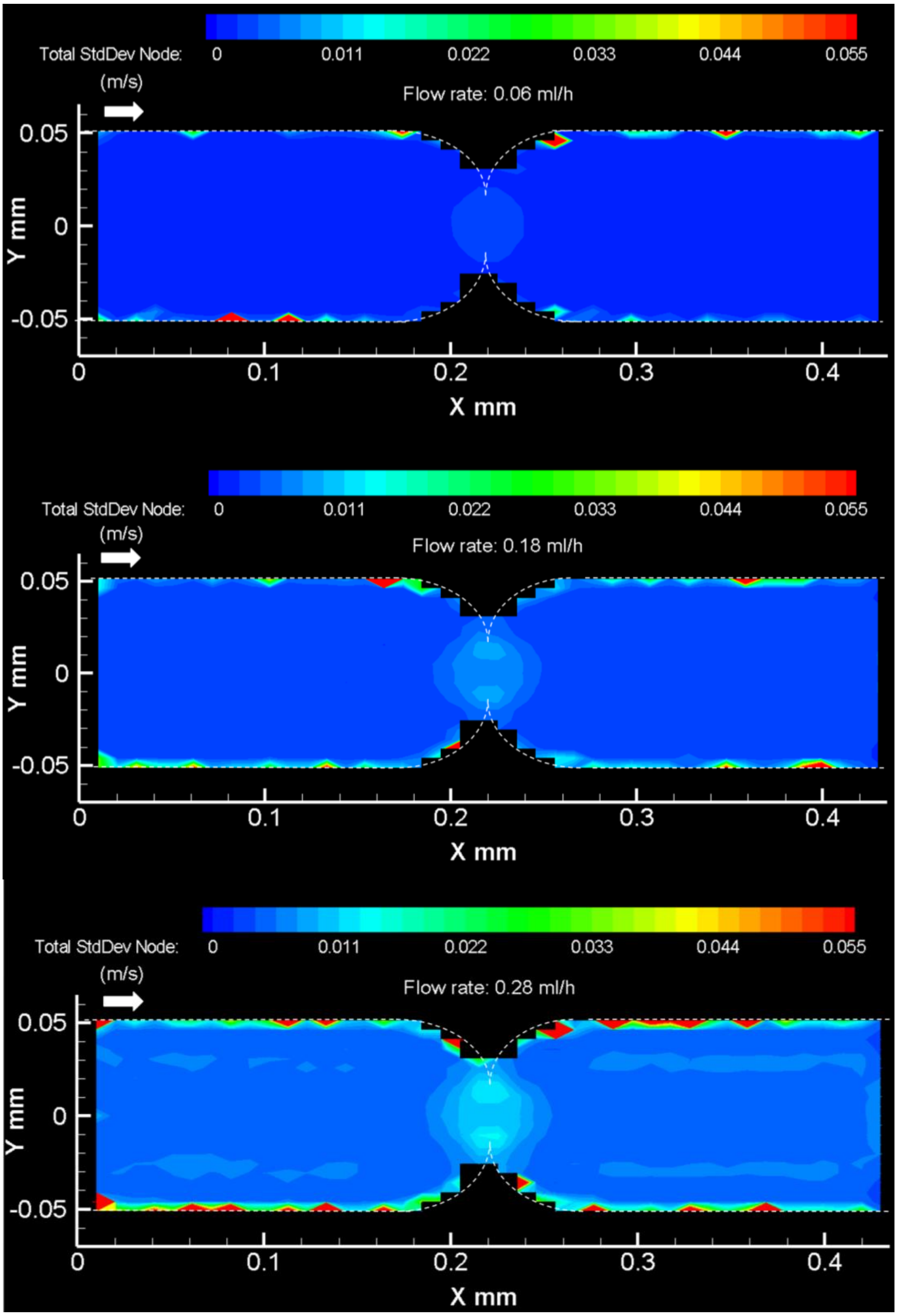


Figure 8. Glycerin solution – Standard deviation for the flow rates of: 0.06, 0.18, and 0.28 ml/h, respectively.

The results for the PEO solution are shown in “Fig. 9”. The linear response region, low flow rates (Q=0.06 ml/h), showed a steady flow over time. In this case, inertial stresses were more important than elastic stresses, i.e., the polymer relaxes faster than it is being unraveled. However, for the non-Newtonian region (Q=0.28 ml/h) large fluctuations were observed in the region of the constriction (the local velocities varied strongly with time). In this case elastic stresses were dominant compared to inertial stresses, which is related to the number Reynolds of Re=0.26. These velocity fluctuations are known as elastic turbulence (changes in the stability of the laminar flow), “Boek, *et al.*, 2006”.

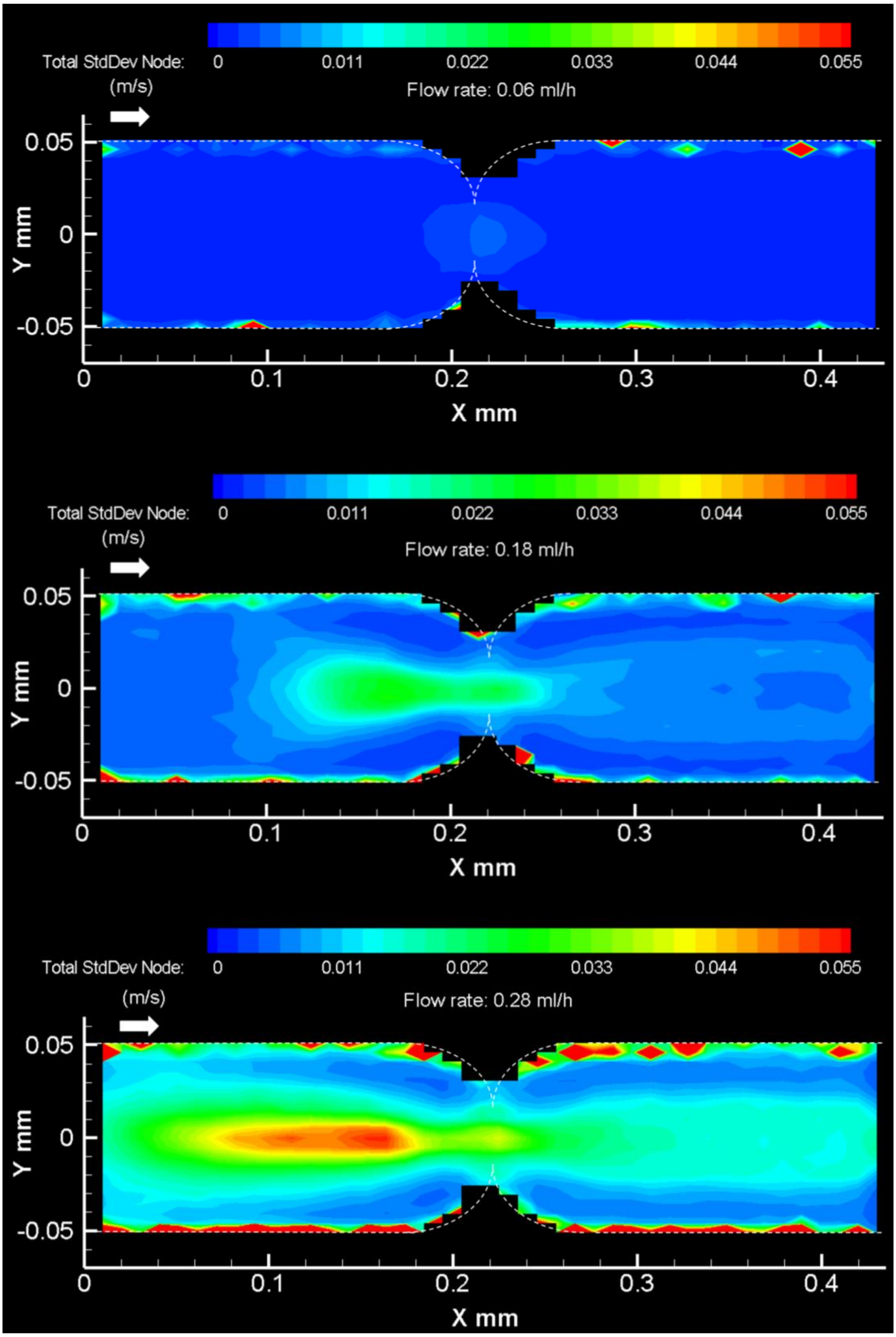


Figure 9. PEO solution – Standard deviation for the flow rates of: 0.06, 0.18, and 0.28 ml/h, respectively.

4. CONCLUSIONS

The flow of a viscoelastic polymeric solution of PEO (0.1 wt%) through a constricted glass microchannel (contraction ratio of $\beta \approx 2.5$) was studied here through measurements of pressure drop along with micro-PIV velocity fields. To identify elasticity effects, experiments with a viscous solution of glycerin (61 wt%), of similar shear viscosity to the PEO solution, were also performed.

The pressure drop measurements showed that the PEO solution presented a non-Newtonian behavior above a critical flow rate (Qc~0.8 ml/h). For flow rates above Qc, it was observed that the pressure drop difference between the PEO solution and the Newtonian glycerin solution increases as the flow rate increases. This enhanced pressure drop is due to the elastic response of the PEO solution when passing through the constriction (polymer chain resistance to extension).

The PEO solution velocity fields showed velocity fluctuations over time (elastic turbulence), coinciding with the onset of the extra pressure drop (non-Newtonian behavior). In addition, vortices´ growth was observed with the increase of the flow rate. For the entire flow rate range explored in this work (0-0.36 ml/h), symmetric and Poiseuille profiles were obtained for the glycerin solution. This confirms that the effects observed with the PEO solution are due to the elasticity of the polymer.

This work helps the fundamental understanding of the behaviour of polymer solutions flowing through pore-throat geometries and can be used to improve oil recovery.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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7. RESPONSIBILITY NOTICE