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EXPERIMENTAL STUDY OF EMULSION FLOW THROUGH A PORE-THROAT CAPILLARY MODEL

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Abstract. *Flow of emulsions in porous media holds potential importance for enhanced oil recovery (EOR) and as emulsified scale inhibitors, among other aplications in oil industry. The impact of operating parameters and emulsions properties in flow´s porous media is far from being entirely understood. A detailed observation at microscopic scale of the flow phenomena involved is essential for the understanding of the flow of an emulsion in a reservoir. This would lead to the development of better simulation models, henceforth increasing the predictability capability of reservoir simulators for EOR applications. In this work, pressure drop – volumetric flow rate response for oil-in-water emulsions passing through constricted capillary systems was studied. Visualization under an optical microscope was carried out to understand the flow phenomena involved. Flow rates were in the 1 m/day to 60 m/day range, to reproduce injection rates used in reservoirs operations. At a set flow rate pressure drop of the flow of emulsions having the same viscosity but different average drop size distribution may be different due to constricion blocking phenomena. This findings show that viscosity function of emulsions is not enough to fully characterize the flow inside porous media, as it is commonly done in reservoir simulations models.*

Keywords*: emulsions, capillary model, enhanced oil recovery, porous media, viscosity.*

1. Introduction

Emulsions are dispersions of two immiscible liquids such as oil and water. Two common fluid configurations or emulsion types are oil-in-water (O/W) or direct emulsions, and water-in-oil (W/O) or inverted emulsions. A third component present in emulsions is called the emulsifier, which has two main functions: (1) to decrease the interfacial tension between oil and water, thereby facilitating emulsion formation; (2) to stabilize the disperse phase against coalescence and coarsening once it is formed.

Emulsions are encountered practically in every stage of petroleum production and recovery operations, from the porous medium, production lines, to well heads and refining processes. Other industrial applications involve food processing, cosmetics, and hazardous material handling.

Oil is generally brought to surface from the reservoir rock by using different flow-driving mechanisms, from primary one to tertiary processes, depending of the development stage in a field. Primary production mechanisms use the initial potential energy available in the reservoir. One instance of these mechanisms is fluid expansion, another being water drive from an aquifer or water influx from the underlying water column in an oil reservoir. The latter two mechanisms typically lead to recovery fractions between a fifth and a third of the original oil in place. To further oil recovery beyond primary production potential, economically viable secondary recovery processes can follow primary recovery exploitation plans, once the economic limit of the latter has been reached. Water flooding is a sensible conventional secondary oil recovery method, often used in field development plans, whether for pressure maintenance or oil displacement. Pressure maintenance is a way to assist insufficient primary water drive by injecting water into edge or bottom aquifers. In its well-patterned strategy (displacement), the method basically consists of injecting water through injection wells to drive the oil towards production wells, by directly injecting into the oil column. The application of this method is responsible for more than half of World oil production, but the process has limited sweep and microscopic efficiency, often leaving a considerable amount of oil in the reservoir. This is sometimes the result of an unfavorable mobility ratio between oil and water, due to lower water viscosity than that of the oil, in many reservoirs. This leaves bypassed portions of the oil pool, often associated with viscous fingering phenomenon.

Waterflooding is also affected by reservoir heterogeneity, which is typically linked to large contrasts in absolute permeability, such as the so-called "thieves-zones", i.e. high permeability layers between injectors and producers that leave lower permeability layers upswept. This situation can be mitigated with the use of blocking agents. These agents increase the effectiveness of injection fluids in sweeping low permeability zones, hence helping to recover some of the remaining oil. Emulsions can be used to selectively block porous media, and consequently improve the efficiency of displacing fronts.

Several laboratory studies have been carried out to understand emulsion flow mechanism in porous media. McAuliffe (1973) determined properties of oil-in-water emulsions and studied their flow through porous media, to show that these emulsions could be used as selective blocking agents for oil recovery in waterflooding projects. He also showed that oil–in-water emulsions displace oil more efficiently than water alone. Later, Soo e Radke (1983) studied the flow of dilute emulsions through porous media and determined the final reduction in permeability. They measured droplet size distributions, both at the outlet and at the inlet of the porous sample and determined how the distribution changed as a result of filtering. They used a glass micro-model to prove that permeability reduction is caused by a capture mechanism similar to that observed in particle filtration processes. Kambharatana (1993) mentions the lack of good physical and mathematical descriptions for the flow of emulsions through porous media. In his work, he observed that viscosity changes of emulsions in porous media have a similar behavior trend as that seen in the viscosimeter, for the shearing rates of interest. Kambharatana confirmed that emulsion drops were captured according to a filtration process.

Emulsion injection as an alternative chemical recovery method is not a mature technology, but has been used successfully in some field trials. In the heavy oil recovery, emulsions may provide an effective mobility control when the oil is displaced through the porous media, so it might be advantageous to use emulsions instead of polymers for injection (Bragg, 1999).

One of the difficulties in developing emulsion injection technologies for EOR relates to the lack of fundamental knowledge about the flow of emulsions through porous media. Blockage of the pores by the discontinuous phase, as one of the controlling mechanisms, is a function of several parameters involved in the physics of the flow. In this sense, it is important to find a rational way to establish a relationship between pressure drop and flow rate, depending upon variables such as emulsion viscosity, viscosity ratio between the continous and discontinuos phase and mean droplet size/mean pore-throat size ratio. Several controlling mechanisms, such as the agglomeration of drops in constrictions, rupture, or drop elongation can occur during the flow of emulsions through porous media. A detailed observation of these phenomena at the microscopic scale is essential for the understanding of the flow of an emulsion in a reservoir. This would lead to the development of better simulation models, henceforth increasing the capability for accurate prediction of reservoir simulators for EOR applications.

In this work, a 200 μm diameter glass capillary with a neck of 50μm in diameter is used as a model for a single pore-throat of a porous media. The flow of different oil in water emulsions flowing through a constricted capillary tube at typical velocities encountered in oil reservoirs is analyzed by measuring the pressure drop as a function of time and volumetric flow rate, and visualizing at microscopic scale the flow of the disperse phase through the constriction. The oil drops may deformation, rupture or obstruct of the capillary constriction, leading to different flow regimes.

2. Experimental work

2.1 Materials

Different oil in water emulsions were used in this analysis. All of them had a 30% in volume concentration of oil (discontinous phase). The oil used in the experiments was a synthetic oil (SHELL, Tivela 150). The density and viscosity of the mineral oil are $\rho_o = 993 kg/m^3$ at 20°C and $\mu = 350 cP$ at 25°C, respectively. Deionized water was used as the continuous phase. It was necessary to add a low molecular weight polymer (Carbopol) to water in order to increase the viscosity of the continuous phase and therefore delay the segregation of the phases due to gravitational effects in all experiments. Surfactants were added to the continuous phase in order to lower the interfacial tension and avoid the coalescence of the oil drops. Two water-polymer-surfactant solutions were used. The first consisted of a 0.082% Carbopol solution in water with SDS surfactant; the second consisted of a 0.1% Carbopol solution in water with Triton X-100 surfactant. The concentration of the surfactants used were approximately 10 times the critical micelle concentration (CMC). Triton X-100 substitued SDS surfactant in the formulation of the emulsions because SDS alteres the pH of the aqueous solution. It turns out that the polimeric solution containing Carbopol is sensitive to pH in such a way that the continous phase viscosity was lower than desired, reason why the nonionic surfactant was preferred.

Each set of oil and water+polymer+surfactant mixture was sheared in a disperser (Ultramax) for about 3 minutes at different rotations. A rotation of 6,500 rpm was used to prepare emulsions with large drops; smaler drop emulsions were prepared at a rotation of 26,500 rpm. Table 1 summarizes the 4 emulsions tested in this work. Each emulsion was labled according to its components and drop size distribution. Emulsions *1L* and *1S* are the large-drop and small-drop emulsions prepared using the 0.082% carbopol solution in water (plus the SDS surfactant), emulsions 2L and 2S are the

large-drop and small-drop emulsions prepared using the 0.1% carbopol solution in water (plus the Triton X-100 surfactant).

Table 1. Fluids used in the experiments.

Emulsion	External Phase	Internal Phase	Emulsion Type	O/W Ratio (% vol)
1L	Water + Carbopol 0.082 % + SDS	Shell Tivela 150 (Synthetic Oil)	O/W	30/70
1S				
2L	Water + Carbopol 0.1% + Triton X-100			
2S				

Information regarding the dispersed phase was obtained by taking microphotography of the emulsion samples. Optically measured droplet sizes were used to build the normalized histogram of drop size distribution. An inverted Zeiss optical microscope, in transmitted light mode was used for all visualizations. The shear viscosity of the emulsions as a function of the shear rate was measured using a rotational rheometer. Couette-type geometry was used for the measurements, using a serrated cylinder to dissipate slipping effects at the walls.

Figure 1 shows the drop size distribution of emulsions 1L and 1S. The difference in the rotation speed of the disperser was enough to produce emulsions with different average drop size. The viscosity curve is presented in Fig.2. As expected, the emulsion with smaller size distribution has the larger viscosity. The larger interfacial area and mutual interaction between different drops increases the viscosity of the emulsion, as explained by Becher (2001).

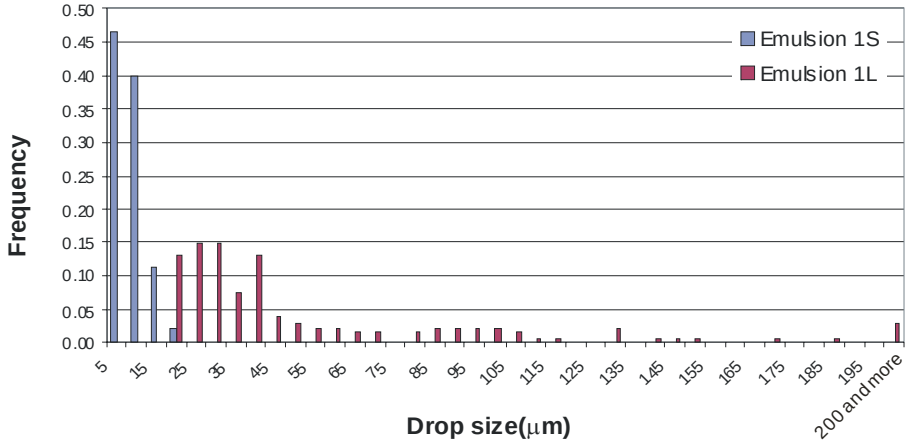

Figure 1. Drop size distribution of emulsions *1L* and *1S*.

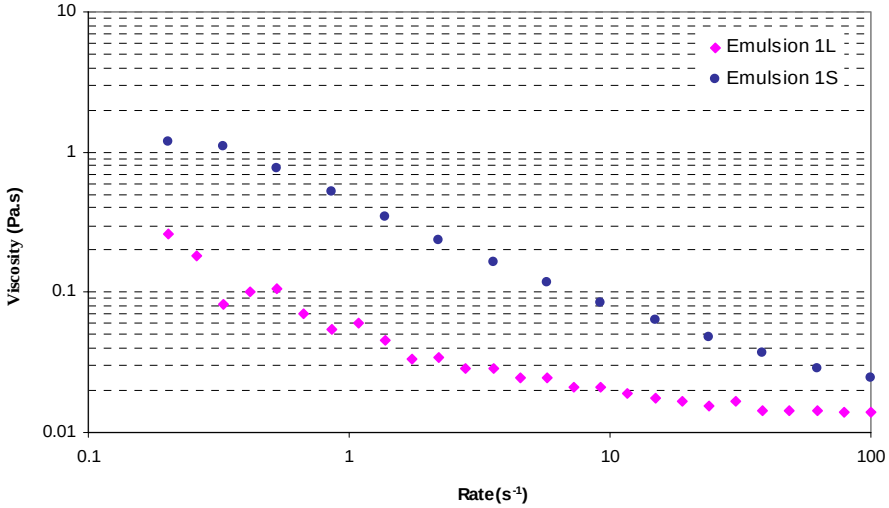

Figure 2. Shear viscosity curves for emulsions 1L and 1S.

The size distribution and viscosity curve of emulsions 2L and 2S are shown in Figures 3 and 4, respectively. These emulsions have slightly higher viscosity then emulsions 1L and 1S, because of the higher continuous phase viscosity (larger concentration of the polymer). Again, the viscosity of the small drop emulsion, e.g. 2S, is higher.

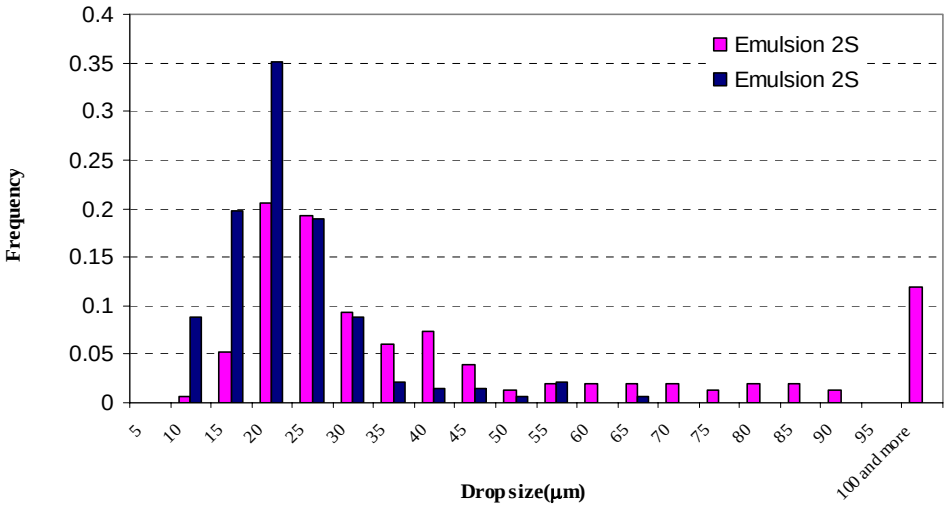

Figure 3. Drop size distribution of emulsions *2L* and *2S*.

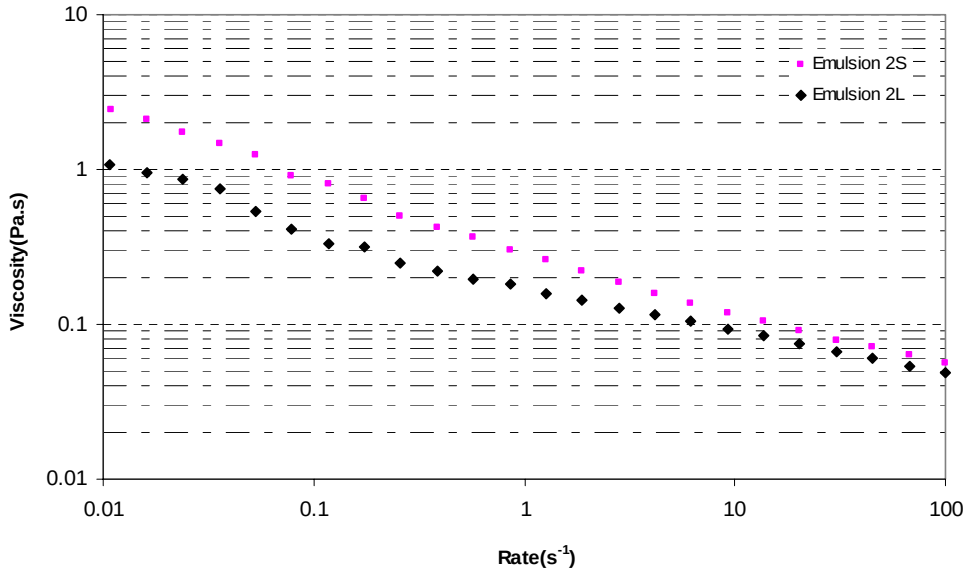

Figure 4. Shear viscosity curves for emulsions 2L and 2S.

2.2 Experimental Procedure

The experimental apparatus used is sketched in Fig.5. A syringe pump is used to feed emulsion through the capillary at a constant volumetric flow rate. A port, connected to a pressure transducer (Valydine), was installed just upstream the capillary tube to measure the pressure. Values of pressure were acquired on the PC by using a multiplexer slot as interface between the transducer and the computer. Pressure data points were taken every 1 second. Systematic error for pressure drop acquisition was ± 2%.

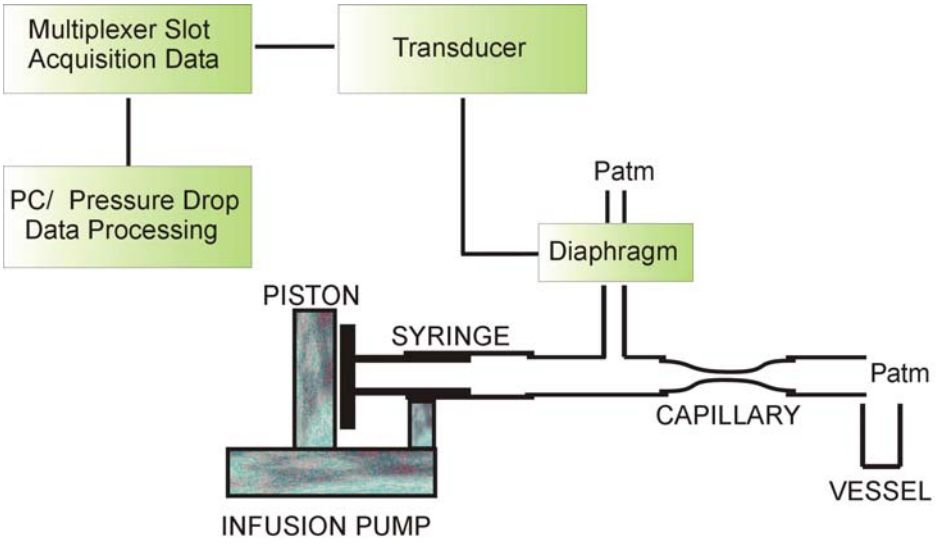

Figure 5. Acquisition system for measuring pressure drop data.

The diameter of the glass capillary tube was 200 μm, and of the neck was equal to 50μm. Figure 6 shows a photograph of the capillary tube used in the experiments.

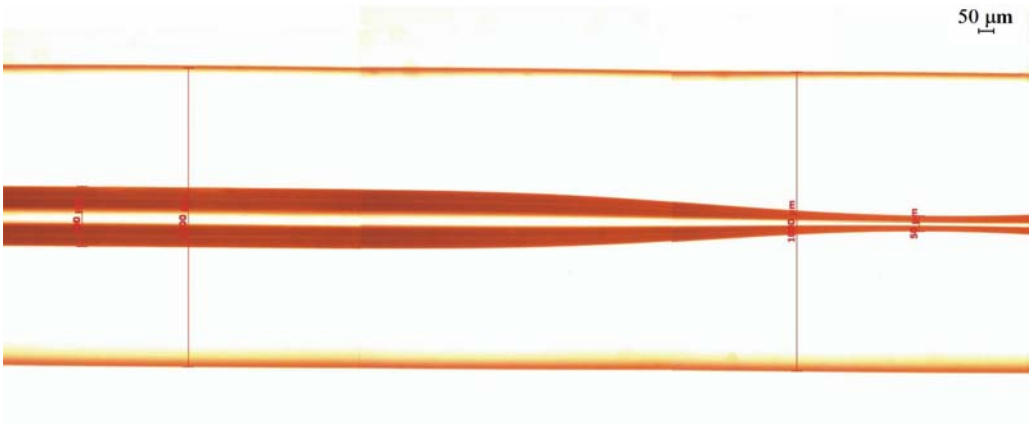

Figure 6. Glass capillary used in experiments. (200 μm in diameter and 50 μm in constriction).

An inverted Zeiss Axioplan microscope with a 5X objective was used to observe the emulsion flowing through the capillary. Images were captured in real time and recorded by a charge couple device (CCD) video camera attached to the microscope and connected directly to the frame grabber and then recorded on a video tape, as sketched in Fig.7.

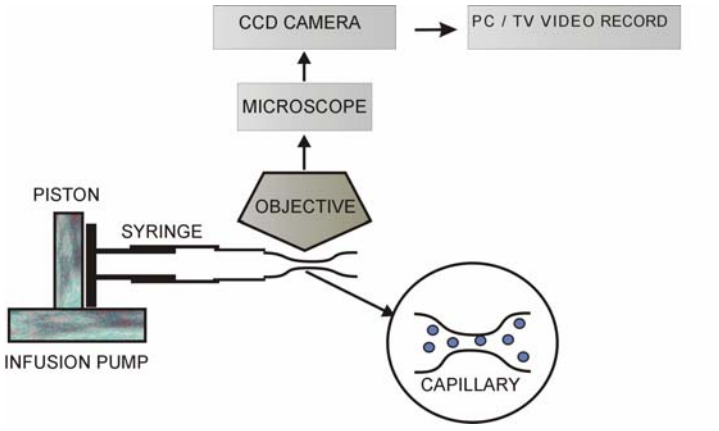

Figure 7. Experimental set-up for microscopic visualization.

3. Results

3.1 Pressure Drop Measurements

Figure 8 presents the time-average pressure drop as a function of volumetric flow rate for emulsions 1L and 1S. At low volumetric rate, the pressure drop is virtually the same. At higher flow rate, the pressure drop obtained with emulsion 1L is slightly higher than that obtained with emultion 1S, eventhough 1S has a higher viscosity. This is an evidence that shows that the viscosity of the emulsion is not the only parameter that affects the pressure drop. At the micro scale, if the oil drops have approximately the same size of the pore-throat diameter, they may partially block the passage, leading to higher pressure drops. This is one of the possiblem mechanism for mobility control using emulsions.

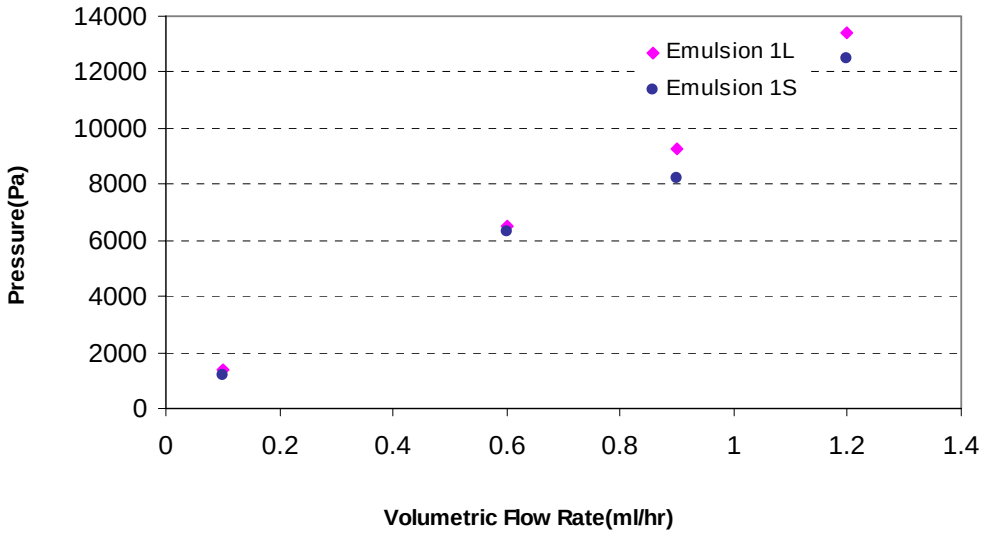

Figure 8. Measured pressure drop as a function of volumetric flow rate for emulsions 1L and 1S.

The variation of the measured pressure drop with time for emulsions 2L and 2S when the flow rate is changed are shown in Fig.9. At each given flow rate, the pressure obtained with the large drop emulsion (2L) was higher than the pressure drop obtained with the small drop emulsion 2S, which has the higher viscosity. Again, the interaction of the large drops with the neck of the capillary increases the pressure drop necessary to drive the flow at each flow rate. No significant pressure drop fluctuations are observed with emulsion 2S. On the other hand, with emulsion 2L, that has an average drop size larger than the constriction diameter, the pressure oscilates around an average value, at each flow rate. This oscillation may be associated with the passage of single large drops through the capillary constriction.

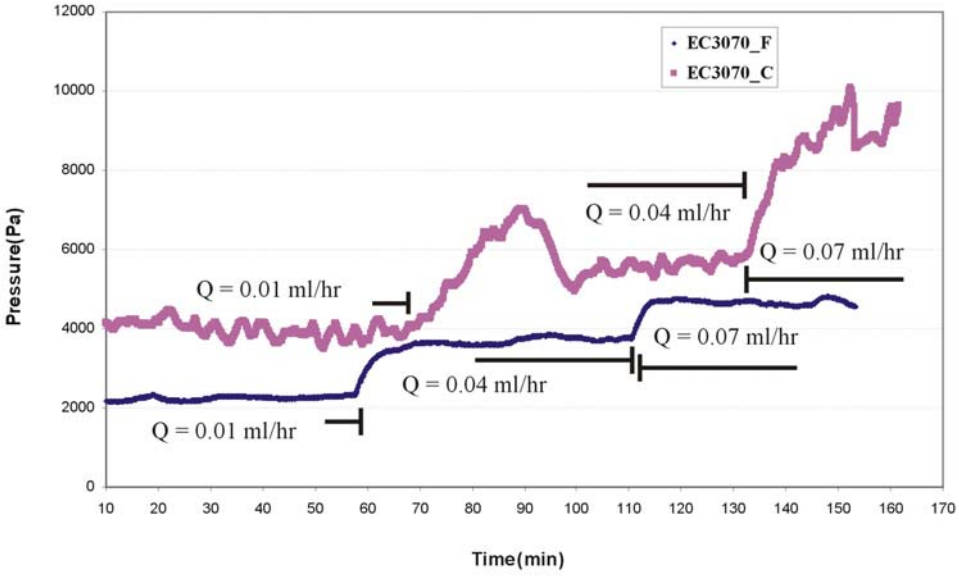

Figure 9. Variation of pressure drop as the flow rate is changed for emulsions 2S and 2L.

As emulsion 2S passes through the capillary neck, drops overcome the constriction without considerable resistance, which would be reflected as a sudden pressure drop increment. However, as emulsion 2L flows through the same capillary, a considerable resistance is offered to the transit of oil droplets larger than the constriction diameter. This can be seen not only by the oscilation of the measure pressure drop, but also from the visualization experiments. Figure 10 shows the passage of small and large drops of emulsion 2L through the capillary constriction at a volumetric flow rate of 0.04 ml/h. Figure 11 shows the pressure drop as a function of time at this same flow rate. Interval A, indicated in Fig. 11, corresponds to the interval at which the images of Fig.10 were obtained. It is clear that the pressure rise is associated with the passage of a large drop through the constriction.

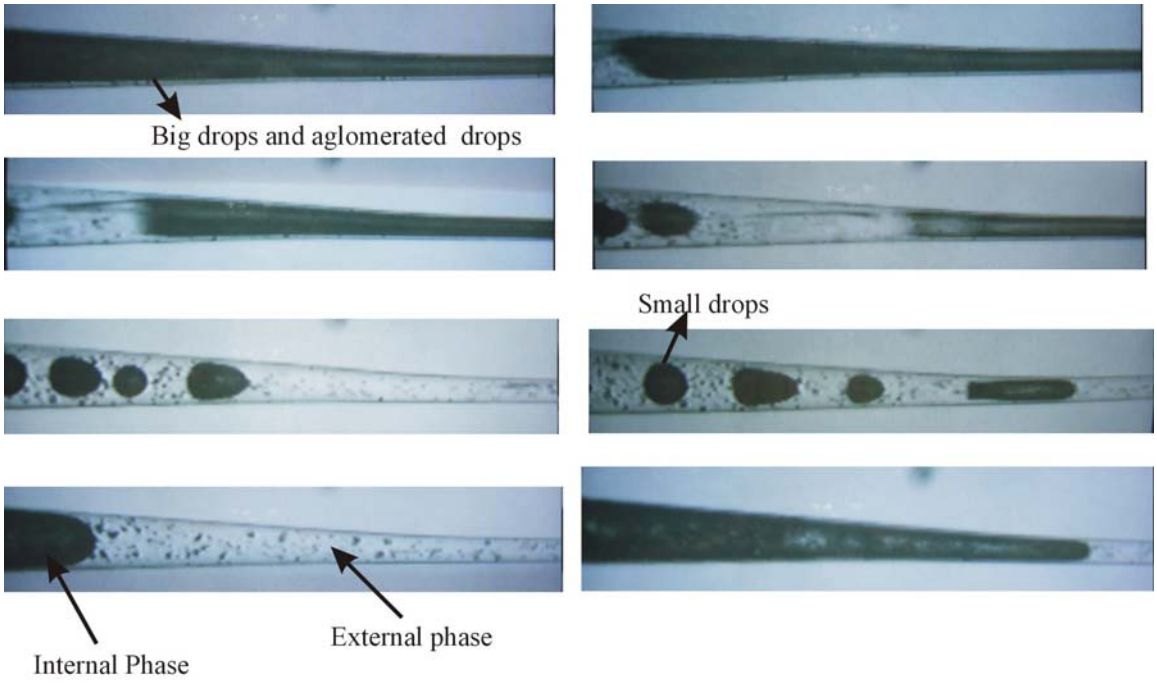

Figure 10 . Visualization of emulsion 2L flowing through the constriction.

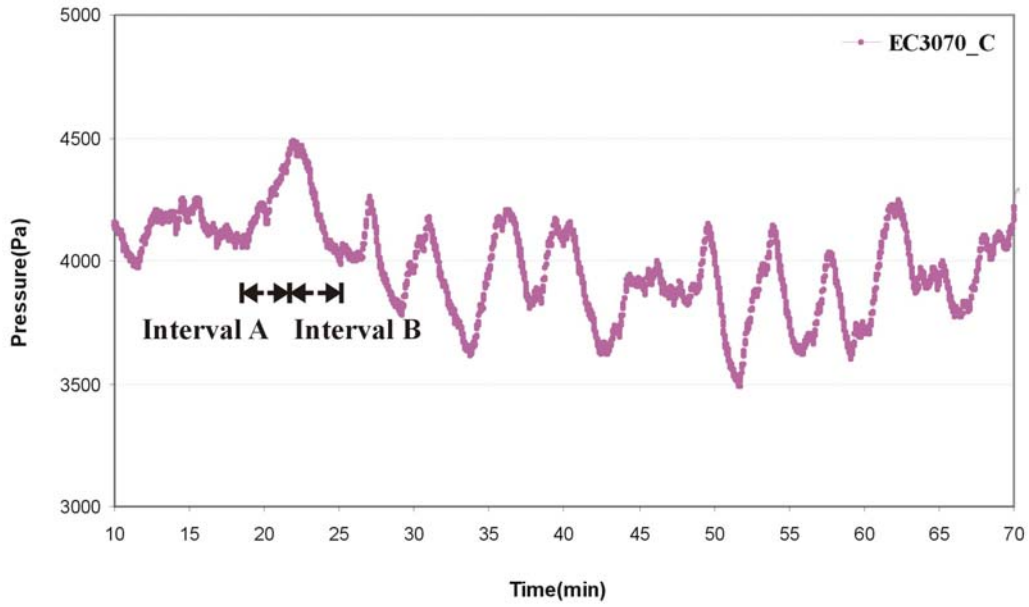

Figure 11 . Variation of pressure at a flow rate of 0.04 ml/h. The interval A marked in the figure corresponds to the time interval at which the images presented in Fig.10 were obtained.

4. Conclusions

The experimental results presented shows that the flow of a emulsion through a porous media cannot be fully described by the macroscopic parameters of the emulsion, like the viscosity. At micro scales, the interaction between the disperse drops and the capillary geometry leads to a partial blocking phenomena that rises the pressure drop. This increase in the pressure drop may be used to control the mobility of emulsions in enhanced oil recovery operations.

5. Acknowledgements

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