FLOW VISUALIZATION OF EMULSIONS THROW A PORE-THROAT CAPILLARY MODEL

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Abstract. *Use of emulsions for enhanced/improved oil recovery (EOR/IOR) applications is of particular interest in the petroleum industry. Extensive literature has shown that oil droplets can selectively block pore passages in a porous medium, thereby improving the sweep efficiency of the displacing phase. The latter would lead to an increase in the amount of oil produced, for instance, under aqueous solution injection. The flow of an emulsion in a porous medium involves several controlling mechanisms, such as agglomeration of drops in constrictions, rupture or drop elongation. 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, thus increasing the capability for accurate prediction of reservoir simulators for EOR/IOR applications, among others. In this work, the pressure drop caused by equal O/W emulsions but with different drop sizes flowing through a 200 μm capillary with a neck of 50 μm in diameter was measured for a constant volumetric flow rate. It was found that for the emulsion with the wider drop size distribution, the pressurre drop increased as function of time drastically. Once the drops obstructing the capillary were liberated, pressure drop decreased until new drops obstructed the capillary neck. Microphotograhps obtained show how the neck blockage took place.*

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

1. Introduction

Emulsions are dispersions of two immiscible liquids such as oil and water. Common emulsions include oil-in water (O/W), or direct emulsions, and water in oil (W/O) or inverted emulsions. A third component is present in emulsions, 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.

The use of emulsions is of particular interest in enhanced oil recovery (EOR) and other oil industry applications. Common primary production mechanisms, which are based on the use of the primary energy present in the reservoir, for instance fluid expansion or water drive from an aquifer, typically lead to recovery fractions between a fifth and a third of the original oil in place. A variety of secondary oil recovery processes can follow primary production, if they happen to be economically viable. A conventional secondary oil recovery method is water flooding, whether for pressure maintenance or oil displacement. Pressure maintenance is a way to assist insufficient primary water drive by injecting water into aquifers, at the bottom or periphery of an oil accumulation. In its well-patterned strategy (displacement), the method basically consists in injecting water through injection wells to drive the oil towards production wells. Despite this method being responsible for more than half of World oil production, 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 viscosity of water as opposed to oil, in many reservoirs. This leaves bypassed portions of the oil pool, often associated with viscous fingering phenomenon.

Water flooding is also affected by reservoir heterogeneities, which are typically linked to large contrasts in absolute permeability, such as the so-called “thieves-zones”, i.e. high permeability layers between injectors and producers, which leave lower permeability layers with a high oil saturation untouched. This situation calls for the use of blocking agents, to later inject another fluid to sweep these low permeability zones, to recover some of the remaining oil.

The injection of emulsions in reservoirs can be used to selectively block porous media, and consequently improve the efficiency of displacing fronts, thus obtaining a better sweep efficiency.

Several laboratory studies have been carried out to learn about emulsions flow mechanism through porous media. McAuliffe (1973) determined properties of oil in water emulsions and studied the flow of emulsions through a porous media, to show that oil in water emulsions could be used as selective blocking agents for oil recovery by water injection. He also showed that oil in water emulsions displace oil more efficiently than water. 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 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.

Emulsions injection technology 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 produce a high viscous front maintaining an effective control of mobility 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, as one of the controlling mechanisms, is a function of the several parameter 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 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/IOR applications.

Up until now and to our knowledge, insufficient attempts to visualize an emulsion passing through a single capillary with a constriction and to offer a pattern mechanism have been made. In this work, flow of O/W emulsions flowing at typical velocities encountered in oil reservoirs is monitored by measuring pressure drop as a function of time for a constant volumetric flow rate. Visualization at microscopic scale is carried out to record deformation, rupture of drops or obstruction of the capillary constriction. The pore-throat model consists of a 200 μm diameter glass capillary with a neck of 50 μm in diameter, similar in scales to some relatively highly permeable porous media.

2. Experimental work

2.1 Materials

Emulsions used here are of O/W type. The internal phase is a SHELL, TALPA 30, mineral oil. The density and viscosity of TALPA 30 are 0.903 at 20°C and 122.9 cSt at 40°C, respectively. The water used throughout all the experiments was deionized. It was necessary to add Carbopol to the water phase to avoid segregation of the phases due to the gravitational effects during pressure drop measurements and visualizations. A 0,1% (p/p) Carbopol in water solution was prepared for this purpose. The surfactant used for the preparation of emulsions was Triton X-100, at concentrations about 20 times the critical micelle concentration (CMC). Triton X-100 is a water soluble surfactant and has a high HLB (Hydrophylic-Lipophilic balance) value of 13.5.

For visualizations under the microscope, the capillary was placed in a pure glycerin pool to eliminate optical distortions due to light refraction. This provided a good refraction index match, since the refraction index of the capillary (borosilicate) is of 1.474 while the refraction index of glycerin is of 1.473.

2.2 Procedure

2.2.1 Emulsions Preparation

Most of the emulsions were prepared in batches of 500 g. Calculated amounts of aqueous surfactant solution, and TALPA 30 oil were put together into a beaker and then sheared by a dispersor (Ultraturrax) for about 3 minutes at 6500 rpm. Emulsions produced were quite stable to coalescence of oil droplets and segregation of the phases for more than ten days, providing an adequate time of stability for the experiments, of 2 hours duration. The system EOW_SB1 listed in Tab. 1 was obtained in trial and hand shaken to obtain an emulsion with bigger drops.

Information regarding the dispersed phase in form of droplets, as the structure and drop sizes extremes, was obtained by taking microphotography of the emulsion samples. A Zeiss optical microscope, in transmitted light mode, was used for all visualizations. A pre-processing was done applying a filter to achieve the font uniformization and to facilitate a posterior segmentation process into white and black colors. Photos were taken after this process.

The shear viscosity of the emulsions was measured using a rotational rheometer. A type Couette geometry was used for the measurements, using a serrated cylinder to dissipate slipping effects at the walls.

2.2.2 Pressure Drop Acquisition

A pressure transducer (valydine) was used to acquire pressure data. It consists basically of a diaphragm with an internal resistance that transforms deformation in tension voltage. The plate was calibrated using deionized water in a static column experiment. A diagram of the pressure acquisition system used is shown Fig. 2. Values of pressure are acquired on the PC using a Multiplexer Slot as interface between the transducer and the computer. Pressure data points were taken every 5 seconds.

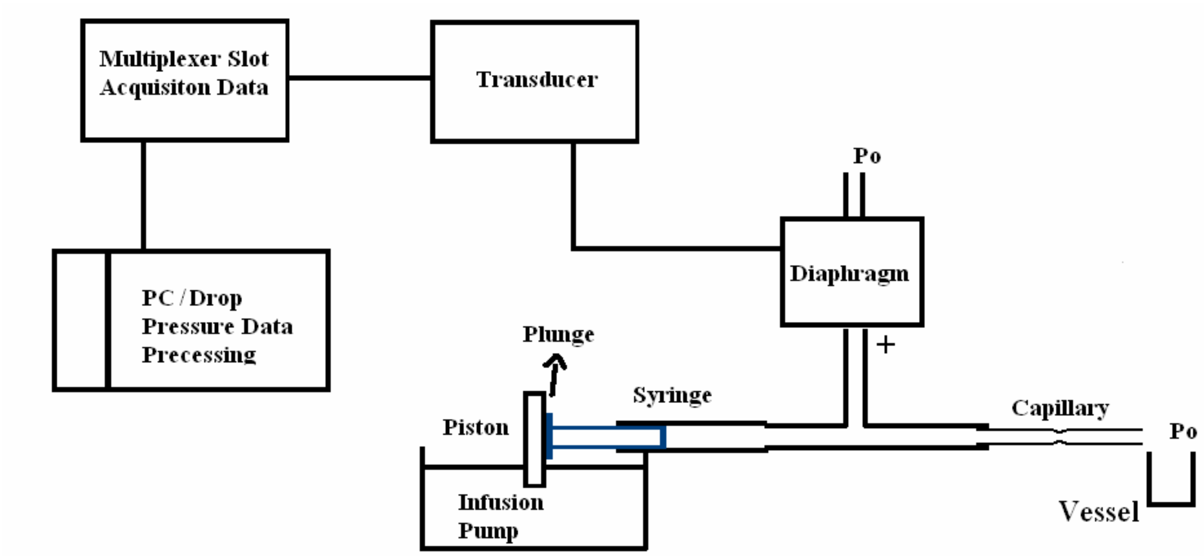


Figure 1. System Acquisition for Drop Pressure Data

2.2.3 Visualization

The 200-μm-diameter glass capillary with a neck (constriction) of 50 μm in diameter was placed within a glycerin pool. Capillary tube was dry (air filled) at start of the injection. The emulsions were injected using a syringe infusion pump at controlled rates. Schematics of the experimental setup are shown in Fig 2. The apparatus consists of the micro syringe pump with a micro liter syringe to inject the emulsion. A Zeiss Axioplan 2 microscope with a 20 x objective was used to observe the emulsion flowing through the capillary. Images with a resolution of 1300 x 1030 pixels were captured at 1 frame per second, recorded by a charge couple device (CCD) video camera attached to the microscope and connected directly to the PC frame grabber (Axiovision) and then stored on hard disk.

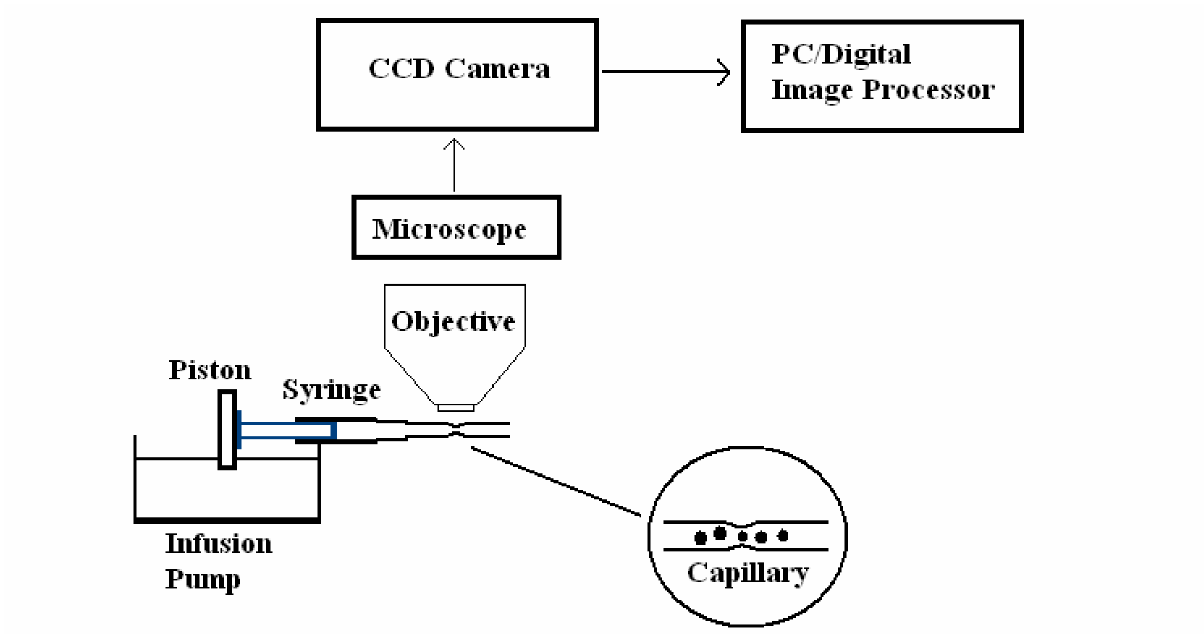


Figure. 2. Experimental set-up for microscopic visualization.

3. Results

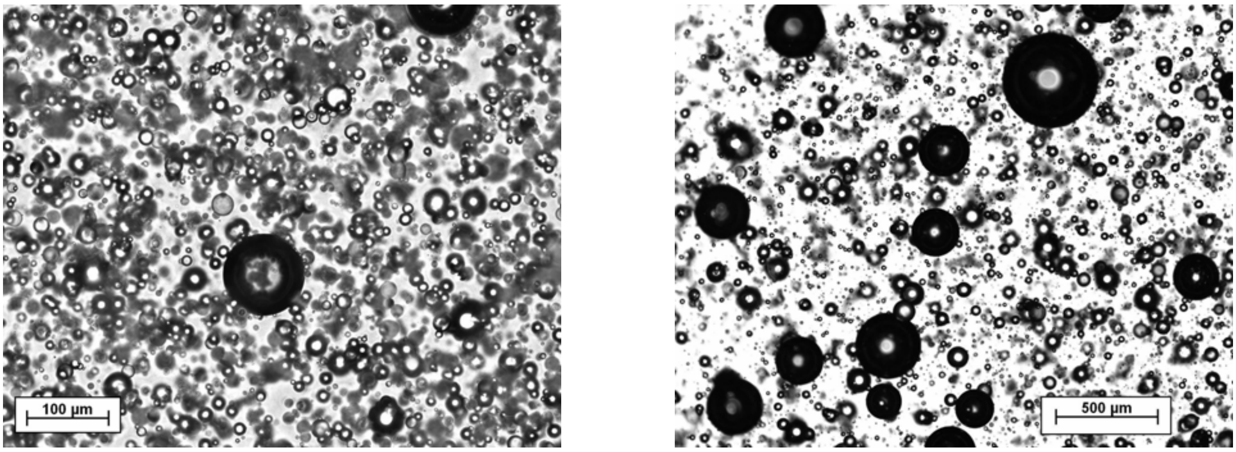
3.1 Pressure Drop Measurements

Pressure drop between the inlet and outlet of the capillary was measured for emulsions with different drop size distributions, but the same volumetric liquid fractions: 10% oil and 0.26% of surfactant. Tab. 1 show the drop size range for the two emulsions used in the experiments.

Table 1. Emulsions used in the experiments.

System	Drop size range(μm)
EOW_SB1	2 to 60
EOW_SL1	2 to 600

Figure 3 shows the microphotographs of O/W emulsions. It can be observed that emulsions are polydisperse. Clear circles in the center of the droplets are optical artifacts as a result of the transmitted light.



(a) (b)

Figure 3. Photomicrographs of O/W emulsions: (a) EOW_SL1, (b) EOW_SB1

The shear viscosity as a function of the shear rate of the emulsions is shown in Fig. 4. It can be seen that viscosity decreases with increasing shear rate, as expected for a Non-Newtonian shear thinning material. The behavior of EOW_SL1 and EOW_SB1 emulsions is quite similar. Is important to highlight here that emulsion EOW_SPW, free of Carbopol is also shear thinning, so shear thinning behavior of the emulsions is not controlled by the addition of Carbopol. It can be noted that emulsions with Carbopol in water solution as external phase have a high viscosity at low shear rates. High shear rates viscosities of Carbopol, EOW_SL1 and EOW_SB1 are similar, suggesting in this case that for high shear rates, the viscosity of the emulsion is controlled by the viscosity of external phase.

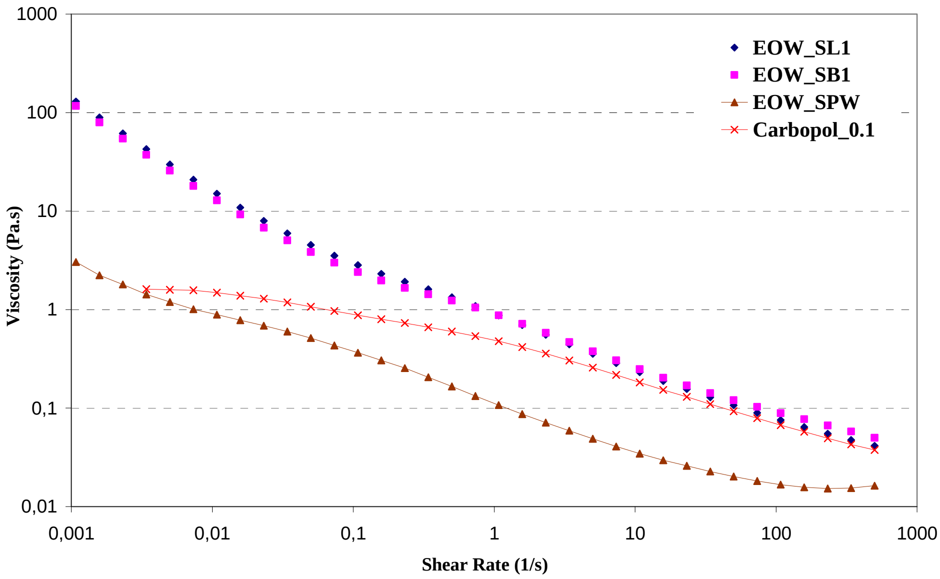


Figure 4. Viscosity versus shear rate for emulsions EOW_SB1 and EOW_SL1.

The overlap of curves for EOW_SL1 and EOW_SB1 systems having the same internal phase concentration but different droplets size suggest that, for low concentrations, viscosity is independent of droplet size.
Pressure drop curves are presented in Fig. 5. The pressure drop measurements started from the moment the emulsions entered the capillary. Curves were obtained maintaining the same flow rate of 0,04 cm^3/hr for both systems. The breakthrough time of the emulsions was roughly 240 seconds for both emulsions.

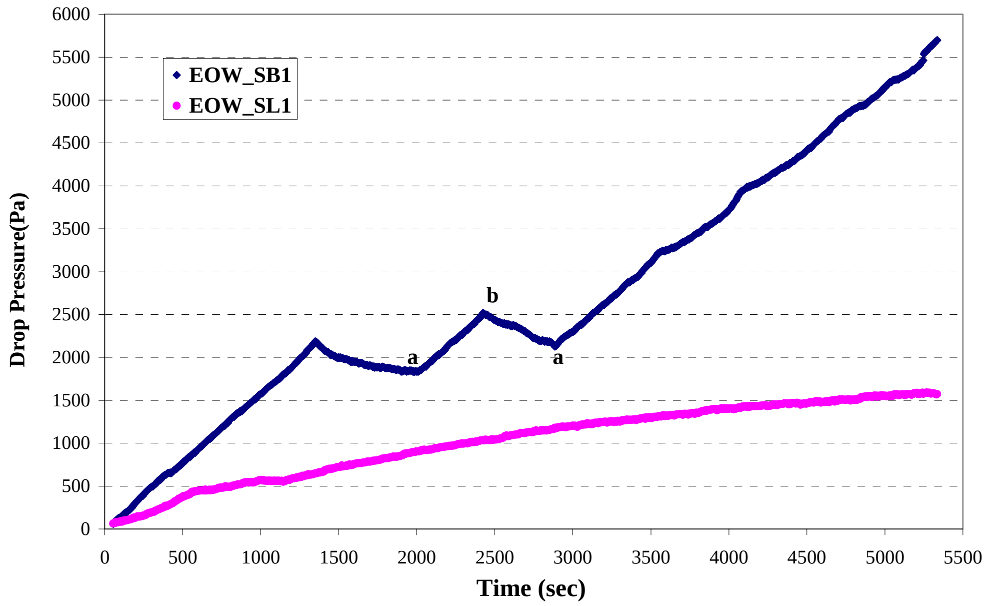


Figure 5. Drop pressure vs. time for the injection of emulsions into the capillary.

Because both emulsions with Carbopol have the same viscosity at the shear rates that occur in the capillary flow, it would be expected that their flow rate/pressure drop relationship would be similar. However, the pressure curves presented in Fig. 5 clearly shows that the pressure grows much larger for system EOW_SB1, corresponding to the wider drop size distribution, hence containing much larger drops. Peaks are observed in the pressure response, most likely due to drops blocking the constriction, and then drops passing through the neck, as indicated in Fig. 5 by points **a** and **b**. The increase in pressure drop could be attributed primarily to reduction of diameter, as a drop starts obstructing the neck, so that the pressure before the constriction tends to increase to maintain the volumetric flow rate until the drop is squeezed through the constriction. Further hypotheses for the increasing of pressure drop may be possible but will require further experimentation.

3.2 Visualization of the flow of emulsions

3.2.1 Drop deformation

First, the visualization of a 10/90 O/W emulsion without Carbopol is shown. In this first experiment, emulsions travel at a speed of 50 m/day. Fig. 6a shows that drops are spherical when diameters are smaller than the throat. Fig 6b shows that drops larger than the neck diameter deform as they enter the constriction. In this case, the viscosity ratio between oil and water is about k = 130. The capillary number, defined as $\mu o V/\gamma$ where V is the average velocity of the flow, μo the viscosity of the external phase, and γ the interfacial tension between drop fluid and the external phase is about Ca ~ 0.003. Polydispersity of the emulsions is evident in the image, with some of the drops smaller than the throat, and some larger.

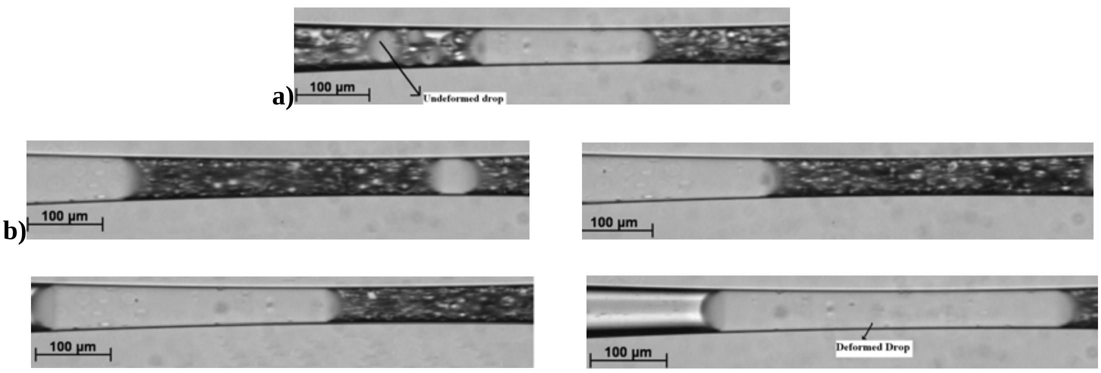


Figure 6. Emulsion EOW_VL1 passing through the constriction

When the undeformed diameter is larger than constriction diameter, drop is deformed and the shape conforms to the contours of the capillary walls, having spherical caps at each end, as is shown in Fig 6b. It is seen how the drop is elongated as it passes through the neck of the capillary. Similar results for the same order of magnitude for Ca, but significantly low *k* are encountered for a unique drop passing through a tube in the work of Olbricht and Kung (1992).
Figure 7 presents a sequence of images for the emulsion EOW_SB1, that show how a drop larger than the constriction can block the passage, is deformed until pressure gradient becomes high enough and finally passes away trough the neck.

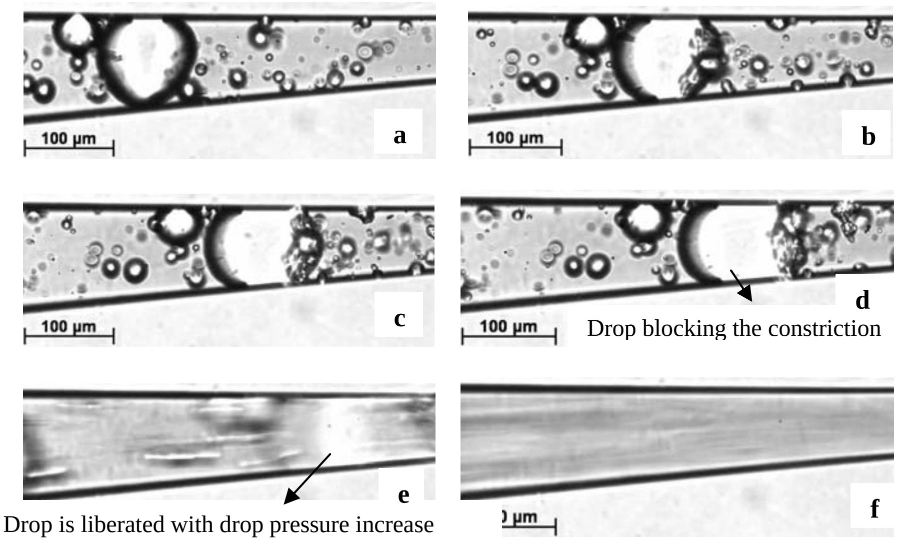


Figure 7. Sequence of a drop deforming as is obstructing the capillary

3.2.2 Filtration Process

Figure 8 shows a sequence of images that illustrate a process that is similar to filtration. A group of drops, bigger than an artificial constriction created by not well dissolved surfactant that adhered to the capillary wall, is stopped upstream of the constriction. The sequence shows how drops smaller than the neck pass trough the constriction.

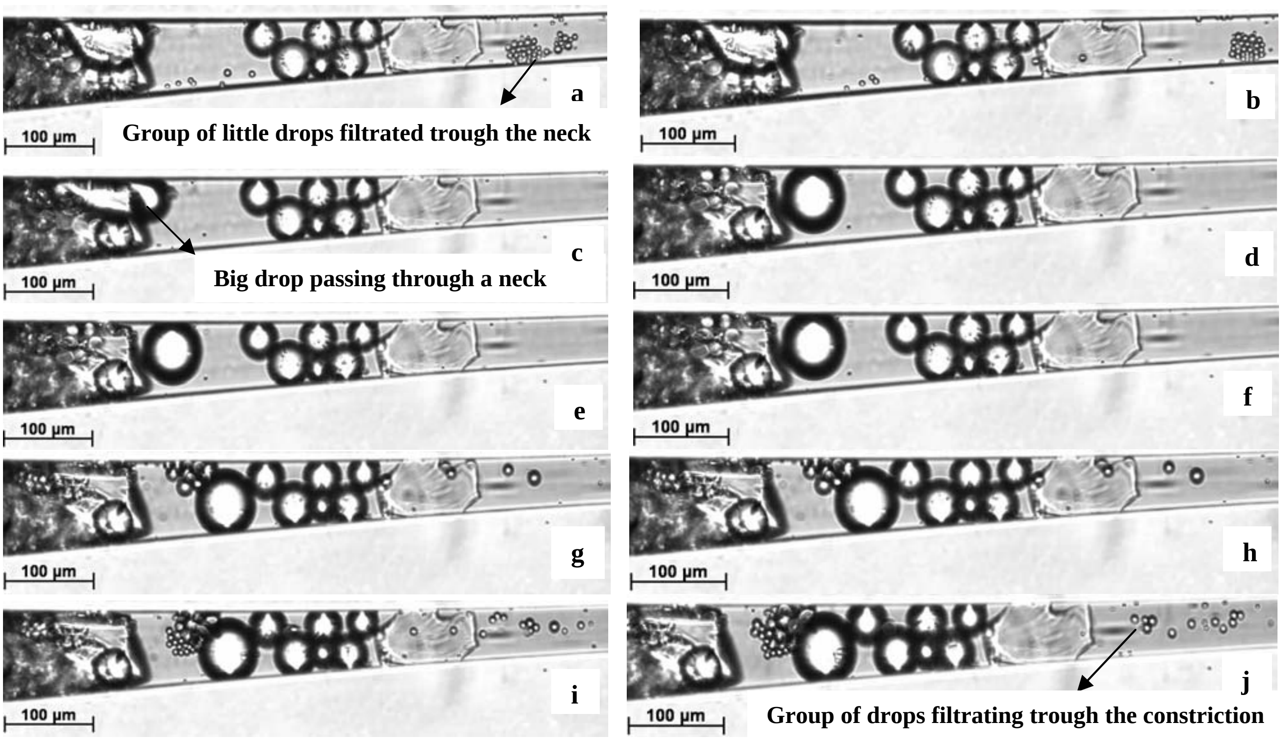


Figure 8. Filtration of drops

4. Conclusions

A succesful attemp to understand the flow of emulsions in a pore throw capillary model was conducted. Pressure drop measurements for a constant volumetric flow rate allowed us to determine that the emulsion with wider drop size distribution (between one to ten times the diameter of the neck) obstructed the capillary causing a considerable increase of pressurre in the zone upstream of the constriction. Once the obstructing drop or group of drops is released, the pressure drop decreases until a new drop is trapped. The visualization under the microscopic shows how some drops can deform as they pass through the constriction, while others can obstruct the neck of the capillary. Preliminary results suggest that a selective constriction blockage might be possible by the appropriate choice of droplet size distribution/geometry constriction relation.

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6. References

Bragg, James R. Oil Recovery methods using an emulsion. United States Patent. No 5855243. Jan 5, 1999.

Khambharatana, F. Flow of Emulsions In Porous Media. Ph.D dissertation. University of California, Berkeley, 1983.

McAuliffe, Clayton D. Oil in water emulsions and their flow properties in porous media. J.Pet. Tech.,727-733, June, 1973.

Olbricht W.L and D.M. Kung. The deformation and breakup of liquid drops in low Reynolds number flow through a capillary. Phys. Fluids A 4(7), July 1992.

Soo H., Radke C. The flow mechanism of dilute, stable emulsions in Porous media. Ind. Eng. Chem. Fundam, 23, 342-347,1984.

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