

24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2726

VISUALIZATION OF OIL DISPLACEMENT BY OIL-IN-WATER EMULSIONS IN MICROMODELS

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Abstract. *Water injection, the most common secondary recovery method in the oil industry, tends to result in high residual oil saturation due to the low sweep efficiency of the water because of the formation of preferential paths. To accomplish a better oil recovery different approaches have been used, one of them consist in altering the paths formed by flooding. This can be done with the blockage of the pores, forcing the water to new paths, thus sweeping a bigger area of the reservoir and displacing more trapped oil. In order to test the effectiveness of this blockage, the injection of different droplet sizes of conventional oil-in-water (O/W) emulsions in micromodels is being studied and compared to the waterflooding in terms of residual oil saturation.*

Keywords: *Microfluidics, Immiscible Displacement, Waterflooding, Emulsion Flooding.*

1. INTRODUCTION

After the exploitation of an oil reservoir its pressure starts to decline, a tendency that can be mitigated by water injection, the most common secondary recovery method, however the water usually has a low sweep efficiency because it creates preferential paths through the pores between the injection well and the production well.

Enhanced oil recovery (EOR) methods are used to increase the amount of oil that can be obtained from an oil field after the secondary recovery, one of those methods is emulsion flooding (McAuliffe, 1973; Karambeigi et al., 2015). In this method a slug of emulsions is injected, usually with the intent of chemically interacting with the rock and affect its wettability allowing alternate waterflooding (Baldygin et al., 2014) to displace higher percentages of oil.

The emulsion can also have a positive effect on the oil recovery due to its physical interactions with the pores (Moradi et al., 2014; Ponce et al., 2013; Cobos et al., 2009), even though it has been less studied in the literature, blocking the preferential paths created by the water and, in doing so, forcing it to take a different path and making a better sweep, displacing oil in pores that haven't been previously swept by the flooding. It can also have a positive effect due to the increase in the pressure gradient, created by the blockage of pores, and the mobilization of oil ganglia if this increase is enough to overcome the capillary pressure around them. (Cobos et al., 2009)

In the present work emulsions with a well-controlled particle size and the potential to block water paths will be studied in a porous media micromodel. All the injections in the microfluidic device will be done with the same flow rate in order to maintain the same capillary number (Ca), so we can differentiate the blockage effect.

2. EXPERIMENTAL PROCEDURE

The emulsion is produced using a T-junction (Fig. 1) in a droplet junction microfluidic device made by Dolomite (Fig. 2) that allows the formation of monodisperse and well controlled particle size emulsions.

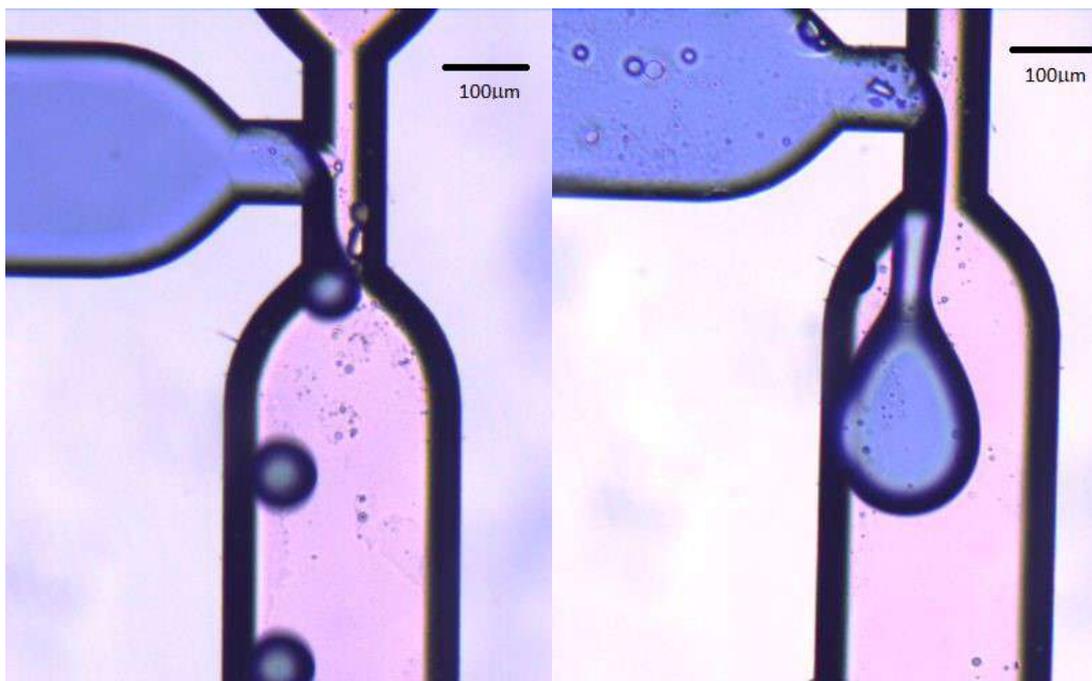


Figure 1. Emulsion production. On the left, small emulsion ($\phi=85 \mu\text{m}$). On the right, large emulsion ($\phi=175 \mu\text{m}$).

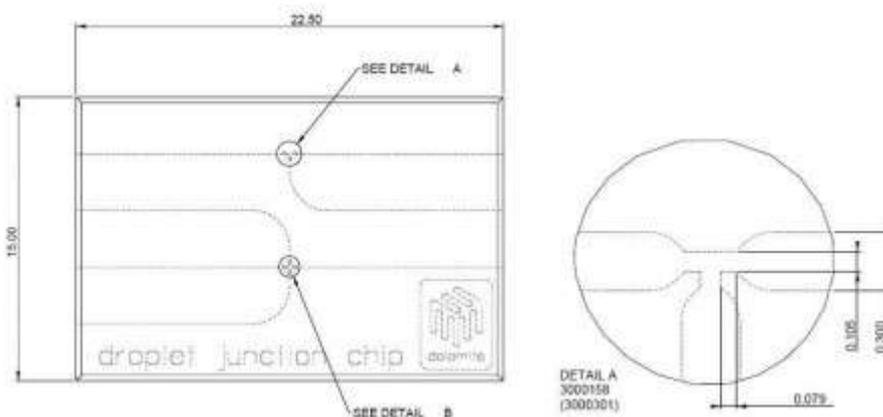


Figure 2. Droplet junction chip schema (Dolomite Microfluidics)

The oil displacement experiment is conducted in a microfluidic device by Dolomite that mimics a porous media (Fig. 3 and 4). The device is composed of microchannels connected by constrictions of two sizes - $85 \mu\text{m}$ and $63 \mu\text{m}$ - reproducing the throat of the pores in a porous media in a network of $110 \mu\text{m}$ channels. The microchannels of the porous media are water-wet.

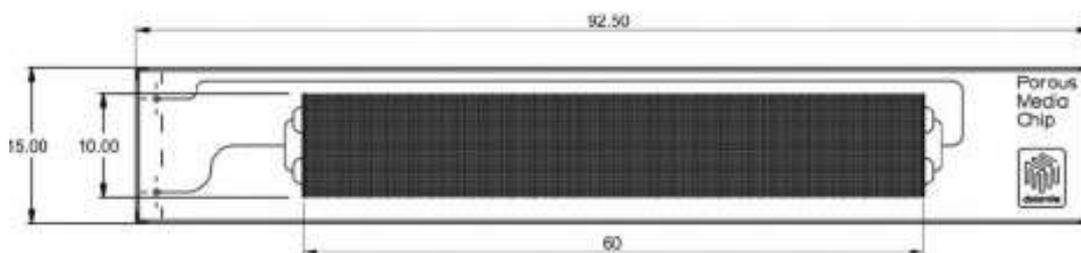


Figure 3. 2D porous media microfluidic device

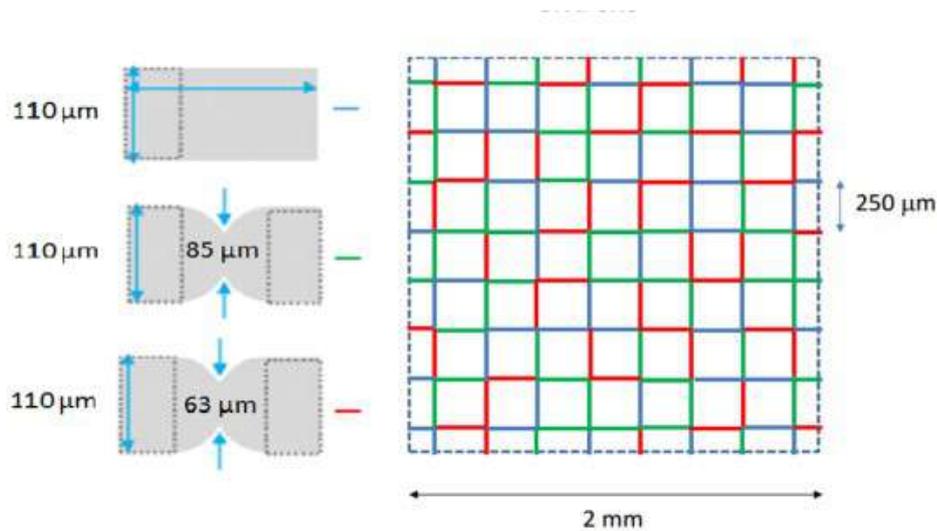


Figure 4. Schematic view of the microfluidic device

The emulsion is formed by injecting oil and water in two of the channels of the T-junction device in a defined flow ratio that allows us to control the emulsion size, resulting a highly monodisperse emulsion. We use a 0.46 % sodium docedil sulfate in water solution as continuous phase and mineral oil (Drakeol 7) as the dispersed phase. With those emulsions of two different diameters (Fig. 1), we study how it affects the sweep efficiency following a waterflooding. Each size has a different pore blockage mechanism, with different levels of efficiency.

As the emulsion is prepared, the porous media device is saturated with Drakeol 7 (Viscosity $\eta = 16\text{cP}$ at 25°C) where we initially perform a waterflooding, injecting two porous volumes of dyed water using a Harvard Apparatus Syringe Pump at constant flow rate. Photos under an inverted microscope (Leica DMI8) of the entire microchip are taken and we can determinate an initial residual oil saturation (Fig. 5). After the waterflooding the emulsion injection is performed “on-line” as its connected from the droplet device into the entrance of the Dolomite porous media microchip. The desired volume of emulsion is controlled by the volume of oil, as the injection of oil is ceased, the water output is set to the same waterflooding flow rate, thus it will carry the emulsion in order to dilute it as it invades the micromodel. New photos are taken to precisely calculate new residual oil saturation (Fig. 6).

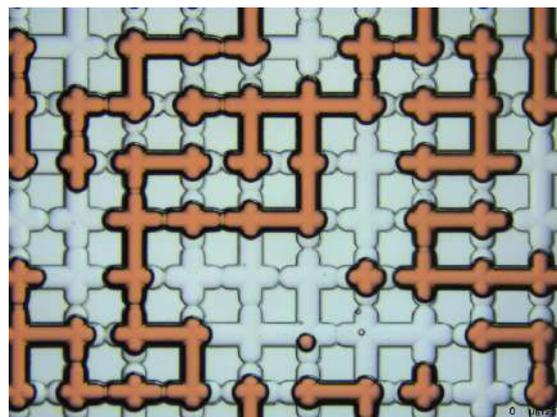


Figure 5- Section of the micromodel after waterflooding, 5x magnified

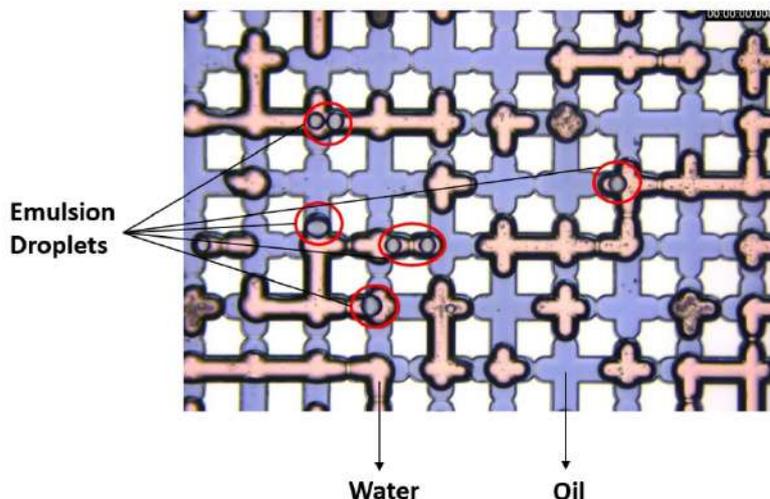


Figure 6- Section of the micromodel after emulsion injection, 5X magnified

To develop a better understanding of what is happening in each area of the micromodel in the emulsion flooding, during image acquisition the microchip is divided in 42 sections, 3 horizontal sections (named A, B and C) and 14 vertical sections (numbered 1 through 14), allowing a better comparison of the emulsion flooding in each area of the model.

The photos are analyzed using a macro developed in the image processing software *Fiji* to differentiate all the phases after the injection and calculate the residual oil saturation after each procedure.

3. RESULTS AND DISCUSSIONS

Two flow ratios were determined to stabilize the emulsions with diameters of 85 e 175 μm respectively.

	Water Rate (ml/h)	Oil Rate (ml/h)	Emulsion Size (μm)
Ratio 1	4	0,27	85
Ratio 2	5	0,52	175

Those sizes (Fig. 7) were chosen with the smaller diameter being bigger than the tightest constriction (63 μm) and the larger diameter being bigger than the duct (110 μm), because the emulsions are able to deform and pass through, increasing the potential to see the blockage effect.

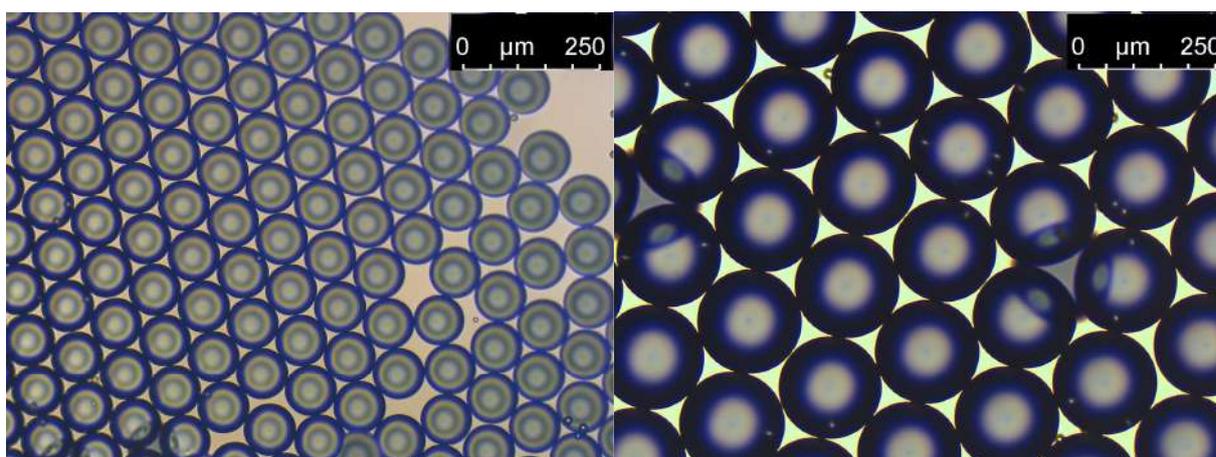


Figure 7- Size characterization. Left, Small emulsion ($\phi=85\mu\text{m}$). Right, Large emulsion ($\phi=175\mu\text{m}$)

The injection protocol has been set with a volume of diluted emulsion, keeping the injection in the microfluidic device similar to that of the waterflooding, injecting two porous volumes at 0.065ml/h. ($Ca = 3.5 \times 10^{-7}$). The volume of injected emulsion was set to 0.04 pore volumes, in agreement with most bibliography (Baldygin et al., 2014; Ponce et al., 2014; Demikhova et al., 2016; Karambeigi et al., 2015; Moradi et al., 2014)



Figure 8- Micromodel after each procedure. Left, After waterflooding and emulsionflooding with the large emulsion, respectively. Right, After waterflooding and emulsionflooding with the small emulsion, respectively

As we can see in Fig. 8, the large oil ganglia originally in the porous media microfluidic device is invaded by water as the emulsion was able to block the paths and create new ones. Interestingly, residual oil saturation was lower in the porous media chip where small emulsions were injected (right). This can be explained considering that smaller droplets can block more constrictions that bigger emulsions that will normally block just straight channels.

	Sor after WF	Sor after EF
Small emulsions	56%	40%
Large emulsions	58%	47,5%

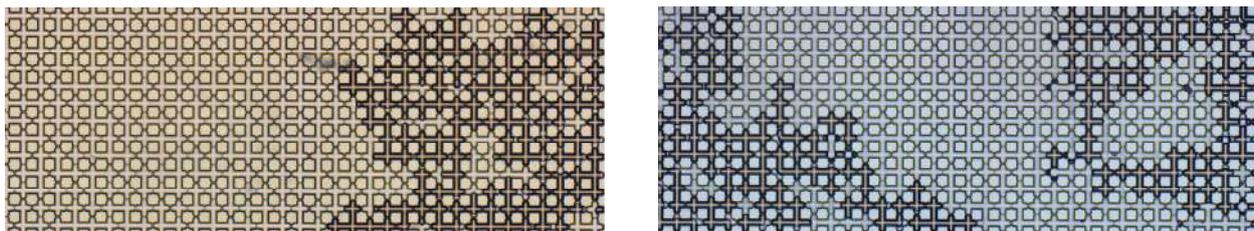


Figure 9 - Sections A13 and A14 after Waterflooding

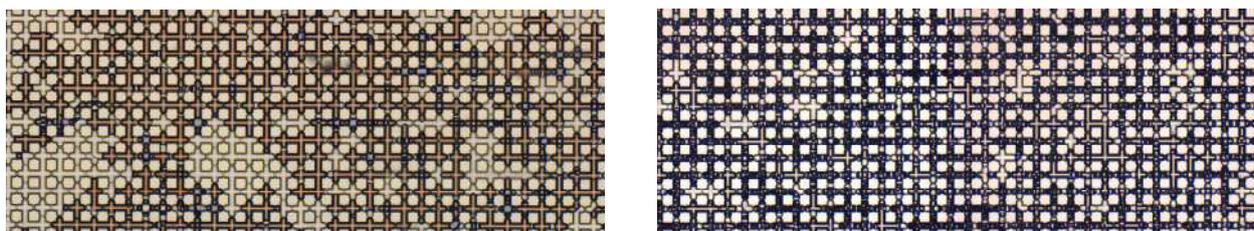


Figure 10 - Sections A13 and A14 after Emulsionflooding (Left, large emulsions. Right, small emulsions)

Both emulsions sizes presented some similarities in the experiments, being possible to notice the reduction in most of the oil ganglia in both cases, despite the smaller emulsion presenting a much more important reduction in size. Both situations also displayed a larger concentrations of emulsions around the entrance of the microchip than near its exit, which was expected because near the exit the volume of emulsions would be diminished, as most of the emulsions would probably already be trapped in the constrictions.

On the other hand, while the larger emulsions usually were well spread across the micromodel, the smaller ones tends to agglomerate in larger groups around the same pore (where we have previously an oil ganglia), as we can see in Fig. 9 and Fig. 10. This can be explained because the larger emulsion have a diameter bigger than that of the duct in the micromodel, so a single droplet can block a path, but smaller emulsions can occupy a spread range of pores resulting in the aggregation of smaller size emulsion in a previously oil-occupied ganglia.

4. CONCLUSIONS

As a result of this work, using monodisperse oil in water emulsions prepared via microfluidic techniques, we demonstrated an enhancement in oil recovery in a porous media chip, as we were able to precisely quantify a decrease in residual oil saturation of 10.5% using emulsions with a diameter larger than the main channel of the porous media and a decrease of 16% using emulsions with a diameter larger than he constrictions but smaller that the main channel of the porous media, at a constant displacement rate. In both cases just 4% of oil was injected (in the form of emulsion) so we still have a net additional recovery. Smaller drops can travel larger distances in the water path, so the potential to block more throats and create new water paths seems to explain this augmentation.

5. ACKNOWLEDGEMENTS

Gabriel Cruz's scholarship is being granted by CAPES.

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7. RESPONSIBILITY NOTICE

The authors, G. Cruz, J. Avendaño and M. Carvalho are the only responsible for the printed material included in this paper.