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VISCOUS FINGERING INSTABILITY IN THE DISPLACEMENTS OF OIL IN WATER EMULSIONS

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ABSTRACT

In this study, the viscous fingering instability that develops during the displacement of oil-in-water (O/W) emulsions by water is investigated. For this purpose, a horizontal rectilinear Hele-Shaw cell is used as an analogue for the porous media. The emulsions are prepared by dispersing a mineral oil in water using non-ionic surfactants. Different concentrations of oil were used to generate different emulsions that are characterized by examining their droplets size distribution and viscosity. The emulsions are displaced at different injection rates and the developments of the instability are characterized qualitatively by identifying the main mechanisms of finger development and growth. These results and the correlations between the properties of the fluids and the flow patterns are used to understand the flow dynamics and its effects on the viscous fingering instability. It is found that the development of the flow instability can be correlated with the rheological behaviour, which in turn depends on the emulsions' concentration and their internal microstructure.

INTRODUCTION

When a less-viscous fluid displaces another fluid of higher viscosity, instability occurs at the interface between the two fluids. The instability manifests itself in the form of finger-like patterns of the displacing fluid propagating through the displaced fluid, and is known as the viscous fingering instability. Such instability is encountered in a variety of natural and industrial applications and can have an important impact on the efficiency of those applications.

There is a large number of studies dealing with the viscous fingering instability that have been reviewed in detail by many authors [1-3]. Most of these studies focused on miscible or two-phase immiscible systems. Furthermore, the past two decades witnessed an increased interest in analyzing the mechanisms of this instability in the case of non-Newtonian fluids such as polymer solutions and particle suspensions [4-7]. Interestingly, there is a real dearth of work on emulsion flows in spite of their importance in many applications. Such fluids are in particular observed in the oil industry where emulsions occur naturally as a result of the displacement of oil by water or are injected in processes of enhanced oil recovery. Even though emulsions share some important characteristics with non-Newtonian fluids such as the shear-thinning or visco-elastic behaviour, they in fact represent a class apart due to the complexity of their microstructure and compositions.

There is only one study dealing with viscous fingering instability of emulsions [8]. In this study, the authors examined the flow in a radial Hele-Shaw cell for emulsions consisting of Silicone oil dispersed in aqueous Hydroxyl Propyl Methyl Cellulose (HPMC) solution. They observed crack-like finger to ramified finger patterns when the emulsion is displaced by an immiscible fluid. The authors related qualitatively the pattern transitions to the changes in the rheological properties of the emulsions and osmotic pressure difference between the injected fluid and the dispersion medium of the emulsion. However, they did not give any correlation between the imposed pressure and the injection rate or relate the physical behaviour of emulsions with the flow dynamics.

The present study aims at further improving our understanding of the fingering instability in emulsions' displacements. It is proposed to examine the instability in the case of a rectilinear Hele-Shaw cell. The rectilinear geometry is different from the radial one adopted in the existing study [8] in that the latter involves a point source injection and contact interface that expands as the flow evolves while the former has a fixed initial interface defined by the cell width. Therefore, the development of the flow and the mechanisms of interactions as well as growth of the fingers can be fundamentally different. This is particularly true in the case of emulsions that exhibit complex rheological behaviour.

NOMENCLATURE

E_V	[-]	Volumetric sweep efficiency
b	[m]	Gap of the channel
L	[m]	The length of the channel
$D[3,2]$	[μm]	Surface weighted mean
Q	[ml/min]	Flow rate
W	[m]	The width of the channel
T	[sec]	Time
Special characters		
$\dot{\gamma}$	[1/s]	Shear rate
μ	[mPas]	Viscosity
Subscripts		
avg		Average
bt		Break though time
eff		Effective

EXPERIMENTAL

Materials:

Emulsions of oil in water (O/W) were prepared using a light mineral oil (trade name Marcol 7) supplied by Esso Imperial Oil, Canada**.** The viscosity and the density of the oil at 23^{o} C were 10.7 mPas and 862 kg/m^3, respectively. The water used throughout the experiments was reverse osmosis water. The surfactant used was Tween-65, a commercially available non-ionic surfactant also known as polyethylene glycol sorbitan tristearate. It is water soluble and has a hydrophilic-lipophilic balance (HLB) value of 10.5±1.0.

Sample Preparation Procedure:

Two different concentration of oil in water emulsions were prepared in batches of 200 ml each. The concentrations of oil were 40 and 60 vol% (surfactant free basis). The details of emulsion samples are listed in Table 1.

For the preparation of oil in water emulsions, the surfactant was dissolved in the aqueous phase by heating for about 15 to 20 min. Once the surfactant was completely dissolved, oil was added to the aqueous phase and heated for 7 to 8 min. The heating of the components reduced the oil viscosity and assisted in dispersing the oil droplets in the continuous water phase. The above mixture was then mixed in a blender for about 20 min at a fixed speed. The emulsions produced were quite stable with respect to coalescence. The emulsions were stored at 23 ± 1^{o} C .

Table 1 Details of emulsion samples

No	Concentration of emulsion (Surfactant free basis) (V/V %)	Continuous phase, wt% of surfactant
1	40%	8
2	60%	11

Hele-Shaw Cell:

The flow displacement experiments were performed in a rectangular Hele-Shaw Cell [9]. The schematic diagram of the cell is shown in Figure 1. It consisted of two plane rectangular parallel glass plates made of plexiglass ($72.39 \times 20.32 \times 5.08$ cm^3) that were separated by a narrow gap using a soft rubber o-ring (Buna- N, diameter 0.3175 cm) along the cell perimeter. The plates were fixed by 24 bolts and nuts.

On the top plate of the Cell, three holes (diameter = 0.3175 cm) were drilled evenly along each short edge of the plate inside the o-ring. The centre hole at one end of the cell was used for the injection of the fluids during displacements while the centre hole at the other end was used for collecting the fluids flowing out of the cell. The use of single line injection/ production avoided the effect of different pressures in the three lines. The other two holes on both sides of the cell assisted in filling the cell with the emulsion as well as in cleaning the cell between displacements.

The inner length, width and breadth of the channel were L=63 cm, W=15.5 cm and b=0.034 cm respectively.

The cell was mounted on a table with a light underneath it to assist in capturing images with better clarity. A differential pressure transmitter was connected across the inlet and outlet ends of the cell to record the pressure drop during the flow. The inlet of the cell was connected to a syringe pump that provides constant flow rates. The error involved in the flow rate was less than 4%.

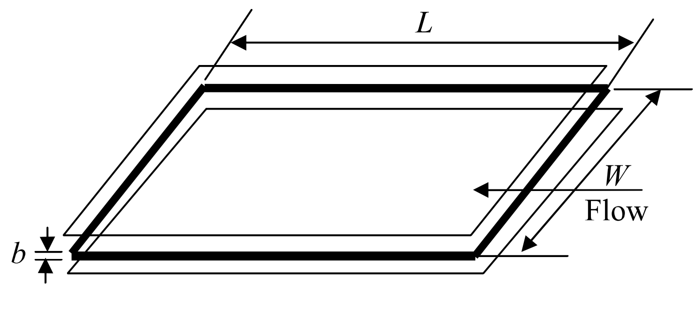

Figure 1 Schematic diagram of rectangular Hele-Shaw Cell

Displacement experiment procedure:

Miscible displacement experiments were carried to understand the effect of change in rheological behaviour of the displaced fluid (40% and 60% concentration emulsions), and injection rates (0.21 ml/min and 4.25 ml/min) on the viscous fingering instability.

For each experiment the following procedure was adopted. The displaced fluid (emulsion) was first injected into the Hele-Shaw cell with the syringe pump at very low injection flow rates to ensure that no gas bubbles were trapped inside the cell. The displacing fluid (water) was then injected into the cell at constant injection rate. For colour contrast between the displacing and displaced fluid, water was dyed with a red food colour.

The growth of the fingers was recorded periodically during the displacements using a camera. These captured images were analyzed using Image J software which is a public domain Java image processing program. The source code is developed and maintained by Wayne Rasband. It is provided through the National Institutes of Health (NIH) and is freely available.

CHARACTERIZATION OF EMULSIONS

The characterization of emulsions was carried based on their drop size distributions as well as their rheological properties. These measurements were conducted at 23 ± 1^{o}C after an elapsed time of approximately 5 hours from the initial time of emulsion preparation. In what follows the results of drop size and rheological measurements for 40% and 60% concentration emulsions are presented.

Drop Size Measurements:

The drop size analysis was carried using a laser diffractometer Mastersizer 2000 (Malvern Instruments Co, UK) with Hydrosizer 2000S module. The results were obtained based on the intensity of the light scattered by the droplets in the range 0.02 to 2000 μm. The size distribution calculations were based on the principal of Mie theory which predicts the way light is scattered by spherical particles and deals with the light diffraction pattern and using the standard software applied to the instrument.

The measurements were performed by preparing samples of 0.3g of emulsion diluted in 8 ml of deionized water. The sample was introduced into the laser beam using the Hydrosizer 2000s dispersion accessory. The measurements were carried out in triplicate and the average value was considered. The surface weighted mean diameter of 40% and 60% emulsion were 0.294 μm and 0.159 μm, respectively. Note that the average drop size of 40% emulsion was larger than the 60% emulsion.

Rheological Measurements:

A stress/rate controlled coaxial-cylindrical viscometer THERMO HAAKE RotoVisco1 (Thermo Scientific, Typo 003-5363) with a temperature controller, was employed to measure the rheological properties of the emulsions. The start and end shear rate range was $\dot{\gamma} = 2 - 150 \text{ s}^{-1}$.

Figure 2 shows the viscosity versus shear rate plot for 40% and 60% oil in water emulsions. The viscosity of 40% emulsion showed Newtonian behaviour with an average viscosity of 39m.Pas, whereas the 60% emulsion showed non-Newtonian shear thinning behaviour. The data is best fitted with a power-law model that is $\mu_{eff} = 1082.3\dot{\gamma}^{-0.43}$ with $R^2 = 0.99$. These results show that with the increase in concentration of the dispersed phase, the rheological behaviour changed from simple Newtonian to non-Newtonian shear thinning.

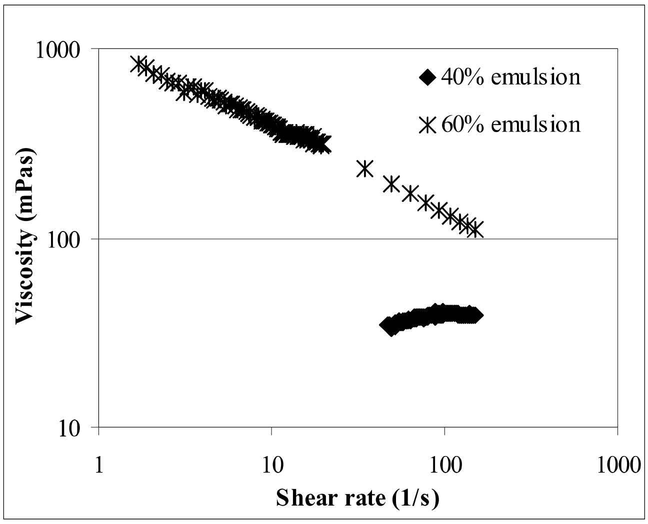

Figure 2 Viscosity versus shear rate plot for 40% and 60% concentration emulsions

RESULTS AND DISCUSSION

In this section the displacement experimental results for both 40% and 60% emulsions are presented. In these displacements the effect of two different injection rates is shown. The fingering patterns observed are presented and discussed in terms of various fingering mechanisms involved. The results for the Newtonian 40% emulsion is discussed first and then followed by those for the non-Newtonian shear thinning 60% emulsion.

Qualitative Characterization:

Displacements in which water displaces the emulsions were conducted at two different injection rates of 0.21 ml/min and 4.25 ml/min. Figure 3-6 show the sequential evolution of interface observed in emulsion displacements. The white space is the area filled with the emulsion and the red coloured region is the area displaced by the injected water. A sequence of four images at different timings is presented.

40% emulsion displacements:

Figure 3 and 4 show the results for 40% emulsion displacement at two different injection rates of 0.21 ml/min and 4.25 ml/min, respectively. At the lowest injection rate 0.21 ml/min, initially the interface started with three dense fingers. As the displacement progressed one finger dominated the flow suppressing the other two. This mechanism is known as *shielding* [10].

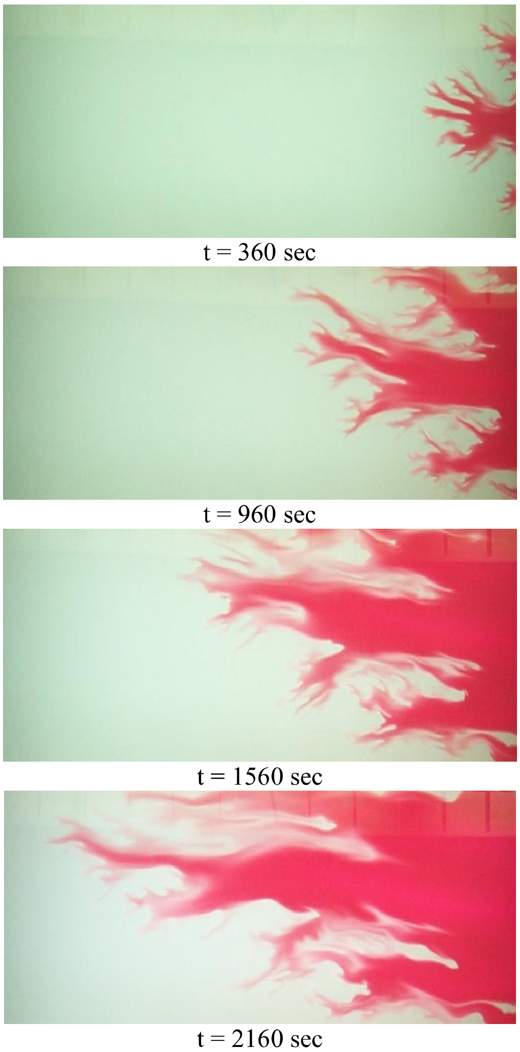

Figure 3 Displaceemnt of 40% emulsion at injection rate 0.21 ml/min

The tips of the fingers were not smooth and became wider as the displacement progressed. This mechanism is known as *spreading*. The widely spread finger split into several thin fingers due to *tip-splitting* mechanism [11]. These fingers appear as faded side branch fingers. There is also noticeable diffusion of injected water into the displaced emulsion.

As the injection rate increased to 4.25 ml/min, the finger structures changed completely (Figure 4). The displacement started with two highly branched fingers out of which one became the dominant finger and moved ahead with continued branching. The dominant finger showed many side fingers known as *side-branching* [3,12,13]. These branched fingers were merging into the dominant finger and evolved through the main dominant finger with the progress of displacement. This is known as *coalescence* [3,13,14]. In this case also the displacing fluid was diffusing into the displaced fluid but this is not as pronounced as in the case of the lower injection rate.

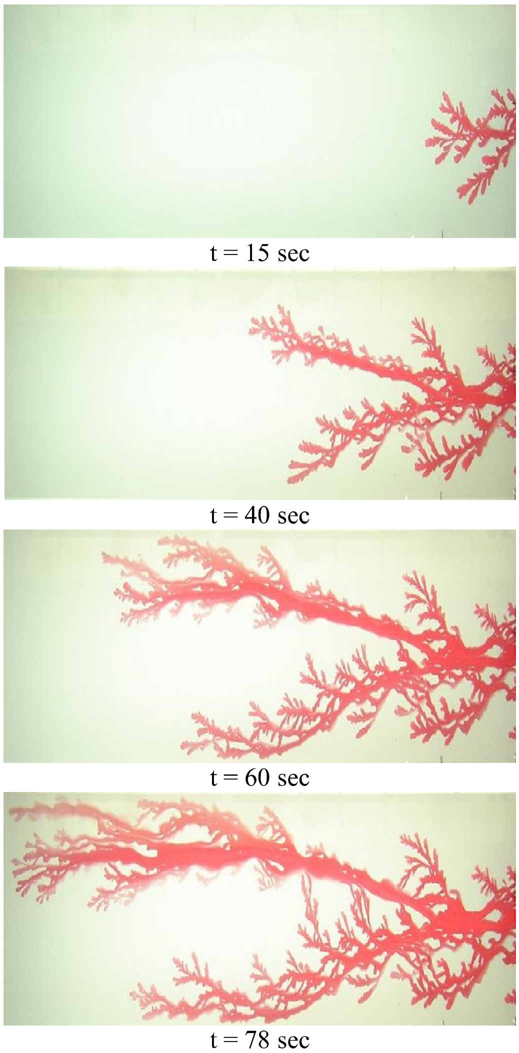

Figure 4 Displacement of 40% emulsion at injection rate 4.25 ml/min

60% emulsion displacements:

Figures 5 and 6 show the results for 60% emulsion displacement at two different injection rates of 0.21 ml/min and 4.25 ml/min. The mechanisms responsible for the evolution of the fingers in these displacements are similar to those described earlier. In these displacements a single finger with many side branch fingers dominated the flow. However the dominant finger observed in this case is thinner compared to the 40% emulsion displacements. The interface between the two fluids is not smooth and showed side-branching mechanism. The growth of side branches increased with increase in the injection rate of the fluid displacing fluid.

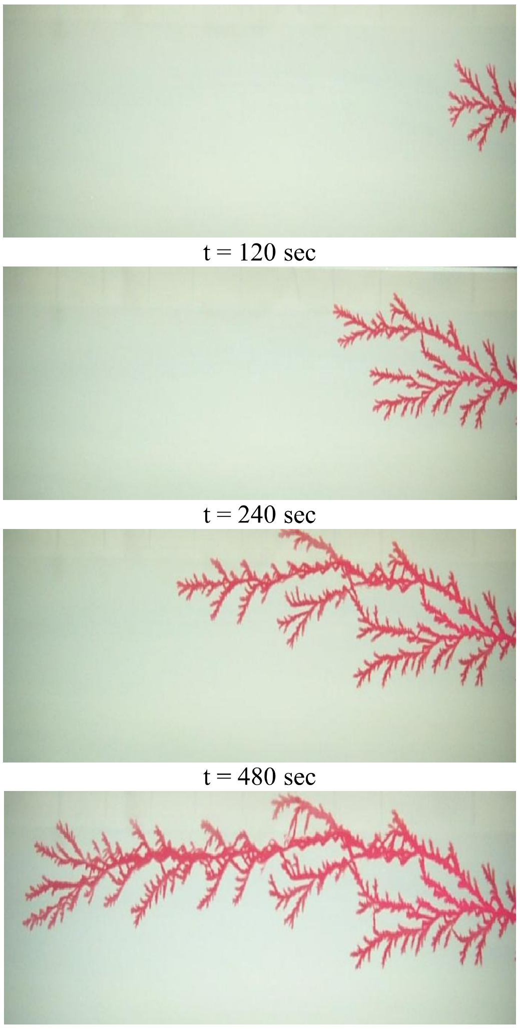

Figure 5 Displacement of 60% emulsion at injection rate 0.21 ml/min

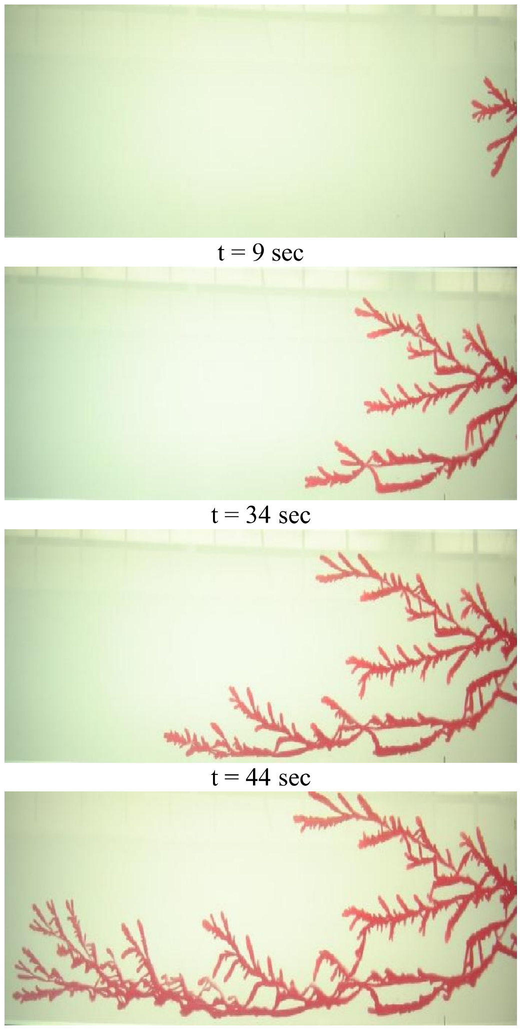

Figure 6 Displacement of 60% emulsion at injection rate 4.25 ml/min

In these shear thinning fluid displacements the phenomena of *shielding*, *tip splitting* and *coalescence* were more pronounced (Figure 5). The fingers formed became more complex with many side branch fingers as the flow rate increased. Furthermore, when compared with the 40% emulsions, there is little or no diffusion of the injected water into the emulsion.

Quantitative characterization:

Figure 7 shows front length vs. volume of fluid injected data for 40% and 60% emulsion at different injection rates. As can be seen in the graph with the increase in injection rate the front length increased for a given volume of fluid injected. This shows that there is a significant effect of the injection rate on the front length, and therefore on the sweep efficiency of the displacement.

In Table 2 the breakthrough time and sweep efficiency measurements are given. Both 40% and 60% emulsions showed a decrease in breakthrough time (t_{bt}) and sweep efficiency with the increase in the injection rate from 0.21 to 4.25 ml/min.

CONCLUSION

The Saffman-Taylor instability in different concentration emulsions at two different injection rates was investigated. The choice of two different concentrations i.e., 40% and 60% (v/v %) emulsions allowed isolating the effects of the Newtonian and non-Newtonian shear thinning fluid behaviour on viscous fingering instability. Experiments were carried at two different injection rates of 0.21 ml/min and 4.25 ml/min.

In the experimental study, water was used as the displacing fluid and emulsions as displaced fluids. These emulsions were characterized based on their drop size and rheological measurements. The average drop size of 40% emulsions was larger than 60% emulsion and their rheological measurements showed that 40% emulsion were behaving as Newtonian fluid and 60% emulsion as non-Newtonian shear thinning fluid.

The displacement experiments showed that as the rheological behaviour of the displaced fluid changed, there is a significant change in their finger structures. The width of the dominant finger decreased and the amount of branching increased. For both emulsions, an increase of the injection rate led to more complex finger structures. It is also found that the front length of the finger increased with the increasing injection rate of the displacing fluid. That means there is a decrease in sweep efficiency and breakthrough time observed with the increase in injection rate.

Table 2 Quantitative analysis results for 40% and 60% emulsions

Concentration of emulsion	Flow rate ml/min	t_{bt} sec	$E_{V,bt}$ %	$E_{V,avg}$ %
40%	0.21	2340	30	30
40%	4.25	76	20	20
60%	0.21	660	8	10
60%	4.25	54	14	18

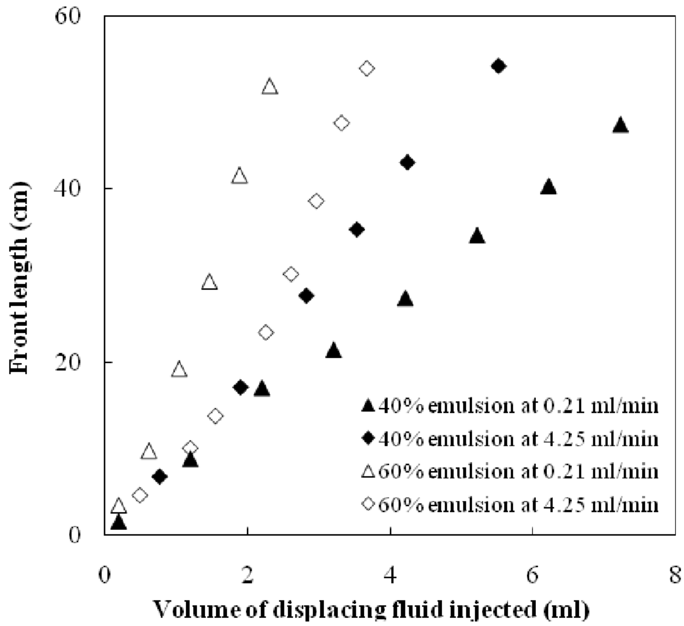

Figure 7 Front length (y) versus Volume of fluid injected (x) for 40% and 60% emulsions at two different injection rates

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