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IMPACT OF POLYMER ON FLOW BEHAVIOUR, PHASE INTERFERENCE, AND DISPLACEMENT OF OIL IN A HELE-SHAW CELL

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Abstract

It is an established fact that polymer additives to water for oil displacement in porous media improves oil displacement by regulating mobility ratio of the phases. This has rarely been examined for oil displacement in fractures through relative permeabilities, flow behaviour and microscopic observations. The research documented here shows experimental evaluation of oil displacement using polymer additives to water in a Hele-Shaw cell. A series of experiments are conducted to examine how aqueous polymer (polyethylene oxide) solution changes the behaviour of the fluids and oil displacement in a narrow gap. Unlike the case of co-current oil and water flow where after the breakthrough, complex fluid distribution patterns with engulfed stationary oil drops resulted, we report that in the case of polymer, the aqueous solution dominant finger expands and occupies a major portion of the cell. Thus, a high oil recovery is resulted, which is also proved by the relative permeabilities and microscopic investigation.

Key Words: polymer additives; Hele-Shaw cell; flow regimes, interfaces; microemulsion; relative permeability.

1. Introduction

When a more viscous phase (oil) is displaced by a less viscous one (water), the fluid interface becomes unstable and the displacing fluid fingers into the displaced phase (Hill et al., 1952; Saffman and Taylor, 1958; Chouke et al., 1959). Consequently, an early breakthrough of the displacing phase to production wells is resulted where a large volume of oil remains unrecovered (Kargozarfard et al., 2018). Decreasing the viscosity difference or mobility ratio of the displacing and displaced phases, minimizes instability of the interfaces and hence the oil production may increase. In the case of displacing a more viscous phase with a less viscous one, the viscosities difference among the phases could be reduced by adding polymer additives to the displacing phase (Lyons, 2010). Polymer solution flooding through core samples extracted from reservoirs or glass micromodels has been experimentally and numerically examined for the past four decades. Donaldson (1985) examined the impact of polymer solutions on oil recovery and found that oil displacement improves because polymers tend to increase the viscosity of the displacing aqueous phase. He further described that the polymer adsorbs on the rock surface causing concentration reduction.

Mungan, (1971) studied different rheological properties, adsorption and transport characteristics of water and oil by injecting different concentrations of polymer solution (polymer molecular weights ranged from 2 to 7 million Daltons). Adsorption studies are carried out on silica samples whereas dynamic adsorption experiments were performed on 20-inch-long and 2-inch diameter sand packs. For fingering analysis, Mungan used a Hele-Shaw cell (dimensions 26.8cm x 26.8cm x 0.006cm) and a porous media sample of Berea sandstone block (dimensions 12" × 12" × 1"). He concluded that viscosity of the polymer is mainly dependant on the flow rate, molecular weight, and the composition of the solvent and that of oil recovery is increased by injecting a small volume of different concentrations of the polymer before water flooding. He observed a breakthrough recovery factor of 84% for viscosity ratio of 0.03 (polymer solution to oil) while 28% for viscosity ratio of 30. Mungan further explained that the interface in case of the lower viscosity contrast is more stable than the higher viscosity ratios and proposed that polymer slug before water injection is more economical and creates a stable front.

Abrams, (1975) examined changes of the interfacial tension, fluid viscosity and flow velocity in case of a polymer aqueous phase flooding through a short water-wet core. He concluded that the oil recovery rises with a drop of the interfacial tension. Abrams proposed a factor 'F' which defines the efficiency of the polymer flooding process in terms of increase in oil recovery from the core:

$$F = (v_m \mu_w / \sigma_{ow}) (\mu_w / \mu_o)^{0.4} \quad (1)$$

where v_m is the homogeneous/combined velocity of both the phases and μ is the viscosity and subscripts 'w' and 'o' refer to the water-based and oil phases, respectively. Abrams explained that if 'F' is greater than 10^{-4} , the residual oil saturation will be low and the oil recovery will be high whereas in the case of smaller values of F , the efficiency of the process will be low. The results implied that

for getting maximum oil recovery, the value of ' F ' should be increased by raising viscosity of the water and reducing interfacial tension between the phases.

Donaldson et al., (1985) and Grillet et al., (2012) investigated the use of polymers for oil recovery. They concluded that it is very costly to inject the polymer solution for the entire oil recovery process, therefore, a small quantity of the polymer should be flooded followed by water flooding as studied by Mungan, (1971) and Daripa and Pasa, (2004, 2005). Gorell and Homsy, (1983) examined numerically three layers flow with the more viscous layer (of displaced phase), intermediate layer of variable viscosity and less viscous layer of the displacing phase, for flow in Hele-Shaw cell where the interfaces are considered as contact discontinuities. Following that, Daripa and Pasa (2004, 2005) also studied three-layers flow in Hele-Shaw cell. They theoretically proposed an optimal viscosity profile for aqueous phase of polymer (polysolution) flooding ahead of water in a Hele-Shaw cell. They concluded that with the use of viscosity profile, the viscosity jump reduces and viscous fingering can be eliminated. In another research, Daripa and Pasa (2005) estimated minimum concentration of polymer and length of the intermediate layer of the polymer aqueous phase. They concluded that with the use of the estimated concentration and length of the polymer layer, instabilities in the interface could be reduced and oil recovery can be increased, experimentally and on field scale.

Hematpour, (2011) studied the effects of different types of polymers for displacing low viscosity oil from two simplified glass micromodels (quarter five-spot pattern) with different porosities. The oil saturated cells were flooded with three different types of polymers at a constant flow rate of 0.0008 cc/min. They reported that the polymer reduces mobility of water and improves oil recovery. Their results showed that the hydrolyzed polyacrylamide (HPAM 25%) solution yields more recovery than other types of polymers. The results showed that increasing the flow rate of water or polymer solution raises the effective permeability of the phase, reduces breakthrough time, and lowers oil recovery. Therefore, for higher oil recovery, they recommended lowest feasible injection rate of the displacing phase (polymer aqueous phase).

Clemens et al., (2012) experimentally and by computational fluid dynamics (CFD) simulation, analyzed fingering in a displacement process of oil by water and polymer flooding in micromodels with area of 25 cm², permeability 950 mD, and porosity 47% which was initially saturated with a 450 cP crude oil. They flooded both the cells separately with water and polymer solution (16 cP). They observed that the polymer creates more fingers but shorter in length than the fingers created by water. The polymer yielded higher oil recovery than water. The results of the CFD simulations were consistent with those obtained from the experiments.

Ying-Jie et al., (2013) studied effects of pore structures on the oil recovery by polymer and synthetic reservoir brine flooded through synthetic oil (1.78 cP) saturated glass micromodels (dimensions 3cm × 2cm with channels 1 to 100 μm) etched represented properties typical of the pore structure of the Shuanghe oil field in China (600 mD). The water cut of the reservoir after extensive water flooding was 95%. To achieve greater oil recovery, polymer (400 × 10⁴ Daltons) was tested in the experiments. The micromodel had single injection and single exit ports at opposite ends. Four models were

prepared on the basis of different pore throat ratio (PTR) and coordination number (CN). After drying and evacuating the models for 2 hours, they saturated them with water for 2 days and then flooded with oil for 3 days. The oil was displaced by polymer flooding after water injection at a constant flow rate of 2 $\mu\text{l}/\text{min}$. They noticed that water flowed through the larger channels, bypassed narrow pore throats, resulted oil entrapped due to higher capillary forces. They also observed that the PTR effected recovery more than the coordination number and explained that the higher PTR implies more heterogeneity. Ying-Jie et al. concluded that the polymer significantly increased oil recovery from all micromodels tested.

In the research documented here, the dynamics of polymer solution and its concentration on multiphase flow and oil-polymer interactions in a narrow gap is examined.

2. Experimental Apparatus and Methodology

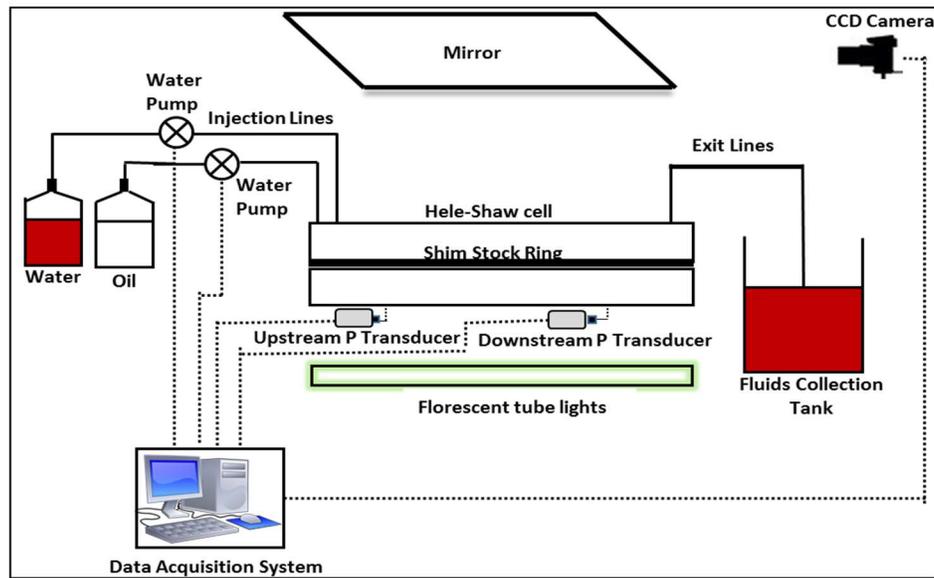
Figure 1a depicts the experimental set-up used for the co-current flow of two phases. The same apparatus and procedure are applied in our previous research published by Raza et al., 2016. The set up consists of a Hele-Shaw cell having a 0.397 mm gap created by placing a shim stock of the same thickness in between the two Plexiglas plates bolted together tightly (Figure 1b). This gap size reflects the fractures of oil reservoirs which are in the range of 0.015 to 1.8 mm (Romm, 1966; Park et al., 1994; Fourar and Bories, 1995; and Hashimoto et al., 2008). The flow is studied in the area in between two pressure transducers (Model PX 209-015G5V, Omega Environmental Inc.) connected to the gap through the lower plate. This domain is 35 cm long and 14 cm wide. There are three injection port at one end of the cell and three production ports at the other end which are drilled through the upper plate (Figure 1c). The central port is used for injecting the displacing fluid (water and polymer solution), whereas the oil (displaced phase) is injected through the two outer ports.

Displacing phases (red colour dyed) used in the experiments are de-ionized water and different concentration solutions of polymer which are prepared by adding 0.5 wt.%, 1 wt.%, and 1.5 wt.% of polyethylene oxide (PEO) to de-ionized water, whereas the displaced phase is colourless mineral oil (colourless) i.e., Marcol 7 (20.236 cP viscosity and 847.0 kg/m^3 density at 22.46°C) provided by Esso Chemicals. A charged coupled device (CCD) camera (Model scA1000-30gc, Basler) is fixed just above the cell to capture pictures of the flow patterns which are further used for calculating sequential phase saturations. For clear visibility of the flow patterns, tube lights are connected below the cell. Both the fluids are injected into the cell by two injection pumps (Models 305 and 307, Gilson Inc.).

Initially the fracture is saturated with the mineral oil (displaced phase) which is then injected at a fixed flow rate i.e., 0.5 ml/minute, whereas the injection flow rate of the displacing phase is step wise increased from 0.25 ml/minute to 9 ml/minute. After reaching the highest flow rate (i.e., 9 ml/minute), the injection rate of displacing phase is kept constant whereas the oil injection flow rate is stepwise decreased from 0.5ml/minute to 0.025ml/minute. At each flow rate and on reaching the steady state conditions, the differential pressure, time, saturations, and images of the flow patterns

are collected by the data acquisition system over a 4-minutes time interval at each flow rate before breakthrough of the displacing phase and after breakthrough, this data is collected when the steady state situation reach i.e., at constant differential pressure and phase saturations.

(a)



(b)



(c)

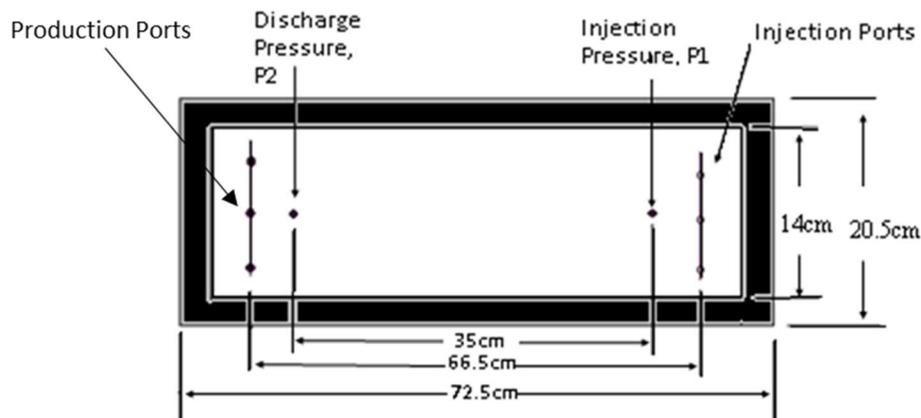


Figure 1: (a) Experimental set up, (b) side view of the cell showing the shim stock and its thickness, and (c) top view of the cell showing area of interest and inlet/outlet ports. (adapted from Raza et al., 2016)

A series of experiments are conducted for water and each polymer solution concentration. The data and images are analysed to evaluate the relative permeabilities and flow patterns. This analysis is carried out for each step of the flow rate. The relative permeability calculation is started as soon as the flow channels/fingers of both the phases extend across the zone of observation. Absolute permeability of the Hele-Shaw cell is obtained from the planar Poiseuille's law by using water flow through gap at different flow rates and the absolute permeability of the cell is equal to 10,923 D (Raza et al., 2016). The relative permeability of each phase is calculated using extended Darcy's equation for multiphase flow through the gap. The average values of Reynolds number in all the experiments are ranging from 0.08 to 0.42 indicating laminar flow of the fluids. Considering no slip conditions and steady state, laminar flow in the cell, Darcy's and the planar Poiseuille's equations for the flow can be used to calculate the relative permeabilities of the phases (Raza et al., 2016).

3. Results and Discussion

3.1. Impact of Polymer on Viscosities and Interfacial Tensions of the Fluids

Figure 2 shows the effect of polymer concentration on viscosity of the aqueous phase. Aqueous phase viscosity is an increasing function of polymer concentration. The figure depicts that viscosity of water increases from 1.07 to 2.97 cP by adding 0.5 wt. % PEO polymer to the water. Similarly, 1 wt. % of the polymer raises the water viscosity to 6.89 cP and 1.5 wt. % of PEO to 11.4 cP. By raising concentration of the polymer more than 1.5 wt. %, the polymer aqueous phase viscosity exceeds the viscosity of the oil. For instance, at 2 wt. % PEO, the aqueous phase viscosity rises to 30.26 cP whereas at 5 wt. % PEO this value reaches to 392 cP. Since, the viscosity of the water rises beyond the viscosity of the mineral oil used in our experiments by adding PEO concentration more than 1.5 wt.%, hence the highest concentration of the polymer solution used in this study is 1.5 wt. %.

Similarly, Figure 3 shows the reduction in interfacial tension, measured by the Du Noüy Ring method using a TensioCAD tensiometer. The interfacial tension falls from 45.7 to 28.62 mN/m by adding only 0.5 wt.% of the polymer to the water but further increase in its concentration (from 0.5 wt.% to 5 wt.%) could not reduce the interfacial tension significantly i.e., its values is in the range of 26.77 to 28.62 mN/m. Hence, among the viscosity and interfacial tension, the polymer mainly effects viscosity of the aqueous phases than interfacial tension.

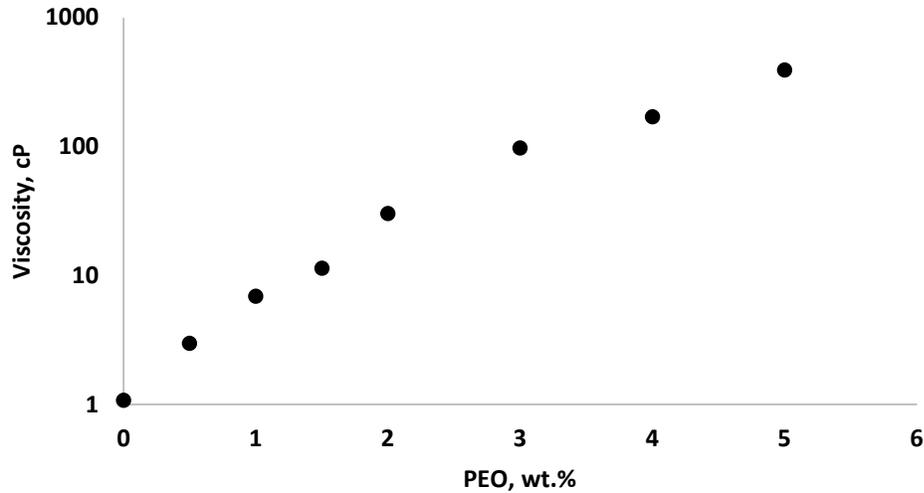


Figure 2: Relationship of viscosity of the polymer (PEO) aqueous phase to its concentration

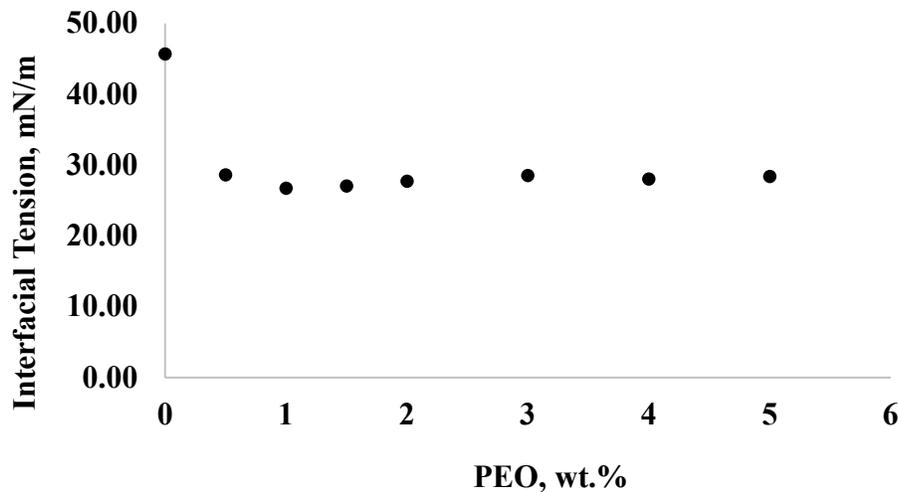


Figure: 3. Interfacial tension between oil and polymer aqueous phase versus concentration of PEO

3.2. Impact of Polymer on Capillary Number and Mobility Ratio of the Fluids

The rise in viscosity of water by adding polymer (Figure 2) and decrease in the interfacial tension (Figure 3), results in an increase of the capillary number (Figure 4) and factor, F (equation 1) displayed in Figure 5 which is introduced by Abrams (1975). The capillary number (N_c) also affects as shown in the following equation.

$$N_c = \frac{\mu U}{IFT} \quad (2)$$

Where μ is the viscosity, U is the characteristic velocity of the flow, and IFT is the interfacial tension.

Hence, in the case of reduced capillary forces associated with the rise of the capillary number, the interference between the phases is high at the tip splitting and small droplets of oil form near the interface (also observed microscopically, Figure 10). These oil droplets hosted in the aqueous phase are then carried out with the aqueous phase from the system. Figures 4 and 5 further reveal that although the capillary numbers and factor 'F' increase with the addition of the polymer, they are still less than unity, which shows that the flow in any case is dominated by capillary forces. Although the values of F are less than that of Abrams, (1975) suggested value for efficient oil recovery from reservoir (10^{-4}). The results show that polymer significantly improves the effectiveness of displacing oil from the cell.

Figures 6 and 7 show drop in mobilities of both the phases with increase in the concentration of polymer. This is mainly linked with its higher viscosity and better adsorption quality of the polymer aqueous phase on the surface which alter wettability of the surface. Thus, after each experiment formation of a thin layer of polymer on the plates surfaces observed and since the polymer solution uniformly displaced the oil from the gap, the deposited polymer layer is nearly uniform in thickness throughout the gap. The polymer thin layer can also be depicted from the reduction in absolute permeability by 642D. The polymer changes wettability of the Hele-Shaw cell from less water-wet to more water-wet, which is also confirmed in Figure 8 where it is noticed that the polymer wettability of the Hele-Shaw plate surface is more than the water. The polymer coating adds a resistance to the flow of the aqueous phase which in turn lowers its mobility leading to increase in the differential pressure and improve displacement of the oil phase. This behaviour is also observed by Donaldson (1985); Jennings et al., (1971); Domingues et al., (1977), and Needham et al., (1987), and Hendraningrat et al., (2012).

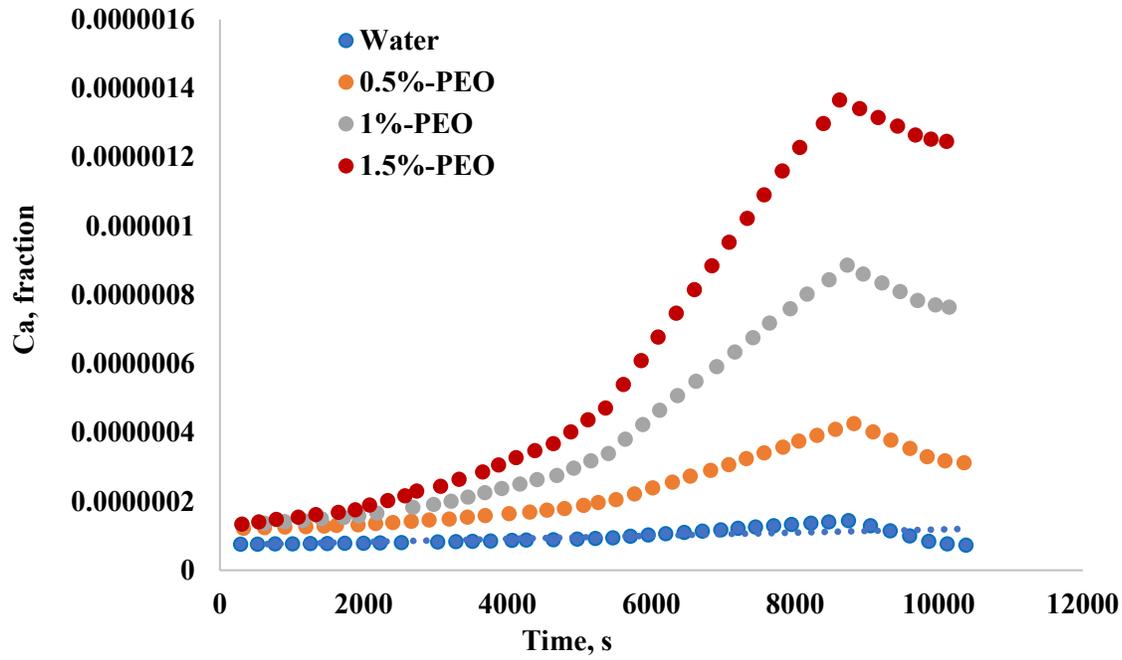


Figure 4.

Relationship of capillary numbers of water and different concentrations of PEO

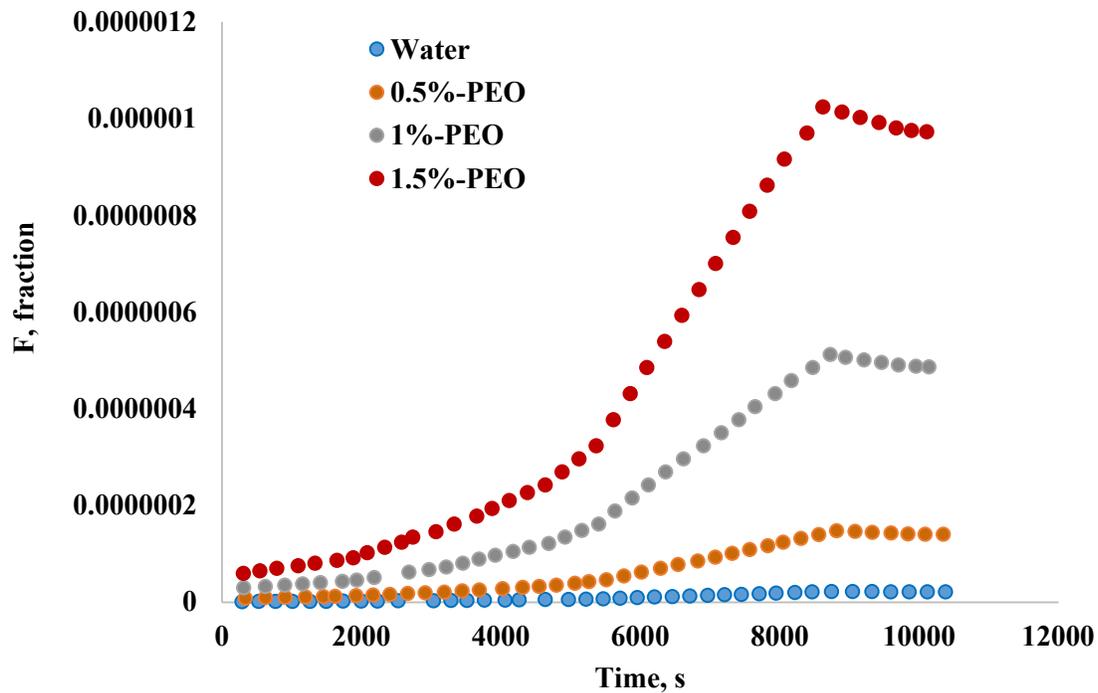


Figure 5:

Comparison of the factor F , introduced by Abrams (1975) for different concentrations of PEO

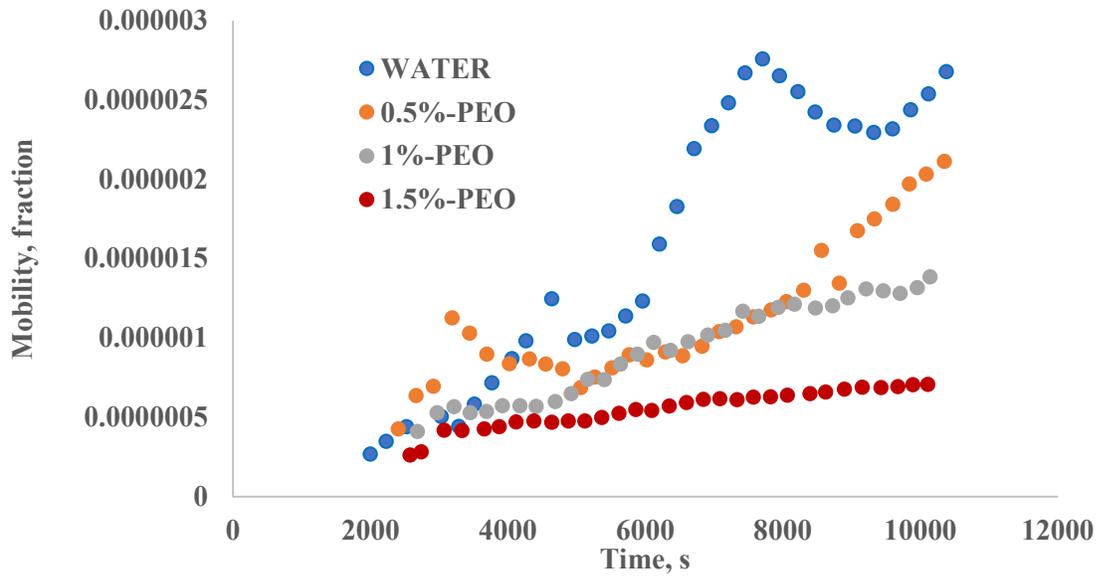


Figure 6: Mobility of the water changes with different concentrations of the polymer (PEO)

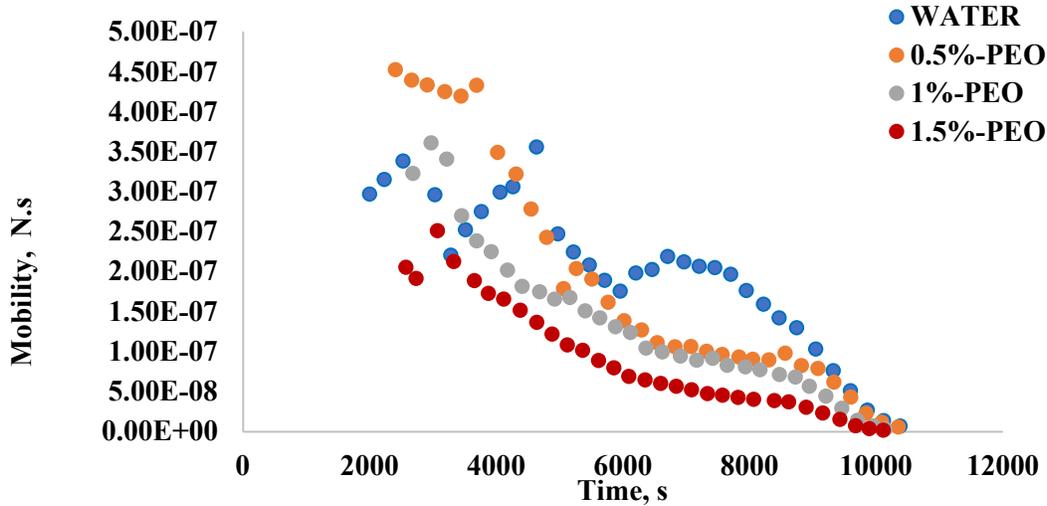


Figure 7:

Changes of mobility of oil with different concentrations of polymer

Water Drop Before PEO Flooding	Water drop after PEO Flooding
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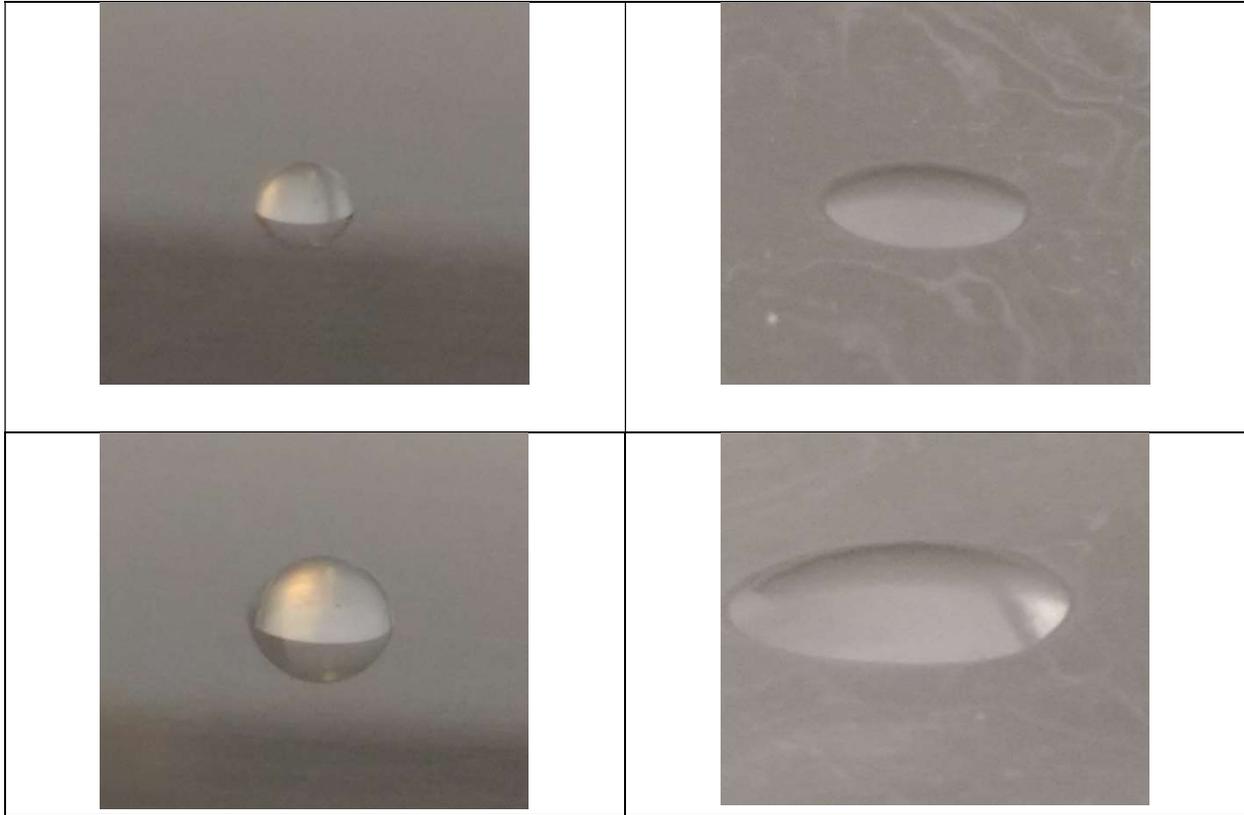


Figure 8: Examples of 0.1 ml water droplets placed on the Hele-Shaw plates before and after PEO flooding.

2. Comparative Analysis of the Flow Patterns Developed in Water-Oil and Polymer Solution-Oil

Table 1 shows a comparison of the water-oil and polymer solution (1.5 wt.%) -oil flow experiments. The differential pressure, phase saturations, and images of the phases (red is aqueous (displacing) phase whereas the colourless is oil (displaced) phase) are acquired for each step of flow rate.

As the flow evolves, the water channel on reaching to the centre of the cell, splits into two parts and then merge, engulfing oil droplets hosted in the water phase (as encircled at serial number (S.No. 11)). This droplet remains stationary throughout the experiment i.e., up to S.No. 18. After splitting and rejoining the channels, the water tends to flow in straight paths through the dominant and secondary fingers which are developed during the flow. On the other hand, the polymer solution exhibits the same behaviour before breakthrough as the water, but after the breakthrough, oil droplets move along the polymer solution towards the outlet end. Initially, the polymer solution on entering the cell, form a narrower finger than water (at S.No. 3) but later it gets wider and uniform channel of the aqueous phase form as the flow evolves to breakthrough (at S.No. 4 and 5). Hence, polymer solution detached

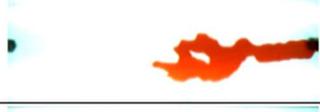
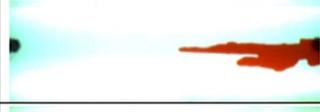
the oil droplet from the cell and facilitated its flow with the water and this is mainly due to slight decrease in interfacial tension and increase in viscosity by adding polymer to the injecting water.

Further observing the flow patterns (Table 1), the water saturation at breakthrough is about 23.3% and after the breakthrough, water channels further split into more narrower channels bypassing the oil. Hence, a major portion of the oil phase remains unrecovered and the end of the experiment, water could displace only 51.7% (S.No.18, Figure 3) of the oil from the cell. Whereas in the case of polymer solution and oil flow, the polymer at breakthrough fingers (S.No. 6) further widen, and occupies 43% of the area of observation, which is almost double of the water saturation i.e., 20.6% at breakthrough.

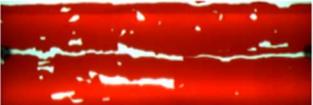
In the water flooding case, the differential pressure fluctuates due to disconnection and reconnection of the water channels and each time the pressure difference rises with the creation of a new channel movement and then declines at the exit of the channel from the cell. As discussed earlier that the water finger gets narrower after breakthrough, and its saturation drops and this can be seen in Table 1, at S.No. 7, 26% water saturation drops to 23% when the readings are taken at S.No. 8. Similarly, the differential pressure also drops i.e., from 0.465 psi at S.No. 7 to 0.445 psi at S.No. 8. In contrast, the polymer saturation and differential pressure consistently increases as the fluid evolves towards the outlet. At any step, the differential pressure of polymer is always greater than the differential pressure of water. In the polymer solution flooding case, the continuous increase of the differential pressure and relatively low fluctuations is due to no disconnection of channels or reduction of its size after the finger reaches the exit end of the cell. This is due to the higher viscosity of the polymer solution and due to the shift of wettability of the plates (shown in Figure 8, which will be discussed later) that in turn lowers the effective mobility of the aqueous phase due to adsorption of polymer that resists their flow. It was also observed that the polymer dissolution in water at room temperature was extremely difficult, for this purpose the polymer solution was used to heat up in oven for a few minutes and then vigorously shaken which facilitated its dissolution.

In the final stage of the experiments, it was observed that in the case of polymer, 98.5% of the oil is recovered from the cell whereas the water recovery is only 51.7% (Table 1, S.No. 18). Hence, polymer solution displaced 47.5% more oil than water. Based on the above observations, it can be concluded that polymer could be effectively used for enhancing oil from fractured rocks.

Table 1: Comparison of water-oil and polymer (1.5 wt. %) solution-oil flow data and images

S.No.	Time s	q_w ml/min	q_o ml/min	Water-Oil			Polymer Solution-Oil		
				dp, psi	S_{or}	Image	dp, psi	S_{or}	Image
1	1222	0.25	0.5	0.0485	0.012		0.044	0.008	
2	1457	0.3	0.5	0.0445	0.058		0.045	0.032	
3	1706	0.35	0.5	0.0485	0.12		0.047	0.076	
4	1947	0.45	0.5	0.0395	0.206		0.052	0.134	
5	2422	0.65	0.5	0.0305	0.252		0.059	0.322	
6	2663	0.75	0.5	0.0415	0.261		0.062	0.446	

S.No.	Time s	q_w ml/min	q_o ml/min	Water-Oil			Polymer Solution-Oil		
				dp, psi	S_{or}	Image	dp, psi	S_{or}	Image
7	3146	1	0.5	0.0465	0.257		0.057	0.545	
8	4614	2	0.5	0.0445	0.230		0.086	0.743	
9	5342	3	0.5	0.0545	0.245		0.112	0.746	
10	5815	4	0.5	0.0615	0.335		0.143	0.863	
11	6305	5	0.5	0.0375	0.39		0.169	0.874	
12	6788	6	0.5	0.0505	0.377		0.192	0.909	

S.No.	Time s	q_w ml/min	q_o ml/min	Water-Oil			Polymer Solution-Oil		
				Δp , psi	S_{or}	Image	Δp , psi	S_{or}	Image
13	7265	7	0.5	0.0525	0.367		0.219	0.914	
14	7743	8	0.5	0.0585	0.406		0.248	0.939	
15	8225	9	0.5	0.0675	0.387		0.256	0.944	
16	8984	9	0.2	0.0685	0.45		0.241	0.969	
17	9224	9	0.1	0.0585	0.476		0.241	0.966	
18	9719	9	0.025	0.0435	0.517		0.234	0.985	

3.3. Impact of Polymer on Relative Permeabilities, Saturations of the Phases and Reynolds Numbers

As described in the last sections that polymer alters the surface of the cell from being less hydrophilic to more hydrophilic. Figure 9(a) shows the relative permeability curves of the oil and aqueous phases of 0, 1, and 1.5 wt. % PEO polymer concentrations. The water-oil curves are relatively straight with the cross-over point equal to about 0.6. The irreducible water saturation in the case of oil water flow is equal to about 0.1 and residual oil saturation is about 0.17. In the case of 1 wt. % polymer solution, the relative permeability curves become less straight, and the residual oil saturation lowered down to about 0.08. In the case of 1.5 wt.% polymer solution, the residual oil saturation is further reduced to about 0.03. In general, the addition of polymer to the aqueous phases raises the aqueous phase relative permeability curve. On the other hand, the oil relative permeability curve follows the same trend as the polymer solution concentration is increased.

Figure 9(b) displays a comparison of the water-oil relative permeability curves for the case where the Hele-Shaw plates are clean (no PEO) and the case after the PEO has coated the plates (experiment conducted after flooding 1.5 wt. % polymer solution). The results show that the polymer coating on the plates significantly changed the relative permeability curves – both their shape and endpoints. The mobile phase region between the endpoints is narrow in the case with the polymer coating. This reveals that the presence of the polymer film lowers mobility of the water within the cell.

We further quantify the relative permeability data for various cases, polymer solutions with different concentrations, as presented in Table 2. From a comparison of the averaged values in the Table 2, it can be observed that the end point saturation of water rises with increase in the concentration of the polymer (as discussed earlier). The table shows that the water saturation increases from 58% to 81.7% by adding 0.5 wt.% polymer and to 97% by adding 1.5 wt.% polymer to the water. It is expected that this value could drop with roughness of the surface or in the actual rock sample of a reservoir, but our results at least gave an indication that the oil recovery could be raised with an increase in the concentration of the polymer. Also, as noticed earlier, the viscosity of water increases with polymer addition and to flood the viscous fluid through the cell, higher differential pressure is needed. Also, from the Darcy's equation for relative permeability, the viscosity of a phase has a linear relationship with differential pressure and relative permeability. Results in co-current flow of oil and polymer depict that the average differential pressures increased from 295 Pa to 521 Pa when the polymer concentration is increased from 0 to 1.5 wt. % PEO. As a result of this increase in the water relative permeability, the averaged mobility ratio also increased slightly from 28.70 (water) to 29.61 (1.5 wt. % PEO), but the individual mobilities of water and oil phases dropped. This reduction in the values of mobility is also noticed by Donaldson (1985). In the same way, the average Reynolds numbers calculated based on the homogenous viscosity, velocity and density defined by Delhaye, (1981) reduced from 0.47 to 0.082 by increasing the polymer concentration from 0 to 1.5 wt.%. On the other hand, the capillary number raised from 0.975×10^{-7} to 6.37×10^{-7} due to the increase in viscosity and decrease in interfacial tension between polymer and oil.

3.4. Microscopic Analysis of the Interfaces Between PEO Polymer and Oil

Figure 10 presents microscopic images of the interfaces between 1.5wt. % PEO polymer and oil as viewed by Nikon Ti-E inverted confocal microscope. For this purpose droplets of oil and polymer solution were sandwiched between two glass slides, and placed quickly after the microscope. Both the phases were in motion and the pictures of the interfaces were retrieved, until the phases movement stopped. This reflects the phenomenon of our experiment and also of reservoir, in which both the phases are in motion. Figure 10(a-c) displays a time sequence illustrating how the interfaces developed just after the two phases contact each other. When zoomed in (Figure 10(d-f)), it can be observed that the polymer solution forms small, less than $2 \mu\text{m}$ diameter, droplets in the oil phase just beyond the main interface. These small droplets tend to be irregular in shape and are positioned within 10 to $20 \mu\text{m}$ of the main interface. The observations show that an aqueous phase in oil microemulsion is created just upstream of the interface. This precursor microemulsion likely aids in displacing oil from the system.

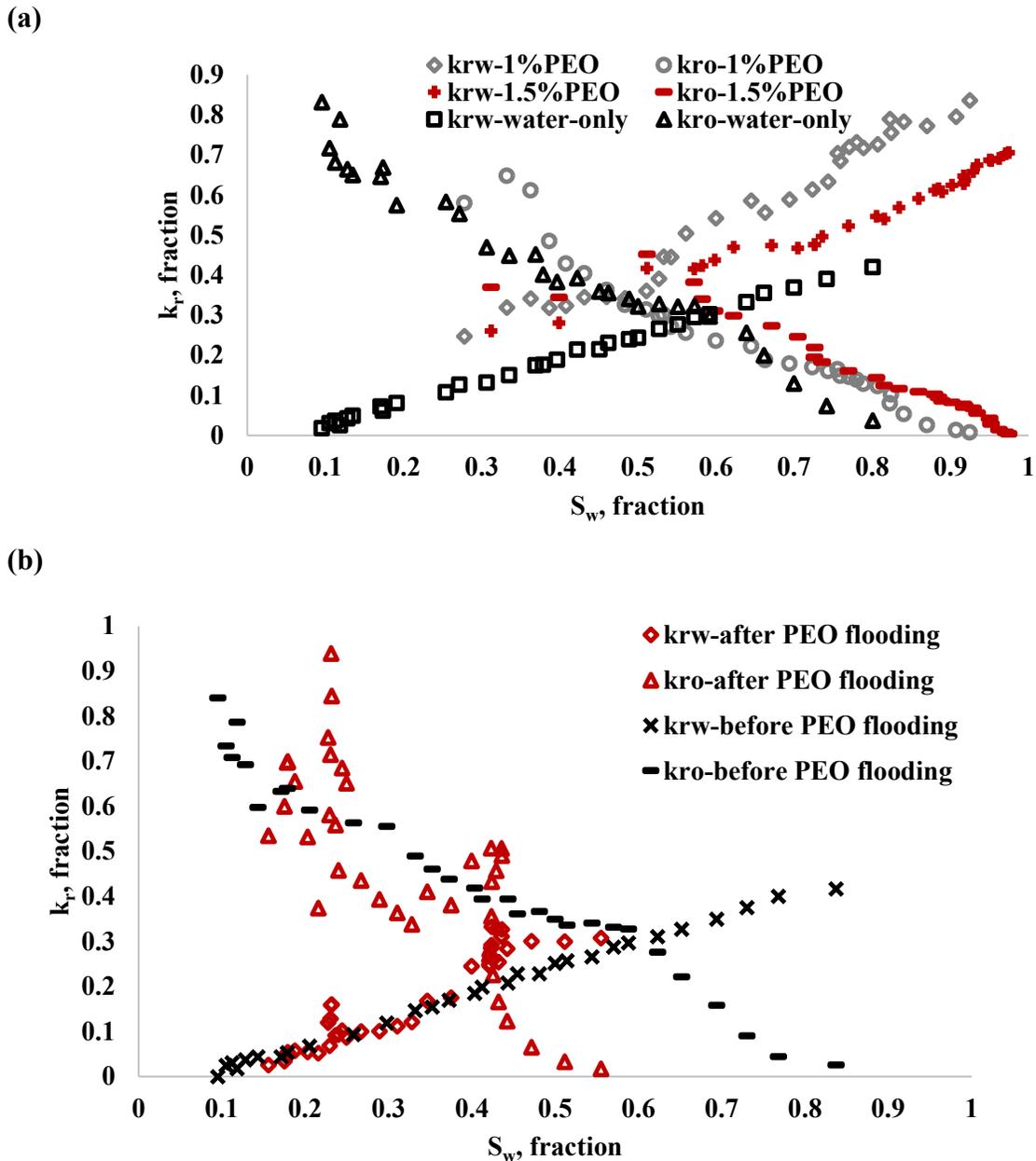


Figure 9: (a)

Relative permeabilities of oil with water and 1 and 1.5 wt.% polymer solution and (b) comparison of relative permeability curves for water (before PEO flood) and water (after PEO flood with thin layer of PEO on Hele-Shaw plates)

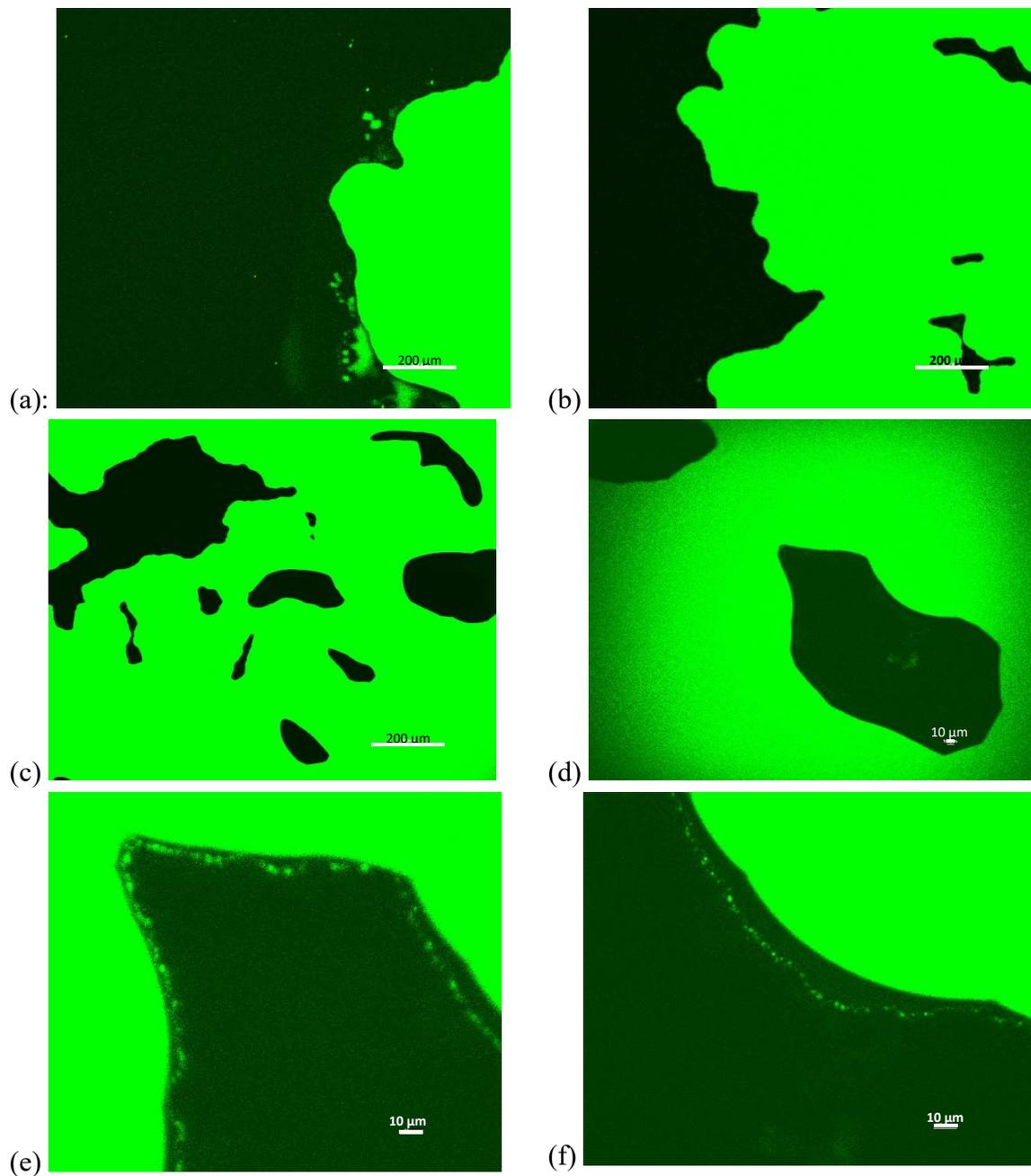


Figure 10: Microscopic images of the interfaces between the polymers aqueous phase (light green) and oil (dark green) phase: (a) interface at start of the observation, (b) image after 8 seconds (aqueous phase moves from right to left), (c) image after 16 seconds, (d) zoom in of a trapped oil droplet, (e) zoomed in (closer) view of interface, and (f) zoomed in view of interface

4. Conclusions

In the research documented here, co-current flow of polyethylene oxide (PEO) polymer solutions with oil through a Hele-Shaw cell is experimentally investigated for the study of interfacial behavior, mobilities of the fluids, flow patterns, oil recovery and capillary numbers. The experiments are repeated for the oil-water phases and their results are compared with different concentrations of the PEO polymer. The results show that due to increase in the viscosity of water and reducing interfacial tension by adding polymer to the water, the capillary forces relative to the viscous forces drop. The results also show that the interferences between the phases rises increase of increasing concentration of the polymer particles. The experiments also show that a thin polymer film adsorbs on the cell plates, which reduces mobility ratio of the phases and help in displacing oil from the fracture. This film tends to shift the wettability of the surfaces to be more water-wet which changes the relative permeability behaviour of fluids within the cell as well. The results suggest that polymer solutions can be effectively used to improve oil displacement from a narrow gap especially fractured rocks.

List of symbols

μ_o = viscosity of displaced fluid (oil), Pa.s

μ_w = viscosity of displacing phase (water or polymer solution), Pa.s

v_m = homogenous velocity of the phases, m/s

σ_{ow} = IFT = interfacial tension, mN/m

Ca = Capillary number

CFD = computational fluid dynamics

CN = coordination number

cP = centipoise, unit of viscosity

D = Darcy, unit of permeability

dp = differential pressure, psi or Pa

F = ratio of viscous forces to the capillary forces as used by Abrams (1975)

HPAM = Hydrolyzed polyacrylamide

k_r = relative permeability, fraction

k_{ro} = relative permeability of displaced phase (oil), fraction

k_{rw} = relative permeability of displacing phase (water or polymer aqueous phase), fraction

$M = k_{rw}\mu_o/k_{ro}\mu_w$, mobility ratio, dimensionless

N_{re} = Reynolds number, fraction

P = pressure, Pa

PEO = Polyethylene oxide

PTR = pore throat ratio

q = volumetric flow rate of fluid, m³/s

q_o = volumetric flow rate of displaced phase (oil), m³/s or ml/minute

q_w = volumetric flow rate of displacing phase (water or polymer aqueous phase), m³/s or ml/minute

S_w = saturation of displacing phase (water or polymer aqueous phase), fraction

μm = micrometer, unit of length

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