MOBILIZATION OF RESIDUAL OIL MECHANISMS SEEN IN MICROMODELS

I. Chatzis
Department of Chemical Engineering
University of Waterloo, Waterloo, Ontario, Canada

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Austin, Texas, USA 18-21 September, 2011

ABSTRACT

The mobilization of residual oil was investigated in glass micromodels consisting of capillary networks with water-wet wettability for three cases: 1) mobilization with increased capillary number; 2) mobilization with rising bubbles in simple pore networks; and 3) mobilization with pressure pulsing. The micromodels used had variable pore throat and pore body size distribution. For substantial mobilization of the waterflood residual oil, the corresponding capillary number needs to be 100 times larger than that for the onset of mobilization of the largest blobs in place at the end of waterflooding. The reduced residual oil saturation with increasing capillary number obtained in micromodels is in qualitative and quantitative agreement with published capillary number curves for water-wet sandstones. A key feature of oil blob mobilization at high capillary number is the break-up of mobilized blobs to sub-pore size droplets as they flow through the pore network, some of which attach to the pore walls and thus making impossible the complete mobilization. For the case of mobilization of residual oil by rising gas bubbles it was found to be a potential oil recovery mechanism for the residual oil in water wet systems. Finally, residual oil mobilization by pressure pulsing was demonstrated to be an effective mechanism that results in the emulsification of residual oil *in-situ* with high recovery efficiency. It was concluded that glass micromodels offer the potential to screen the best surfactant formulations for EOR application using residual oil mobilization experiments and for other types of recovery of the residual oil in place.

INTRODUCTION

A very significant fraction of the oil initially in place in an oil field is permanently trapped at the end of waterflooding operations. This trapped oil is referred to as waterflood residual oil and is a strong function of the pore structure heterogeneities, flooding rate and wettability conditions. The residual oil saturation can be 15% of pore volume in homogeneous unconsolidated sands and as high as 50% of the pore volume in pore systems with vugs and high aspect ratio of pore body size to pore throat size[1-2]. The waterflood residual oil is recoverable by chemical flooding at high capillary number, the ratio of viscous to capillary forces. A key objective of this work was to develop a better understanding of the residual oil mobilization process and thus improve the design of chemical flooding projects in water-wet reservoirs. Improved oil recovery technologies will become a reality very soon, as the producing oil fields will run out of the primary and secondary oil recovery phases.

The glass micromodels are made using a microlithography based technique similar to the making of printed circuits on boards and microchip manufacturing. The desired pattern of pore channels is etched on a glass plate using hydrofluoric acid. After we drill inlet and outlet ports in the etched glass plate, it is next fused on to another flat glass plate at 725 ^{o}C, thus creating a sintered 2-D glass micromodel with a capillary network in place between the sintered glass plates. This porous medium can be used for studying immiscible displacements of oil with water injection[1] and other cases. An example of a square capillary network and photograph of the selected pores in the micromodel seen under a microscope is shown in Fig. 1. As indicated on this figure, the residual oil blobs are found to occupy one to several pores. The pores with residual oil in water-wet media are generally of predominantly large pore size. The water phase occupies the predominantly smaller pores and the pore corners of space that has residual oil occupancy.

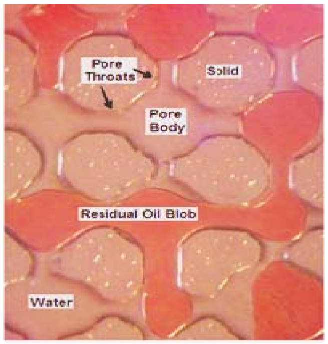


Fig.1: Portion of micromodel with residual oil blobs

In this study we focus attention to the mechanisms of oil recovery by waterflooding and the mobilization of residual oil as a function of flow rate (capillary number). The model was first saturated with water and then the water was displaced with oil to establish initial oil and connate water conditions. Subsequently, water was injected at constant rate to waterflood the system and establish the residual oil condition. The magnitude of residual oil was monitored by video-recording and by image analysis of the residual oil blobs. After a displacement condition, a photograph was taken and the amount of residual oil was determined by image analysis. A commercially available image analysis software (Image Tool^{TM}) was used.

THEORY

The mobilization of trapped residual oil requires the viscous forces across the length of a blob to exceed the capillary forces. Consider the oil blob in a simplified pore network shown in Fig. 2 with water-wet characteristics. The pressure difference in the water phase from point A to point B must become greater than the difference between the drainage capillary pressure at position 1 and imbibition capillary pressure at position 2 for the oil blob to mobilize in the downstream pore junction at position B. Expressing the capillary pressure using the pore constriction size at location 1 and the pore body size at location 2, we can write[1]:

$$(P_{w,A} - P_{w,B}) = \Delta P_m \text{; and } \Delta P_m \geq \left(\frac{4\sigma_{ow}\cos\theta_R}{D_1} - \frac{4\sigma\cos\theta_A}{D_2}\right) \quad (1)$$

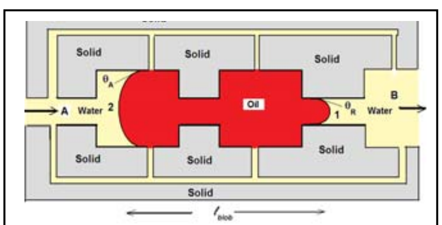


Fig.2: A schematic of an oil blob trapped in a water-wet capillary network

where ΔP_m is the required mobilization pressure difference, σ_{ow} is the oil-water interfacial tension, D_1 and D_2 are the pore throat and pore body diameters respectively, θ_R is the receding contact angle, and θ_A is the advancing contact angle.

The velocity of the water phase with residual oil present is governed by Darcy's law:

$$v_w = \frac{Kk_{rw}}{\mu_w}\frac{\Delta P_w}{L} \quad (2)$$

where v_w is the Darcy velocity of water, μ_w is the viscosity of water, $(\Delta P_w/L)$ is the macroscopic pressure gradient, K is the absolute permeability and k_{rw} is the relative permeability to water. By equating the macroscopic pressure gradient with the capillary pressure difference across the blob divided by the blob length l_{blob}, then we can derive:

$$\frac{\Delta P_w}{L} = \frac{1}{\ell_{blob}}\left(\frac{4\sigma_{ow}\cos\theta_R}{D_1} - \frac{4\sigma_{ow}\cos\theta_A}{D_2}\right) \quad (3)$$

Let $\lambda = \frac{\ell_{blob}}{D_1}$ and $\beta = \frac{D_2}{D_1}$ (4)

Using the above definitions, equ.(3) can be re-arranged as:

$$\frac{\Delta P_w}{L} = \frac{4\sigma_{ow}}{\lambda D_1^2}\left(\cos\theta_R - \frac{\cos\theta_A}{\beta}\right) \quad (5)$$

The larger the aspect ratio is, the larger is the pressure gradient required for oil blob mobilization. If one combines equ.(5) with equ.(2), the following dimensionless expression, known as capillary number, can be obtained[2]:

$$\frac{v_w\mu_w}{\sigma_{ow}} = \frac{Kk_{rw}}{\sigma_{ow}}\frac{\Delta P_w}{L} = 4\left(\frac{Kk_{rw}}{\lambda D_1^2}\right)\left(\cos\theta_R - \frac{\cos\theta_A}{\beta}\right) \quad (6)$$

The relative permeability function for k_{rw} can be expected to be constant at a given saturation condition for systems having similar pore geometry[3]. Therefore, the macroscopic pressure gradient for the flow of water in systems having the same residual oil saturation is proportional to (1/K), where K is the absolute permeability. The relation of residual oil saturation as a function of capillary number is known as the capillary number curve. Based on equ.(6), systems of same wettability and microstructure of residual oil are expected to be described by the same capillary number curve.

EXPERIMENTAL ASPECTS

Mobilization of residual oil: It was desirable to determine how representative are the pore network micromodels etched on glass as porous media models to describe the capillary number curves for the mobilization of waterflood residual oil. The visualization of the residual oil microstructure with capillary number was another objective to provide experimental evidence of the break-up of the oil blobs during the residual oil mobilization process. Two glass micromodels of pore networks with a square lattice topology and having different pore structure at the pore scale were utilized as test porous media. Details of the fabrication technique are given elsewhere[1]. The glass micromodels have water-wet characteristics in waterflooding tests. The fluids used were kerosene with a red dye added to it to simulate the "crude oil" for visualization and de-ionized water was used for the displacement of oil. The interfacial tension σ_{ow} was about 26mN/m for the dyed oil-water system and about 3mN/m when using water with soap. Micromodel SRC-1 had a length of 102 mm and width of 44mm (87 pores long by 41pores wide) and a pore volume of 350μL. The micromodel (SX-4) had a width of 46mm, length of 80mm and pore volume of 250μL. The absolute permeability to water for micromodels SRC-1 and SX-4 was measured by the falling head permeameter method[3] and the two models had similar permeability values (20-23μm^2). Pore throats were in the range 30-100 μm.

The experiments for the mobilization of residual oil as a function of capillary number were as follows: The micromodel was first saturated with water and then the micromodel was oil-flooded to establish high initial oil saturation by flowing 10cm^3 of oil at 20cm^3/min. Normal waterflood residual oil saturation was established by water injection at low flow rate (0.01cm^3/min) using a constant rate syringe metering pump. After water-breakthrough, the residual oil remained in place without any sign of mobility and a picture was taken. The picture was analyzed to determine the area occupied by the residual oil in the pore network. This area was used as the reference area to denote the normal waterflood residual oil saturation (S^*_{or}) in the micromodel. The water injection rate was subsequently increased in a step-wise manner (e.g. 0.02, 0.04, 0.8,…20 cm^3/min). At each flow rate of water injection, the state of residual oil was observed until no further oil blob mobilization was happening. At that time, a new picture was taken to determine the reduced residual oil content; the water injection rate was increased again to a higher value for a further reduction of the residual oil content in the micromodel. Thus we collect enough data points for the amount of the residual oil remaining in place as a function of flow rate conditions. The corresponding capillary number for each flow rate was determined by calculating the Darcy velocity first (dividing the water flow rate by the cross-sectional area of the micromodel to fluid flow) and then apply Equ. (6). The cross-sectional area for fluid flow is the total width of the pore network (W) times $2D_{dep}$, where D_{dep} is the depth of pore etching.

The residual oil in place was determined by image analysis of the digital photographs taken at the end of each displacement condition[5]. It was assumed that the projected area of isolated oil blobs is proportional to the volume occupied, as the depth of etching is fairly constant[5]. The maximum area of the isolated blobs was used to normalize the residual oil fraction remaining in place at any given flow rate (or capillary number) condition. The term (S_{or}/S^*_{or}), is the ratio of residual oil saturation established at a particular flow rate relative to the waterflood residual oil saturation, S^*_{or}. Residual oil mobilization can also be obtained by the rise of bubbles in pore networks under the action of buoyancy and by pressure pulsing. Only example results are presented here due to limited space for this paper.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 illustrates that during waterflooding a water-wet porous medium there is a preferential selection of the relatively small pores where water imbibes and the trailing oil/water interfaces are in the relatively large pores. The residual oil is seen to be predominantly trapped in the larger pores in the pore network in the form of isolated oil blobs involving one to several pore bodies

Furthermore, the length of the oil blob structures tends to be longer along the direction of displacement. Typical results obtained for the residual oil remaining in place as a function of flow rate are as shown in Figure 4 for a small section of the micromodel SRC-1. After trapping the oil at an injection rate of 0.1cm^3/min, the mobilization process was monitored by taking pictures at the end of each step-wise increase in water injection rate. As seen in the few pictures shown in Fig. 4, there is very little change occurs in the residual oil content as the flow rate was set at 0.4cm^3/min although some oil blobs were locally mobilized a bit. However, at increased flow rates it is observed that the large residual oil blobs are broken-up into smaller segments and by the stage where the flow rate was 5cm^3/min there are no branch like blobs any more. Further increase in flow rate causes more residual oil mobilization as well as more smearing of blobs creating sub-blob size oil droplets.

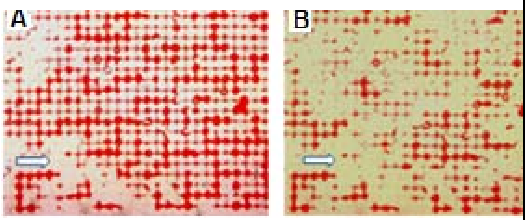


Fig.3: Illustration of the waterflooding process in model SX-4.. The water is a clear liquid imbibing along the direction shown by the arrow and the oil in pores is shown in red in stage A; b) The state of residual oil blobs after the end of low capillary number waterflooding is shown in stage B.

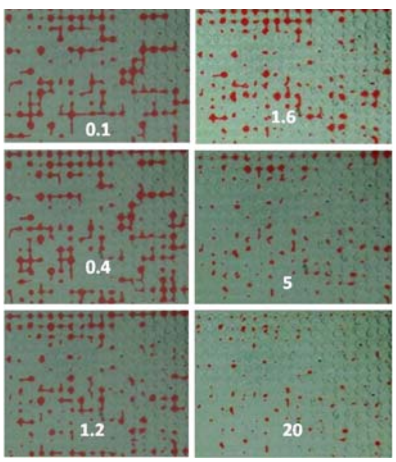


Fig.4: Details of the microstructure of residual oil at different flow rates during mobilization tests in SRC-1. Number in picture s is flow rate of water in cm3/min

A display of the residual oil fraction remaining in place as a function of capillary number for the mobilization experiments using micromodel SRC-1 is shown in Figure 5. At a capillary number of about 5x10^{-5} some reduction of the normal waterflood residual oil saturation happens and for a capillary number greater that 5x 10^{-4}, about half or more of the original residual oil has been mobilized. These results are in agreement with capillary number curves for mobilization of residual oil in sandstones reported in literature[1]. A significant mobilization of residual oil occurs after exceeding a critical capillary number.

The effect of the oil-water interfacial tension was also examined. Figure 6 is a set of pictures showing the residual oil microstructure at different conditions of waterflooding and mobilization. The surfactant was a hand-washing liquid in the laboratory. About 1wt% aqueous solution was made of it and this surfactant solution was injected as a slug in the inlet tube leading to the model's inlet fitting. This slug was driven into the micromodel by water injection at constant rate using the syringe pump. As seen in the pictures in Figure 6, the low injection rate surfactant flooding produced the residual oil microstructure which is similar to that obtained with much higher interfacial tension in normal waterflooding shown in Figure 5 at the rate of 0.1cm^3/min. Similarly, the state of residual oil remaining with surfactant flooding carried out at 1cm^3/min and shown in Fig. 6 is very similar to that obtained at no surfactant conditions with the flow rate at 10 cm^3/min shown in stage (c) in Fig. 6.

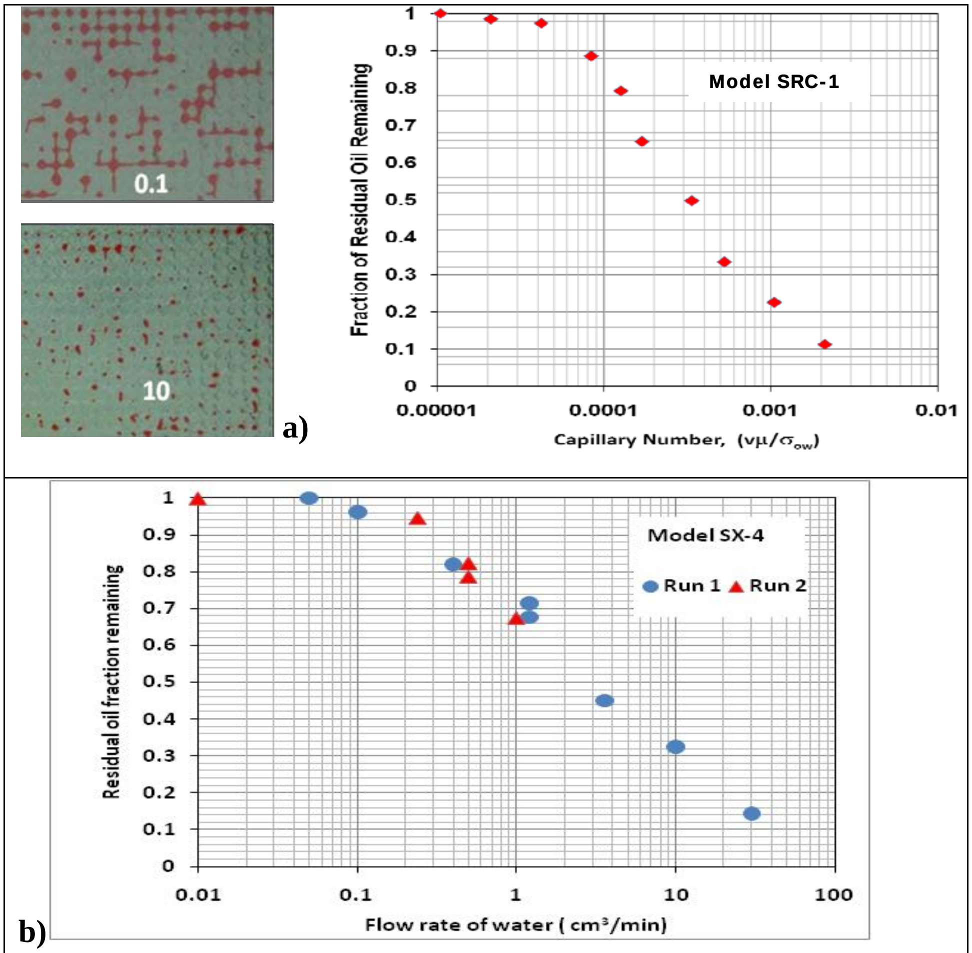
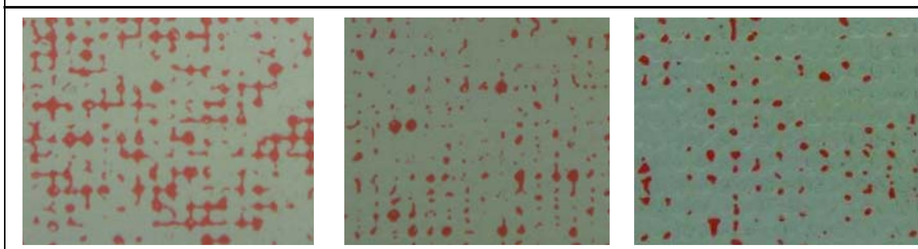


Fig.* 5**: ***Mobilization of residual oil in micromodels SRC-1 and SX-4



a) 0.02cm3/min

b) with surfactant at 1 cm3/min

c) at 10cm3/min without surfactant

Fig.6: The microstructure of residual oil with surfactant flooding and without surfactant

These results are in qualitative agreement because the corresponding capillary numbers at these different velocities are the same when for the low oil-water interfacial tension case in surfactant flooding is compared to the capillary number corresponding to high flow rate mobilization without surfactant[2]. For surfactant flooding at high capillary number, the residual oil that has not mobilized is seen to consist of tiny oil droplets of size smaller than the pore dimensions, yet this residual oil remains in place because of some finite contact angle they are attached to the pore walls. An example of this is the picture shown in Figure 7**.** It is evident that the type of residual oil remaining at a capillary number of about $5x10^{-3}$ is very difficult to mobilize. For high capillary number conditions, there are locations that can retain these oil droplets attached to the pore walls. The water relative permeability at this condition approaches unity value, as reported in literature[4]. The results of this study have helped in providing the direct evidence as to the reason why the relative permeability value to water at reduced residual oil conditions approaches unity at water saturations of about 90% PV.

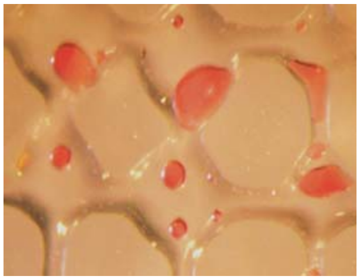


Fig.7: Close-up of oil droplets at high capillary number in SX-4.

Mobilization of residual oil by rising bubbles: Examples of residual oil mobilization by gas bubbles rising in a pore network are shown in Fig. 8 and Fig. 9 respectively. For the case of bubbles rising in porous media with residual oil, there is a great potential to carry upwards a significant amount of an oil blob attached to a rising bubble and attain very high recovery efficiency with multiple contacts[6]. As a rising bubble contacts a residual oil blob, the oil blob spreads over the bubble and eventually it transfers to the trailing- end as shown in Fig. 8. In the migration process, the oil carried at the trailing-end of a rising bubble breaks-off. However, a smaller mass of oil is still attached at the trailing end. Subsequently, another bubble will access the remaining oil blob again and the new bubble will carry this oil blob upwards a few pores and repeat the phenomenon is repeated again. A large number of bubble contacts are required for complete oil recovery[6].

Mobilization by pressure pulsing: For the case of pressure pulsing in water injection in a micromodel with residual oil, it is observed that the residual oil blobs are emulsified in-situ (see stages A and B in Fig. 9). The oil in water emulsion created *in-situ* can be made to flow towards the production end when water is injected at low flow rate with pressure pulsing at a frequency of about 10-30 pulses per minute. The diameter of oil droplets in water is smaller than the pore throat size and this emulsion is produced. For this method to be successful it is required not to have residual gas in the system, as the compressible gas affects the emulsification of residual oil. Wettability issues are also very important for the pressure pulsing technology. A systematic investigation of wettability effects in pressure pulsing is currently underway in my laboratory for a variety of conditions.

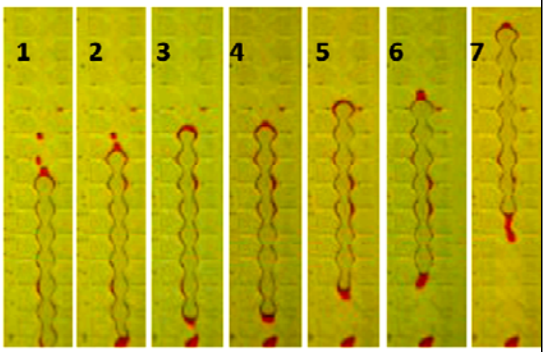
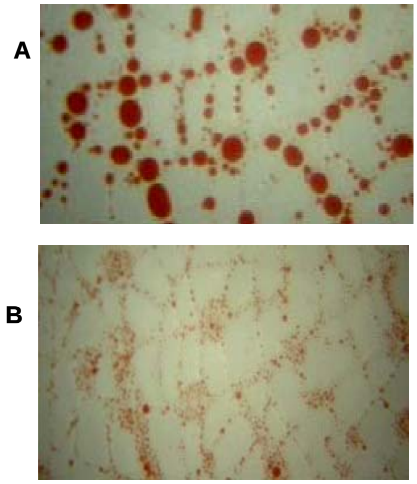


Fig. 8: **Mobilization of oil by a rising bubble. The oil blobs in the migration pathway are accessed by the front of bubble and later it drains by gravity to the tail of the bubble where part of it is snapped-off.**



Fg.9 Mobilization caused by pressure pulsing

CONCLUSIONS

1. The capillary number curves obtained using micromodels in this work are in agreement with published results for water wet sandstones. It was found that at capillary numbers greater than 10^{-3} the reduced residual oil is held in the pore space in the form of oil droplets that have a size smaller than the pore body size and are not recoverable.
2. Residual oil blobs in water-wet media can be mobilized by rising bubbles of gas. A rising bubble lifts a portion of the contacted oil blob upwards. A very large number of bubble contacts with an oil blob are required for complete residual oil recovery.
3. Water injection with pressure pulsing was demonstrated in micromodels to cause emulsification of trapped oil and the oil in water emulsion to be recoverable.
4. Micromodels have great potential for visualizing specialized core flooding tests and can be used to study various EOR processes in addition to oil blob mobilization.

REFERENCES

1. I. Chatzis, N.R. Morrow and H.T. Lim: Soc. Petr. Eng. J. (April 1983) 311-326
2. I. Chatzis and N.R. Morrow: Soc. Petr. Eng. J. (October 1984) pp.555-562
3. F. A. L. Dullien: Porous Media: Fluid Transport and Pore Structure, Academic Press, Second Edition, New York (1991)
4. N. R. Morrow, I. Chatzis, and H.T. Lim: J. Canadian Petr. Tech. **24**, 62-69, 1985.
5. NA Sahloul, MA Ioannidis, I Chatzis: Advances in Water Resources, **25**, 1, 33-49, 2002
6. T. Li, M. Ioannidis, I. Chatzis: "Recovery of non-aqueous phase liquids from ground sources", USA patent **20070014633,** Issued on Nov. 27, 2007