SCA2003-06: THE ACCESSIBILITY OF WATERFLOOD RESIDUAL OIL BY THE OIL BANK WHEN SLUGS OF SOLVENT ALTERNATE WITH SLUGS OF WATER (SAW) UNDER OIL-WET AND WATER-WET CONDITIONS

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ABSTRACT

Flow visualization studies were carried out to determine the accessibility of waterflood residual oil by oil-miscible slugs in 2-D glass micromodels of capillary networks having features of variable pore structure. The wettability was varied to represent strongly water-wet and strongly oil wet conditions. As the front of the oil bank propagates in the region with residual oil, three forms of oil in the oil bank are realized, namely, the flowing oil, the dendritic oil and the isolated (or inaccessible) oil, respectively. The fraction of resident residual oil which 1) becomes flowing, 2) becomes dendritic oil and 3) remains inaccessible oil was studied as a function of pore volume throughput and solvent slug size in various micromodels with different pore structure. Experimental results demonstrate that the residual oil under oil-wet conditions is 100% accessible by the oil bank. However, there is limited accessibility of the waterflood residual oil by the oil bank in water-wet conditions and the solvent is highly dispersed to the extent of having very early solvent breakthrough. It was found that no additional residual oil reconnection takes place after 2 slugs of solvent alternating with 2 slugs of water have passed through a region of the system with residual oil. For low capillary number at the front of the oil bank, the accessibility of waterflood residual oil by the oil bank decreases significantly as the pore structure becomes more heterogeneous.

INTRODUCTION

The waterflooded residual oil is the part of the oil that is left in the reservoir at the end of waterflooding. In water wet conditions the oil phase trapped during waterflooding is in the form of disconnected oil blobs or oil ganglia constituting the residual oil [2-3, 5, 10]. In water-wet porous media, residual oil ganglia may occupy part of a single pore, two pores, or extend to several pores to form an interconnected cluster of pores [2]. In Berea sandstone core samples, it was found that large blobs of up to ten pore bodies are common[2]. However, in oil-wet porous media, the residual oil tends to be held in smaller pores and pore throats, as well as in large clusters of pores that are accessible through smaller sized pore throats. These clusters of pores with residual oil are by-passed by water in waterflooding an oil-wet reservoir, as the invading water prefers to maintain a continuum of pore space constituted by the network of relatively large pore throats connecting pore bodies. Furthermore, the residual oil under oil-wet conditions maintains hydraulic continuity throughout the medium because of the presence of oil films in the pore wedges of pores invaded by water. The bulk films of oil remaining in pores that get drained by water invasion communicate with the pores that remain completely filled with residual oil trapped by the by-passing mechanism in a drainage process [2, 5]. Miscible or near-miscible displacements may be realized by injecting a fluid that mixes with the oil, namely liquid hydrocarbons or carbon dioxide. An oil bank zone is formed with the injection of a solvent that is miscible to residual oil. The oil bank tends to reconnect and hence recover the residual oil in the porous medium as it propagates towards the production well (Fig. 1). The oil saturation at the trailing end of the oil bank is higher than the residual oil saturation and approaches the value $S_o = 1 - S_{wc}$, where S_{wc} is the immobile water saturation. As most of the initial residual oil in the oil bank becomes reconnected by the solvent injected, it is expected that a subsequent flooding with high capillary number flow at the water/solvent tail will recover most of the residual oil compared to the case where solvent flooding is conducted without forming an oil bank. An unsteady-state flow regime exists locally within the oil bank until the stable saturation of the flowing bank is achieved. Diffusion processes increase the solvent saturation continuously but slowly. The distance required for the saturation build-up is generally unknown and depends on various parameters such as pore structure, wettability, residual oil saturation, mobility ratio, and solvent slug size.

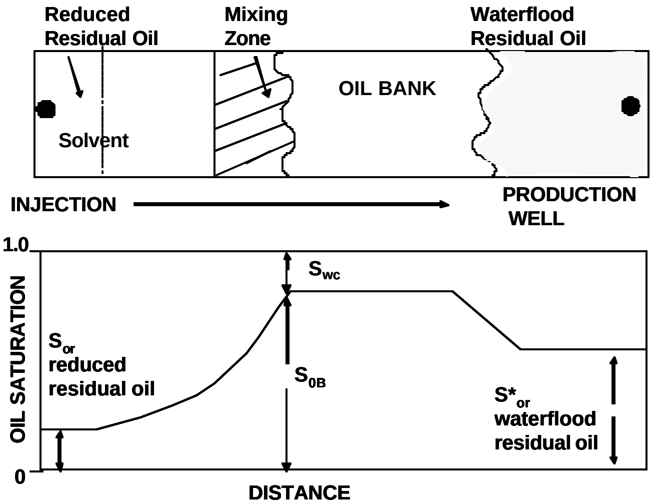


Fig. 1: Schematic of EOR Process

The oil phase in the oil bank zone can be classified into three categories: flowing, dendritic (or dead-end) and isolated (or inaccessible) oil, respectively. The flowing oil represents the oil phase found in an interconnected network of pores through which oil is flowing by convective transport. The dendritic oil is held in pores connected with the pores with flowing oil but does not contribute to convective flow. Recovery of the dendritic oil in a miscible displacement occurs via diffusion into the flow paths of the flowing oil and is not easily recoverable unless the length of the dead-end paths is short. The isolated oil is completely surrounded by pores filled with water through which no diffusion can occur if the solvent is immiscible with water. Therefore, the isolated oil (not accessible oil to solvent) is not recoverable. However, in a miscible displacement such as CO_2 miscible flooding, diffusion of CO_2 through the water-filled pores and subsequently into the isolated residual oil blobs can make additional isolated oil become reconnected to the oil continuous network of pore space by swelling mechanisms. This phenomenon occurred in CO_2 miscible flooding of residual oil as seen in visualization experiments using glass micromodels [1]. 2-D network micromodels etched on glass and 3-D micromodels with glass beads sintered between glass plates have found extensive use in porous media research [2, 5, 8]. They were found to be excellent research tools for visualizing capillary and transport phenomena in porous media and for studying the effects of pore structure and wettability on oil recovery processes [1-2, 5, 8].

Mobilization of residual oil by flow of water occurs when viscous forces are sufficient to overcome capillary forces. The ratio of these two forces is known as the capillary number. The expressions used most frequently include the following two forms [3]:

$$N_{Ca,1} = v\mu/s \qquad (1)$$

$$N_{Ca,2} = K_W\ ?P/\ L\ s \qquad (2)$$

where v is the velocity and μ is the viscosity of the displacing phase, s is the oil-water interfacial tension, K_w is the permeability to water and ?P/L is the applied pressure gradient across a sample of length L. Complete recovery of waterflood residual oil by mobilization mechanisms in water-wet media is possible [3] only if $N_{Ca,2} > 2x10^{-3}$. The microscopic distribution of residual oil and what it takes to mobilize it has been studied extensively [2-3, 5, 10]. In the region of the oil bank in hydrocarbon miscible flooding, the prevailing conditions are not typically those defined by high capillary number conditions. To understand how the water and oil phase distribute in solvent miscible flooding, several experimental studies used miscible displacement flooding tests that involved simultaneous injection of water and solvent. It was found that the displacement of wetting phase was not affected greatly by the presence of the non-wetting phase. However, a large amount of oil that initially appeared to be trapped by water was eventually recovered by continuous solvent injection [12-14]. Raimondi and Torcaso [13] found that some oil, particularly at high water-to-solvent injection ratios, was trapped permanently, provided that the injection rates, viscosity ratios and pressure drops were unchanged in switching from water/oil to water/solvent injection. Fitzgerald and Nielson [6] also found that only part of the in-place crude was recovered by solvent injection. Moreover, solvent appeared in the effluent shortly after oil breakthrough. Oil recovery was further decreased when solvent and water were injected simultaneously. From several experiments, it was found that only part of the oil flows in the presence of high water saturation[14]. The remainder resides in locations that are blocked by water, but it can be recovered by molecular diffusion into the flowing solvent in a water/propane solvent displacement test. Much of the bypassed oil in dead-end pores is in communication with the flowing solvent and is recovered by diffusion. High water saturations increase the amount of bypassed oil and increase the dispersion coefficient in the oil phase. As mixing of the oil bank with resident residual oil takes place by convection, diffusion and dispersion, much attention has been paid to dispersive mixing. Salter and Mohanty[11] studied the mechanisms of multiphase flow and attempted to correlate pore level mechanisms with macroscopic laboratory observations. They did most of the work on a single porous medium, namely strongly water-wet, fired-acidized Berea sandstone, conducting a series of tracer displacement tests during two-phase, steady state flow, much like in previous studies[12-13] and fit the effluent concentration profiles with the help of the Coats and Smith[4] capacitance diffusion model. They estimated the dendritic, flowing, and isolated fraction of oil and water saturation, respectively as a function of saturation in drainage and imbibition mode of displacement. Jones [7] made a different study from previous authors and investigated the mixing of resident residual oil with a miscible solvent. The resident oil was initially at residual oil saturation and was mobilized by injecting a micellar fluid. For several surfactant free runs (i.e. displacements not involving micellar slugs), oil at the residual saturation was displaced by the injected hydrocarbon. Like Fitzgerald and Nielson [6], Jones [7] also noted that early breakthrough of solvent takes place during miscible displacement tests. This greatly reduced the recovery efficiency of residual oil by the injected solvent. It was postulated that the early breakthrough and abundant dispersion were caused by the hydrocarbons (residual oil) trapped in smaller pores because the other cause, the unfavourable oil/solvent viscosity ratio, was eliminated by using favourable oil/solvent viscosity ratios. Jones[7] also conducted miscible displacements with the injection of an aqueous phase to displace resident water in a water-wet core, reaching a conclusion that the recovery of the wetting-phase was complete. Results of a visualization study of the mechanisms at work when carbon dioxide displaces oil, with and without water in simple 2-D pore networks etched in glass plates, have also been reported [1].

The scope of this paper is to elucidate further the accessibility of waterflood residual oil by the oil bank through direct visualization of mixing phenomena at the pore scale in glass micromodels having different pore structure and residual oil for water-wet and oil-wet wettability conditions. We outline the materials and methods used, present visualization results, provide quantitative results and discuss the accessibility of residual oil as a function of solvent injected. The effect of injecting a slug of solvent followed by a slug of water (SAW) on residual oil recovery was also investigated.

EXPERIMENTAL

Materials and Methods: The porous media used in this study were 2-D capillary network type of micromodels etched on glass using a photofabrication technique [2-3, 9]. The 2-D pore networks do not, of course, represent all the complexity of pore structure of reservoir rocks. The various pore structure features incorporated in the micromodels were aimed to capture aspects typical of homogeneous and heterogeneous porous media. Figure 2 shows some of the features in some of the micromodels used. The fluids used to represent the residual oil phase and the solvent simulating the oil phase in the oil-bank were common laboratory solvents in oil recovery research such as Soltrol oil, Varsol, kerosene, hexane and heptane. Water was the wetting phase when simulating water-wet conditions in glass micromodels and the oils were the non-wetting phase. For the case of simulating oil-wet wettability, the residual water (wetting phase) trapped in a water-wet micromodel after oil-flooding a micromodel initially saturated with dyed water is approximating the residual oil conditions in an oil wet reservoir after a waterflood. The microscopic distribution of residual dyed water in our micromodel simulates the “residual oil” in an oil-wet reservoir.

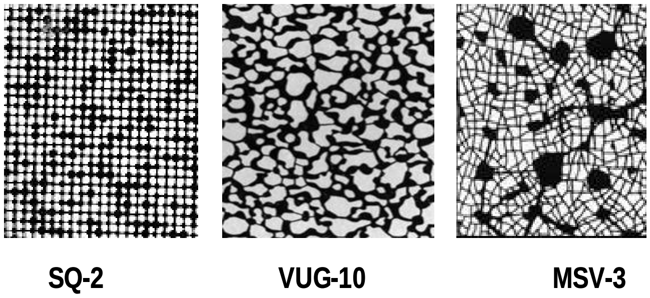

SQ-2 **VUG-10** **MSV-3**

Fig. 2: Typical pore structure features in some of the glass micromodels used in this study

Oil Bank Injection and Video-Recording of Displacements: The micromodel was first cleaned with acetone to displace any oil or residue left inside the model from a previous experiment and then cleaned with a detergent formulation for cleaning glass (diluted Contrad 70). Then water was flushed through the model with a syringe at a high velocity. The oil (dyed blue or red) was injected next at high velocity to fully saturate the model with oil and thus establish the initial oil conditions with some residual wetting phase trapped in the model. After this, free imbibition of colourless (or lightly coloured) water was performed by introducing the water manually with a syringe as an island of water pool above the inlet port of the model and allowed to proceed until water breakthrough. This usually took about 10 to 15 minutes in our micromodels and corresponded to a capillary number ($v_W \mu_W/s$) of about 5×10^{-5}, where v_W is the pore velocity of water. After a micromodel was waterflooded by free imbibition, C-clamps with 1/8 inch tube fittings were fastened to the inlet and

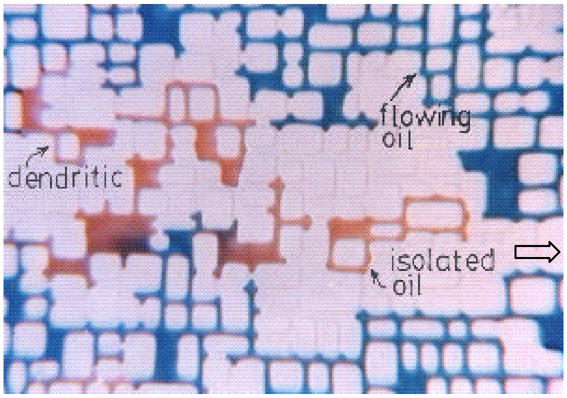


Figure 3: Pore scale visualization of the dendritic oil, isolated oil and flowing oil in micromodel RBS-1

outlet ports of the micromodel for carrying out the oil bank injection experiments. Constant flow rate injection for solvent/water slugs into the micromodel was used through-out a test. For experiments that dealt with the investigation of the effect of slugs of solvent alternating with slugs of water (SAW process) on the accessibility of residual oil, the micromodels had two inlet ports forming a T connection etched in the micromodel inlet junction: one for water injection and one for solvent injection. A syringe containing the blue oil (or red oil) that simulated the solvent and a syringe containing water for the SWA process were placed on the syringe pump. The tubing from each syringe was connected to the model at the injection port via a three-way valve (the third port of the valve was used for venting).

Video-recording and image analysis aspects: With a model at waterflood residual oil conditions (the residual oil dyed red or blue dye), all portions of the micromodel were video-recorded while the model was set on a light-table. After this, the syringe pump was started and only the blue (or red) oil simulating the solvent was injected into the model. As soon as the coloured solvent oil was seen to enter the model, the stopwatch in the video camera was started and recording began. For every part of the model that was image analyzed, that part of the model was video-recorded for a few seconds. During this period, the time display on the TV monitor screen was eliminated, so that it would not interfere with the pore structures in the field of view. The video-recording was continuous until the oil bank breakthrough point and thereafter for detailed visualization analysis of the history of residual oil accessibility. After several pore volumes of oil bank solvent were injected, the solvent injection was stopped. Immediately, the water slug was injected into the model to waterflood the oil bank in the model at the same velocity by switching to the vent position on the 3-way valve for the oil, and to the injection position for water. The recording procedures were repeated until the end of the experimental run with the water slug chasing the solvent. Images of a portion of the model were taken at the fully water saturated and at waterflood residual oil conditions, respectively. The area of all the pores in view in an image and the area of pores with oil trapped was measured using image analysis software. The area of pores with waterflood residual oil expressed as a percentage of the total pore area in view was taken as the waterflood residual oil saturation in the image analyzed. Results of image analysis from selected two to four portions of a micromodel were averaged to define the mean saturation for the entire micromodel. During constant rate solvent injection the displacement front position was monitored to determine the pore velocity of the advancing displacement front for a given pumping rate. For the prevailing flow conditions the capillary number was computed using the pore velocity and the known fluid properties of the water, solvent and oil. The propagation of injected solvent and the evolution of the state of the oil phase in the oil bank as a function of time was monitored by image analysis of selected portions of the oil-bank in a micromodel edited from the video-recording. A sample snapshot is shown in Figure 3 to illustrate the instantaneous state of the oil phase in the oil bank region. The pores filled with blue-dyed oil (darker colour) represent the injected solvent. The pores containing residual red-dyed oil (lighter colour) that communicate with the solvent appear in dead-end (dendritic) pathways. The volume fraction of waterflood residual oil held in dendritic pathways comprises the dendritic fraction of residual oil.

RESULTS AND DISCUSSION

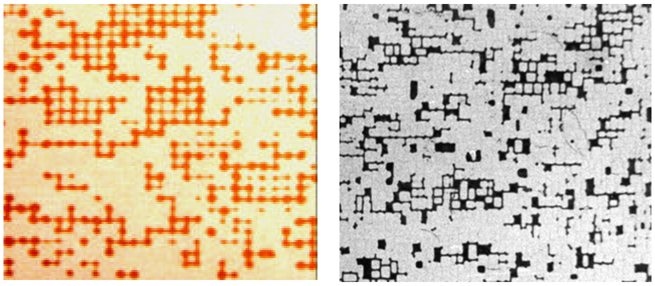
Table 1 summarizes the results of residual oil accessibility obtained using a large variety of micromodels with different pore structure and using different flow and fluid properties. Based on the results presented in Table 1, the following general observations can be made:

1. S^*_{or} varies significantly from model to model due to pore structure effects.
2. The higher the pore velocity, the higher the recovered fraction of the resident residual oil by flowing pathways in the oil bank.
3. The lower the interfacial tension, the higher the accessibility of the residual oil.
4. Pore structure plays a very important role in the recovery of the resident residual oil.
5. Wettability of a model is very important in determining the final recovery of the residual oil by oil bank. Oil-wet conditions result in high accessibility of residual oil.
6. Generally, no one single characteristic of a model can determine the final recovery.

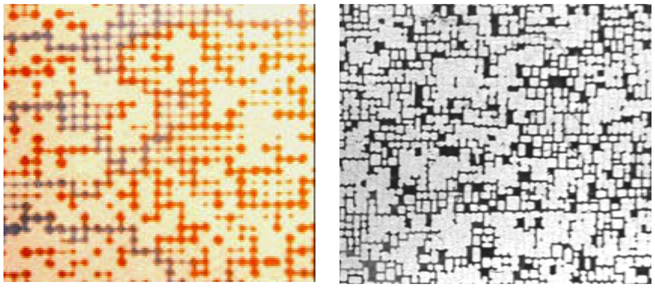
Table 1: Summary of residual oil accessibility results under various conditions

Model No.	Run No.	μ_s mPa.s	s mN/m	v_o cm/min	$N_{Ca,1}$ x10^6	S^*_{or} % PV	**% of the original residual oil remaining in the micromodel as isolated and as dendritic**		
							Isolated	**Dendritic**	**PVI**
SQ-2	1	0.98	22.9	0.64	4.55	53.1	27.1	40.7	2.5
MSV-3	1	0.98	22.9	2.28	16.70	50.8	36.8	15.8	3.3
	2	0.98	22.9	1.14	8.10	53.6	50.0	21.5	1.3
VUG-14	1	0.98	22.9	0.74	5.30	46.7	20.0	30.0	1.5
	2	4.70	2.07	2.00	757	32.0	0.5	0.0	1.6
	3	4.70	2.07	0.95	360	32.5	1.0	0.0	1.2
VUG-14 **(oil wet case)**	1	1.01	22.9	1.16	8.27	56.2	0.0	0.0	3.3
RBS-1	1	0.98	22.9	0.57	4.07	48.5	34.9	15.0	2.0
VUG-10	1	0.98	22.9	0.80	5.71	54.8	29.6	44.3	2.8
VUG-15	1	0.98	22.9	1.10	7.85	59.1	3.5	23.0	3.8
RBS-1	6	3		0.20			3	10	10
	2	3		0.25			3	8	10
	3	3		0.91			2.5	4.5	10
	4	3		2.95			0.3	0.0	10
RBS-1	9	0.3		0.15			4.4	8.3	10
	7	0.3		0.56			2.9	8.3	10
	8	0.3		1.07			1.3	5.4	10
SX-3	1	3		2.9			35	33	5
	2	3		5.7			25	24	5
SX-4	3	3		0.51			43	33	5
	2	3		3.4			29	22	5

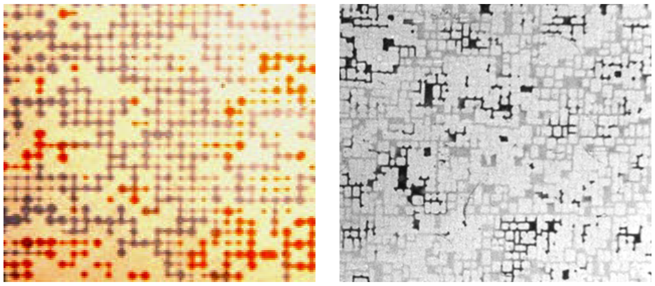
Note: Some runs with models RBS-1, SX-3, and SX-4 were conducted at constant pressure and were terminated after a certain volume of solvent was passed through. The capillary number conditions varied from start to finish continuously.



A: at waterflood residual oil conditions



B: at solvent breakthrough



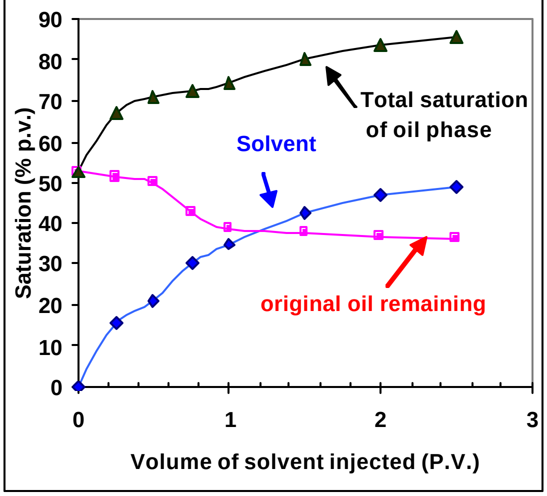
C: after 5 PV solvent injected **after 2PV injected**

Fig 4: Residual oil accessibility in micromodels SX-4 (left) and RBS-1 (right)

Additional observations will be discussed by outlining the experiment performed in each model, the pore structure of the model and the microscopic distribution of the resident residual oil at waterflood conditions and thereafter, the injection of a simulated oil bank. Snap-shots of the oil bank reconnection processes were taken, as shown in Figure 4. Each picture represents only a portion of the micromodel and shows a view of about 3 - 5 cm long of the real model, depending on the micromodel size. Micromodel SX-4 is a square network type of pore interconnection having a random distribution of pore sizes, as shown in Figure 4. The residual oil was varsolene dyed red. Upon solvent injection (blue varsolene), breakthrough occurred at about 0.2 pore volume (PV) injected. The solvent injected (blue oil) appears lighter in the picture than the red residual oil. As can be seen from Figure 4, the solvent tried to establish a continuum in the larger pores connected by larger pore throats (normally, large pores trap residual oil in a water-wet reservoir), thus bypassing a substantial amount of resident residual oil. This phenomenon contributes to the early solvent breakthrough. With continued solvent injection, the solvent in the trailing end of the oil bank entered smaller pore throats because the capillary pressure increased as the water content decreased. The presence of isolated red oil and dendritic oil (appear darker in a B&W print of Figure 4) is seen even after significant pore volumes of solvent were injected.

Model SQ-2 was another micromodel containing a square network type of pore interconnection with pore sizes randomly distributed (Figure 2). Visualizations of oil bank solvent injection were similar to those in micromodel SX-4 shown in Figure 4. Quantitative results of total oil saturation, solvent saturation and reduced residual oil saturation in the model as a function of solvent pore volume injected are shown in Figure 5. The curve designated as 'original oil remaining', represents the resident residual oil still left in the model and is the reduced residual oil saturation after solvent flooding. The curve 'solvent' is the saturation of the solvent in the oil bank. The 'total saturation of oil phase' curve is the sum of the solvent saturation in the oil bank and the residual oil saturation

Fig.5: Evolution of oil phase saturation in model SQ-2 after solvent injection



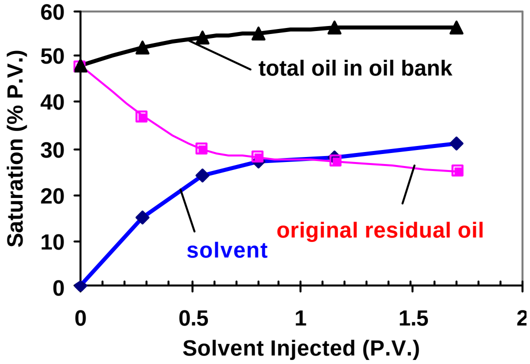


Fig. 6: Evolution of oil phase saturation in micromodel RBS-1 after solvent injection

remaining in the medium as dendritic and isolated oil at a particular time of displacement. The saturation values seen on the plots right after the start of solvent injection correspond to the solvent breakthrough condition. For the case of micromodel SQ-2, the resident residual oil was reduced from the 53% P.V. waterflood residual oil saturation in model to only 36% PV due to the wide pore size distribution and due to the low capillary number conditions used.

Micromodel RBS-1 is a network model characterized with high aspect ratio pores (pore body to entry pore throat size) randomly distributed and has a narrow distribution of pore throat diameters, however, the length of pore throats varied (see figures 3, 4). Note that the length of residual oil ganglia is longer along the direction of flooding. The solvent entered from left to right and reconnected the oil ganglia without entering that much into pore space where water had imbibed during waterflooding because of the very low capillary number at the front of solvent slug (4.1×10^{-6}). The breakthrough of the solvent was observed at 0.27 PV of solvent injection. The evolution of oil phase saturation during solvent slug injection in this model is shown in Figure 6.

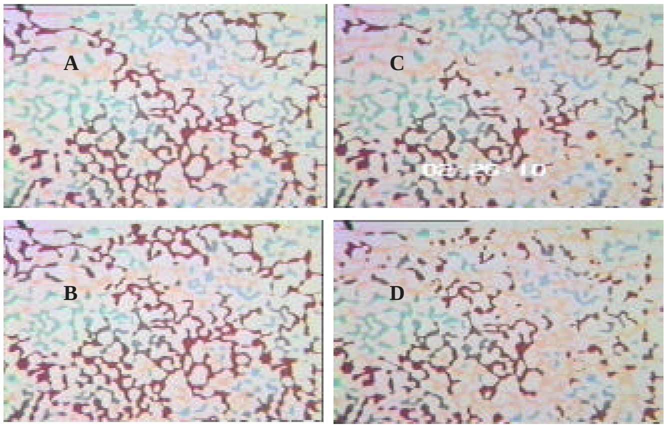


Fig. 7: Various states with SAW operation in model MSV-3: A. stage after 1st solvent slug; B: at 2nd solvent slug; C : after the 2nd waterflood; D: after the 3rd waterflood

Micromodel MSV-3 is a random network of pores with a distribution of throat sizes and pore body sizes, as seen from pore features in Figure 2. Different flow rates of 0.02 and 0.04 mL/min were used, respectively. An additional run that simulated a solvent alternating with water (SAW) process mode was made at the flow rate of 0.02 mL/min. Solvent breakthrough occurred after 0.21 PV solvent injection when the injection rate was 0.04 mL/min and at 0.38 PV for the 0.02 mL/min flow rate. It was noted that the breakthrough PV for the higher flow rate was smaller than that for the lower flow rate (0.02 mL/min) due to capillary fingering phenomena. With other conditions being the same (wettability, fluids, pore structure), the difference in solvent amount to reach breakthrough is due to the effect of capillary number. Subsequent waterflooding and solvent flooding was carried out in the SAW mode of operation at 0.02 mL/min. Greater reduction in resident residual oil was achieved after the oil bank was followed by a second waterflood, however, a significant amount of solvent always was trapped like waterflood residual oil after waterflooding. Qualitatively, more slugs of SAW did not improve the final recovery of the resident residual oil (see Fig. 7). The residual oil changed from 32.2% to 26.7% PV for the case of 0.04 mL/min and from 42.3% to 38.3% PV for the case of 0.02 mL/min.

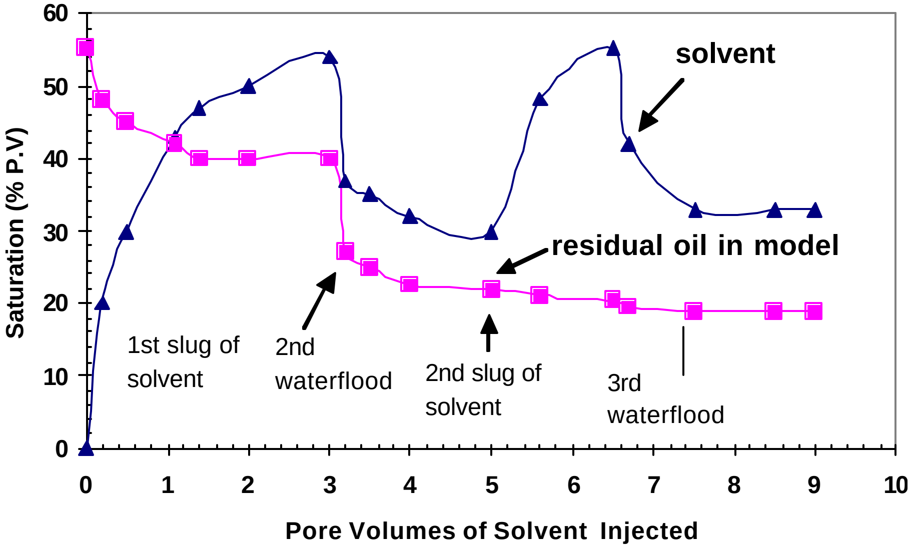


Fig. 8: Accessibility of residual oil in micromodel Vug-10 when slugs of solvent alternated with slugs of water in SAW mode of operation.

Micromodel VUG-10 is a model with randomly distributed pores. A low injection flow rate (0.01 mL/min) was used. Alternate slugs of solvent and slugs of water were injected. During the first slug of solvent injection, the solvent breakthrough occurred at approximately 0.25 PV. The entire displacement process was image analyzed and the results are shown in Figure 8. The region up to 3 PV injected in Figure 8 represents the first slug of continuous solvent injection. It was observed that the resident residual oil was continuously reduced with each injection while the total residual oil in the model changed from 55% to 47.6% PV after the 2nd waterflooding.

Micromodel VUG-14 has a network of vuggy pores randomly distributed. Some of the vugs are interconnected by a continuum of large pore throats and others are completely surrounded by much smaller pore throats. The vugs are much larger than the throats. Different injection flow rates of 0.0075 mL/min and 0.02 mL/min were used. Also, slugs of solvent followed by slugs of water were injected to investigate the effects of slugs on the accessibility of oil residual oil. The solvent saturation at breakthrough for the flow rate of 0.0075 mL/min was smaller than that when solvent was injected at 0.02 mL/min, as seen in frames B and D in Fig. 9. Looking at Figure 9, only one

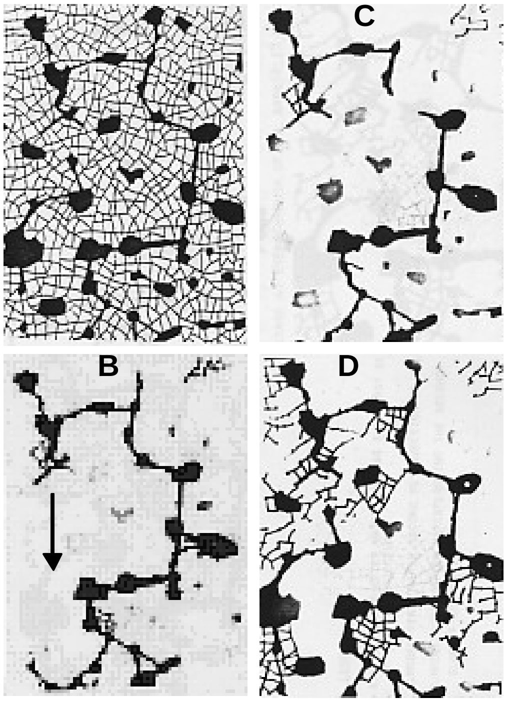
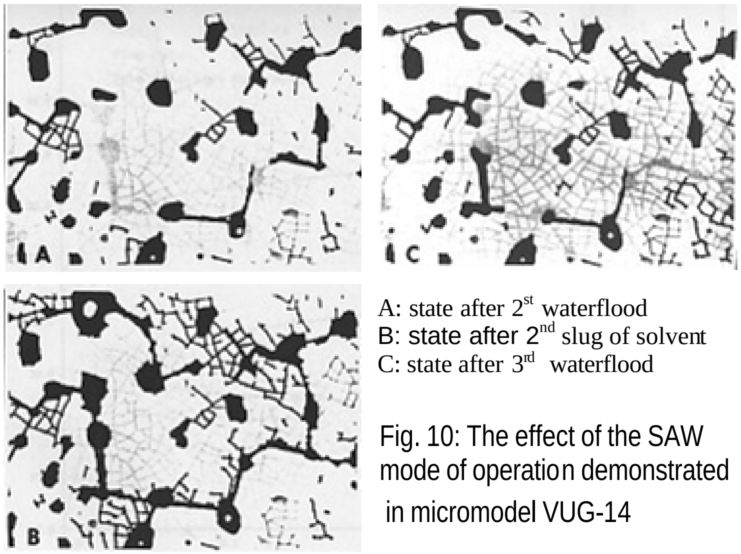


Fig. 9: Illustration of the effect of injection rate in the water-wet micromodel VUG-14

pathway along the largest pore throats and vugs was found at the lower flow rate. A second waterflooding apparently did not succeed in recovering much of the oil (shown in Figure 10, frame C). The results from the digitized image for the run at 0.02 mL/min (first slug injection) show that the oil saturation in the oil bank remained constant after solvent breakthrough. Higher viscosity and low IFT solvent was also used in model VUG-14. Isobutanol was used as the oil phase to function both for the residual oil phase and the miscible solvent phase. Visualization pictures for flow rates of 0.01 and 0.02 mL/min, respectively, show that the residual oil reconnection was nearly complete for both runs. Unfortunately, more oil was trapped when waterflooding the slug of solvent in the oil bank than that during the first waterflood [8]. Therefore, when a slug of water follows a slug of solvent without having established a low IFT value at the trailing-end of solvent, the oil recovery is strongly affected in a solvent miscible enhanced oil recovery (EOR) process.



A: state after 2st waterflood
B: state after 2nd slug of solvent
C: state after 3rd waterflood

Fig. 10: The effect of the SAW mode of operation demonstrated in micromodel VUG-14

Micromodel VUG-14 was also used to study the effect of wettability on oil bank reconnection during solvent injection. Under “oil-wet conditions”, the residual oil is trapped in the relatively small pores or clusters of pores accessible to the nonwetting phase through entry via the relatively small pores[2,15]. The water simulated the oil in an oil-wet reservoir and the oil used in this experiment represented the water when waterflooding an oil-wet reservoir. For an injection flow rate of 0.04 mL/min the breakthrough occurred at 0.47 PV. Compared with the runs simulating water-wet conditions in Figure 9, the pore volume of solvent injected up to the breakthrough time was larger in the oil-wet conditions, due to the effect of wettability that causes lower dispersion of the solvent. In oil-wet conditions, the solvent seeks a continuum in the smaller pores (during a secondary imbibition displacement) and also enters into larger pores. The displacement front was relatively more uniform by comparison to that observed under water-wet conditions. The accessibility of residual wetting phase by a solvent (also the wetting phase) was seen to be complete. It was observed in the oil-wet case experiment that after about 5 PV of solvent injected into the micromodel, the residual wetting phase was displaced completely. Therefore, the residual oil is 100% accessible by the oil bank under oil-wet conditions in a reservoir even in heterogeneous micromodels with the pore structure of model VUG-14.

Micromodel VUG-15 had a wide distribution of both pore bodies and pore throats, and trapped over 50% PV residual oil. Vuggy pores are high aspect ratio pores and also have high pore coordination number. Solvent breakthrough in this micromodel occurred at 0.25 PV, similar to other water-wet cases in other models. However, due to the high pore coordination number of vuggy pores that trapped residual oil in this micromodel, the residual oil ganglia were accessed by the solvent better than in other micromodels (see Table 1), leaving only 3.5% of the original residual oil in the form of isolated oil.

The effect of capillary number in miscible solvent flooding is very significant as seen from Table 1. In water-wet systems, having high capillary number at the front of the oil bank ensures higher accessibility of the residual oil, while the isolated fraction of residual oil in the oil bank becomes much smaller compared to displacements with low capillary number conditions. However, efficient recovery of oil in the oil bank is affected by the capillary number at the trailing-end of the solvent slug. For achieving high recovery it is required to have low interfacial tension values as the slug of water displaces the slug of solvent.

Pore structure affects both the magnitude of residual oil as well as the accessibility of residual oil for low capillary number conditions. In general, early solvent breakthrough is a characteristic of a water-wet and heterogeneous pore structure. The larger the pore volume of solvent injected, the higher is the accessibility of residual oil as well as the extent of recovering the dendritic oil by diffusion mechanisms. When comparing the effect of capillary number on residual oil accessibility to the effect of solvent slug size, direct flow visualizations show that the effect of capillary number is more important than solvent slug size in water-wet systems. The residual oil is readily accessed by the solvent under oil-wet conditions; however, for efficient oil recovery the water slug chasing the solvent must have a low interfacial tension value for high capillary number conditions.

Experiments conducted with solvent injection at constant pressure in micromodels RBS-1, SX-3, and SX-4 have shown that the accessibility of residual oil improves at higher pore velocities. When the viscosity of the solvent is smaller than the viscosity of residual oil, viscous fingering phenomena in the oil bank are important and the residual oil accessibility becomes a bit more difficult (see Table 1, RBS-1 run 6 versus run 9). The results obtained with solvent injection at constant pressure indicate that the accessibility of residual oil was better than that when the solvent was injected at constant rate. More detailed examination is required to evaluate systematically what is the effect of mode of operation (constant rate versus constant pressure solvent injection) on residual oil accessibility in solvent miscible flooding.

CONCLUSIONS

1. Residual oil reconnection by the oil bank in various water-wet 2-D micromodels varied significantly (30% up to 99%) depending on pore structure and flow conditions.
2. Wettability was found to be a very important parameter. In oil-wet systems, the residual oil accessibility at the pore scale is always complete because the resident residual oil maintains hydraulic continuity throughout after waterflooding.

3. Direct visualizations of residual oil accessibility in water-wet micromodels have shown that after injecting a 3-4 PV slug of solvent, there is no further accessibility of isolated residual oil. The isolated oil in water-wet conditions is a very significant fraction of the original residual oil when low capillary conditions prevail.
4. Alternating slugs of solvent with slugs of water (SAW) in water-wet media does not increase the accessibility of the resident residual oil after the second slug of solvent.
5. Capillary number is a very important parameter in determining maximum recovery in solvent miscible flooding. The higher the capillary number, the higher the accessibility of the residual oil by the oil bank. The effectiveness of the slug of water chasing the solvent slug also depends on capillary number conditions.

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