[Regular Paper]

The Role of Initial Gas Saturation in Tertiary Oil Recovery by Micellar Solution

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(Received January 9, 1991)

The principal objective of this research is to understand and determine the role of initial gas saturation in tertiary oil recovery by use of a micellar solution.

For this study, relatively high permeability (about 275 md) Berea sandstone cores were employed. All displacement runs were tertiary in nature. All of these runs were carried out in horizontally positioned cores.

It was found that tertiary oil recovery increased with increasing initial gas saturation, up to the optimum value of 15% PV; thereafter, it showed a decrease with further increase in gas saturation. Reduced sulfonate adsorption and relative permeability to oil were obtained in the presence of gas phase. The optimum slug size, the stabilized oil–water bank, and micellar slug recovery were found to be a function of initial gas saturation.

Effects of initial gas saturation on oil recovery are discussed and analyzed in terms of micellar slug adsorption, relative permeability, viscous and capillary forces, and mobility control. The effect of initial gas saturation on the formation of the stabilized oil–water bank has also been used in this analysis.

1. Introduction

Laboratory tests^{1)~5)} have shown that oil recovery by conventional water flooding is improved as a result of the establishment of free gas saturation in the oil reservoir. It is proposed that since the interfacial tension of a gas–oil system is less than the interfacial tension of a gas–water system, the reservoir fluids, in a three phase system will tend to arrange themselves in a minimum energy relationship. In this case, this would indicate that the gas molecules enclose themselves in oil globules. If any gas bubble existed inside the oil globule, the amount of residual oil left in the reservoir would be reduced by the size of the gas bubble within the oil globule.

Owens *et al.*⁶⁾ were found that rock wettability played an important role in the waterflooding process. In the water-wet sandstone, water would preferentially be pulled into the smaller pore spaces by capillary action, and the residual oil would hence be located in the larger pore spaces. At some later time, when gas is flooded through the core, it moves preferentially through the larger pore spaces since it is nonwetting. However, in passing through these large pore spaces, the gas displaces some of the residual oil left by water displacement⁷⁾.

It is known that the presence of gas saturation would drastically limit liquid phase (oil and water)

relative permeabilities. The effect will be serious in the case of a tight, low permeability porous medium. However, the resulting high pressures necessary to maintain fluid flows at the designed rates may cause collapse of gas saturation in the oil phase. Thus, the effect of gas saturation on micellar solution flooding would be governed indirectly by the injection rate. More directly, the oil bank saturation. The main objective of this research is to investigate the role of initial gas saturation on oil recovery by micellar flooding. The results of this study will be helpful in selecting the field injection rate and operating pressure range for a given set of conditions that will maximize oil recovery.

2. Experimental Work

The experimental work performed in the present study was designed to investigate the effects of initial gas saturation on the micellar flooding process. The composition of the petrostep-465

Table 1 Composition of Petrostep-465 Surfactant

Active sulfonate	47.5%
Oil	12.9%
Water	34.4%
Inorganic salt	4.0%
Equivalent weight range	440—465
Density	[gm/cc] 0.9—0.94

Composition of the micellar slug used in displacement: 40% polymer solution+40% crude oil+20% Petrostep-465.

Table 2 Physical Properties of Fluids Used

Fluid	Specific gravity	Viscosity [cp]	Interfacial tension between oil and fluid [dyne/cm]
Crude oil	0.83	6.0	—
1% NaCl brine	1.0	0.95	12.0
Micellar slug	0.945	see Fig. 2	1×10^{-3}
Polymer solution	1.01	see Fig. 2	—

Table 3 Properties of the Porous Media

Type of cores	Berea sandstone	
Core length	[ft]	1
Core diameter	[in]	2
Average porosity	[%]	20
Average permeability	[MD]	275

micellar solution used for displacement is shown in Table 1. The properties of the different liquids used are presented in Table 2. Berea sandstone cores were used as porous media having the properties shown in Table 3.

2.1 Displacement Apparatus

The displacement apparatus is schematically shown in Fig. 1. The apparatus is grouped into the following operational systems:

a) Flow System

The main purpose of this system is to conduct oil and water into the core samples. The fluid is

driven from the pressure multiplier accumulators into the mercury reservoir; the mercury then pushes the oil (or micellar solution) into the core sample. The oil is filtered before entry into the core sample.

b) Overburden System

The overburden system controls the confining pressure applied with a hand pump using water as the pressure medium to the core sample.

c) Backpressure System

The backpressure system is connected to the downstream end piece of the core holder and it resists the upstream pressure. The pressure from a nitrogen tank is multiplied in the small panel mounted pressure multiplier and applied to the backpressure regulator.

2.2 Displacement Procedure

A core sample was cleaned and evacuated; it was then saturated with water (or brine) under vacuum.

Fig. 1 Displacement Apparatus

Complete saturation with water (or brine) was carried out when two pore volumes of water (or brine) were injected and passed through the Berea sample, and the absolute permeability was then calculated by measuring the flow rate of water, or brine at a given pressure drop across the core.

Water (or brine) was displaced by oil, and the process was continued until two pore volumes of oil were injected. The core was believed to contain irreducible water saturation, at this point. Oil was displaced by injection of two pore volumes of water (or brine) until the residual oil was established. The assigned initial gas saturation was then injected. Air was used as the gas phase.

A tertiary process started with injecting a slug of micellar solution. The slug sizes used in displacement runs were 5, 10, and 20% PV. The micellar slug was then driven by 50% PV of 500 ppm-pusher-500 polymer solution. Displacement process was stopped after injection of about one pore volume of brine. After the run was completed, the apparatus was cleaned well, dried, and left for twenty four hours to prepare it for the next run. The collected samples were then left, undisturbed overnight, to allow time for the two phases to separate. After separation, the oleic phase was analyzed with an infrared spectrophotometer to determine the percent of sulfonate in the oleic phase. The amount of gas produced was measured with a wet-test meter. Tertiary oil recovery was then determined by the following Eq. (1):

$$\text{oil recovery} = \frac{V_{om}}{V_{oi}} \quad (1)$$

where:

Fig. 2 Rheological Behavior of Micellar and Polymer Solutions

V_{om} = amount of oil produced during micellar flooding,

V_{oi} = oil in place just before micellar flooding.

2. 3 Measurement of Micellar Solution Adsorption

A series of displacement experiments was devoted to study micellar solution adsorption with and without the presence of gas inside the Berea core, which was saturated first with brine. Assigned initial gas saturation was then established. One pore volume of the micellar solution was then injected. The resulting micellar was then analyzed with an infrared spectrophotometer to determine the percent of sulfonate in it. This value was then compared with the percent of sulfonate in the original solution. The difference between the two values is the percent of sulfonate adsorbed.

2. 4 Measurement of Relative Permeability

A Berea sandstone sample was evacuated for about five hours and then saturated with brine. The sample was transferred to the core holder and the required confining pressure was applied. Brine was displaced by oil, and the process was continued until no brine was produced. The initial gas saturation was then established. Water was then injected to displace the oil. Individual samples were collected and then measured for certain periods of time at the given pressure drop.

3. Results and Discussion

The basic objective of this investigation is to study the effect of initial gas saturation on tertiary oil recovery by use of a micellar solution. The following results and discussion are an effort to systematically examine the effect of initial gas saturation on the mechanics of displacement of oil and water by a micellar slug. A summary of the experimental results is presented in Table 4.

3. 1 Design of Micellar Slug Used in Displacement Tests

A pseudoternary diagram for the micellar slug-crude oil-brine system tested was obtained on the basis of phase properties of a large number of samples chosen on the ternary diagram. Figure 3 is a ternary diagram of the petrostep-465 micellar-crude oil-sodium chloride brine system. Since it is necessary to add a polymer slug to displace a micellar slug, the polymer will mix with the micellar solution to the extent that depends on composition and type of the surfactant concentration and type of the polymer, the type of crude oil displaced, and the distance traveled by the micellar slug. Therefore, a phase diagram of the petrostep-465 micellar-crude oil-polymer (500 ppm-pusher 500) system was constructed as seen in the

Table 4 Summary of Experimental Results

Run No.	Gas saturation [%PV]	Porosity [%]	Absolute permeability [md]	Pore volume [cc]	Oil saturation before water flooding [%PV]	Oil saturation before micellar flooding [%PV]	Maximum pressure [psi]	Micellar slug [%PV]	Tertiary oil recovery [%OIP]
1	0	20	270	117	64.3	27.7	30	10	47.30
2	2.5	19	260	126	70.0	27.9	25	10	62.85
3	5.0	20	290	133	65.3	28.3	30	10	65.96
4	10	21	280	131	75.9	29.5	30	10	69.15
5	15	20	275	128	65.9	24.4	30	10	80.71
6	20	20	250	121	75.8	34.5	25	10	68.45
7	25	20	300	121	65.3	29.6	25	10	42.28
8	0	19	270	125	62.4	33.3	30	15	48.08
9	0	20	280	158	60.4	27.5	30	20	50.30
10	15	20	275	158	53.0	21.2	30	15	70.20
11	15	21	300	115	70.9	35.0	30	20	73.40
12	0	20	275	147	63.1	21.9	30	5	18.20
13	15	21	260	129	70.9	38.4	25	5	55.61

Fig. 3 Phase Diagram of Petrostep-465 Micellar Solution/ Crude Oil/ Brine (or Polymer) System

same **Fig. 3**. As shown in this figure the main result of adding the polymer is that the two-phase region is decreased on the water-rich side, thus improving miscibility; on the oil-rich side, the two-phase region is increased thus reducing miscibility. This behavior is not reported in the literature, but may be useful in practical applications.

The effect of adding polymer is drastic. Other investigators⁷⁾ noticed that adding a polymer to the micellar solution reduced miscibility for water-rich and oil-rich sides. This was attributed to sulfonate-polymer incompatibility that depended upon several factors including salinity, polymer concentration, and the concentrations of both surfactant and Co-surfactant. It is believed that the reduction of the single-phase region noticed on the oil-rich side is due to the interactions of these factors.

The composition of the injected petrostep-465 micellar slug used in displacement tests is, therefore, represented by point 0 on the phase diagram shown in **Fig. 3**. This includes 40% crude, 40% polymer, and 20% petrostep-465.

3.2 Optimum Slug Size

The experimental plot of tertiary oil recovery as a function of slug size for Berea sandstone cores with no initial gas saturation is shown in **Fig. 4**. It is evident that recovery increases with increasing slug size. This behavior is attributed to the higher amounts of sulfonate associated with larger slug sizes.

A method has been reported in the literature for determining the optimum slug size⁸⁾ which is

Fig. 4 Effect of Slug Size on Tertiary Oil Recovery for 0% and 15% Initial Gas Saturation

defined as the slug size that will maximize the profits, other things remaining constant.

The point of tangency of a straight line having a slope of $[C_s / (S_o P_o)]$, on the oil recovery versus slug size curve, represents the optimum slug size (Fig. 4), where C_s is the cost of injected slug, \$/bbl; S_o is the average oil saturation before start of flood, and P_o is the price of oil, \$/bbl.

Based on the oil price of \$20/bbl, $C_s=22/\text{bbl}^{(9,10)}$ and S_o (average saturation obtained from displacements)=0.31, the optimum slug size is 10% PV as shown in Fig. 4. This slug size was used to investigate the effect of initial gas saturation on oil recovery.

3.3 Effect of Initial Gas Saturation on Tertiary Oil Recovery

Figure 5 shows the variation of oil recovery with gas saturation. Oil recovery increases with increasing initial gas saturation, up to an optimum value at 15% PV. Thereafter, it shows a decrease with further increase in gas saturation. This is also seen from the production histories of the displacement runs shown in Fig. 6. The interpretation of this effect in the light of the mechanisms presented is given in a subsequent section and after discussing the different mechanisms that interplay in the displacement process. The variation of tertiary oil recovery with micellar slug size in the presence of the optimum gas saturation (15% PV) is shown in Fig. 4. It is seen that oil recovery increased with increasing slug size; however, it decreased slightly with higher slug sizes. It is also seen from Fig. 4 that the optimum slug size (8% PV) in the case of 15% gas saturation was less than that obtained when there was no gas.

Fig. 5 Effect of Initial Gas Saturation on Tertiary Oil Recovery

Fig. 6 Cumulative Oil Recovery Versus Pore Volumes Injected for Different Gas Saturations

3.4 Effect of Initial Gas Saturation on Micellar Slug Adsorption

One of the difficulties associated with tertiary oil recovery is that the surfactants, the polymers and the other materials added to the flood solution can be adsorbed onto the surface of the porous media. If such adsorption occurs, it may be difficult to maintain the physical properties. Studies have shown that this adsorption phenomenon is rather complicated⁽¹¹⁾. A series of experiments to determine if the adsorption of the micellar slug used in displacement tests is affected by presence of the gas phase. Figure 7 shows the variation of micellar slug adsorption in the absence and in the presence of gas phase with time (or pore volume). It is apparent from this figure that sulfonate adsorption in the presence of gas phase decreased. This result was not reported in the literature, and it

Fig. 7 Effect of Initial Gas Saturation on Adsorption of Micellar Slug

Fig. 9 Effect of Initial Gas Saturation on Relative Permeability to Oil and to Water (gas saturation below its critical value)

Fig. 8 Effect of Initial Gas Saturation on the Production Histories of Micellar Slug

Fig. 10 Relationship between Initial and Residual Gas Saturation

may be attributed to the possible changes in the rock properties in the presence of gas phase.

This finding is confirmed by the results of the production histories of the micellar solution shown in Fig. 8. It is seen from this figure that the micellar solution produced increases with increasing initial gas saturation. This may indicate less adsorption at high values of gas saturation. At the same time, the figure depicts the early breakthrough of micellar slug at higher initial gas saturation.

3.5 Effect of Initial Gas Saturation on Relative Permeability to Oil and Water

Figure 9 shows the variation of relative permeability to oil and water with water saturation

in the presence of 0, 5, and 20% initial gas saturation. It is assumed that the gas phase is below its critical value (*i.e.* immobile). This assumption is justified by determining the relationship between initial gas saturation and residual gas saturation as shown in Fig. 10. It is seen from the figure that the values of initial and residual gas saturation were not varied in the ranges used in the present experiments.

Figure 9 depicts that relative permeability to oil was reduced by increasing gas saturation. At low gas saturation the relative permeability to oil was slightly affected.

3.6 Effect of Initial Gas Saturation on the Stabilized Oil-Water Bank

It can be said that the formation of the stabilized oil-water bank is governed by the change in gas saturation. This can be seen from Fig. 11, in

Fig. 11 Cumulative Oil Recovery (linear part) vs. Pore volumes Injected for Different Gas Saturations

which a plot of cumulative oil recovery versus the pore volumes produced at different initial gas saturations is shown. The pore volumes produced at the termination of the linear oil recovery will be denoted as PV_L . By linear oil recovery, it is meant the recovery obtained from the stabilized oil-water bank and before the micellar slug breakthrough. It is seen from the figure that the value of PV_L increases with increasing initial gas saturation up to 15% gas saturation, thereafter, a sharp decrease in PV_L with further increase in gas saturation. This indicates that at higher gas saturation the possibility of forming the stabilized oil-water bank is small. This conclusion is supported by the pore volumes produced at the breakthrough of oil-water bank shown in Fig. 12. It is evident that early oil-water bank breakthrough occurred at high gas saturation indicates bypassing of the core residual oil and water by the micellar slug front. Figure 12 also shows that the oil-water bank is stabilized more at the optimum initial gas saturation.

3.7 Role of Capillary and Viscous Forces and Mobility Control

Capillary and viscous forces play an important role in the movement of oil and water through a porous medium¹²⁾. The most important variable in this regard is the capillary number N_c defined as the ratio between viscous forces, F_v , to capillary forces, F_c , and it can be written as:

$$N_c = F_v / F_c = \mu V / \phi \gamma \quad (2)$$

where,

μ = viscosity, ϕ = porosity,

V = superficial velocity, γ = interfacial tension.

Fig. 12 Effect of Initial Gas Saturation on the Production Histories of Oil Bank

If this ratio is sufficiently high, more residual oil will be produced. This, in fact, recognizes the importance of viscous and capillary forces in the displacement process. At high values of initial gas saturation the viscosity of oil will be lower due to the high pressure gradient. This will lead to decreasing the capillary number as can be seen from Eq. (2), and hence decreasing the oil recovery at high values of gas saturation. On the other hand, adequate mobility control is an important requirement for the micellar-polymer displacement process. In order to obtain a favorable mobility ratio, the mobility of the buffer and micellar slugs must be equal to or less than the total mobility of the oil-water bank, *i.e.*,

$$[(K_{rpm} / \mu_{pm})] / [(K_{ro} / \mu_o) + (K_{rw} / \mu_w)] \leq 1 \quad (3)$$

where K_r is the relative permeability and μ is the viscosity (o, w, and pm refers to oil, water and polymer micellar, respectively).

3.8 Interpretation of Initial Gas Saturation Effect on Tertiary Oil Recovery in the Light of the Mechanisms Presented

Figure 5 shows the variation of tertiary oil recovery with initial gas saturation. As indicated before, oil recovery increases with increasing initial gas saturation, up to an optimum value (15%); thereafter, it decreases with further increase in gas saturation.

There are many mechanisms (capillary and viscous forces, mobility control, adsorptions and oil-water bank formation) that play an important

role in the interpretation of the effects obtained of initial gas saturation on oil recovery leading to the optimum shown in **Fig. 5**.

The recovery increase may be due to the reduction in micellar slug adsorption in the presence of initial gas saturation leading to a more enhanced preservation of the integrity of the micellar slug.

The increase in oil recovery with increasing initial gas saturation from 0 to 15% may also be attributed to the favorable mobility resulting from the reduction in oil viscosity due to the gas and its additional sweeping or driving action.

On the other hand, the relative permeability changes discussed before, play an important role in the interpretation of the behavior obtained at high values of initial gas saturation. It can be seen that the presence of gas saturation inside the oil phase will reduce the relative permeability to oil which exists at any water saturation as shown in **Fig. 9**.

In addition to the relative permeability characteristics, the behavior of the stabilized oil-water bank at different values of initial gas saturation explains the results of low oil recovery at high values of gas saturation. Also, this result is supported by the early breakthrough of the micellar slug observed at high values of gas saturation.

4. Conclusions

Displacement runs were carried out wherein petrostep-465 micellar slugs were injected at initial gas saturations in the range from 0 to 25% PV into waterflooded one-foot Berea sandstone cores. The following conclusions obtained are:

- 1) Polymers improve miscibility on the water-rich side, but they decrease it on the oil-rich side.
- 2) Tertiary oil recovery was found to be dependent on initial gas saturation. It tends to increase with increasing gas saturation, up to an optimum value at 15% PV; thereafter, it shows a decrease with further increase in gas saturation.
- 3) Reduced sulfonate adsorption was observed in the presence of gas phase.

4) The optimum micellar slug size was found to be a function of initial gas saturation.

5) The oil relative permeability was reduced by increasing the initial gas saturation. At low values of gas saturation, the oil relative permeability was slightly affected.

6) The stabilized oil-water bank and its breakthrough time was a function of initial gas saturation.

7) Micellar slug recovery and its breakthrough were found to be dependent on gas saturation.

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要 旨

界面活性剤を用いた原油回収法における初期ガス飽和率の影響について

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本研究の主要目的は、界面活性剤を用いた原油二・三次回収における初期ガス飽和率の影響について理解することにある。

本研究においては比較的高浸透率（約 275 md）を有するベレア砂岩が使用されている。全ての実験は水攻後の三次回収条件下で実施された。また、コアは常に軸が水平になるように設定されている。

実験結果では、初期ガス飽和率が 15% のとき原油回収率が最大となった。また、ガスが存在する場合はスルホン酸塩の吸着量が減少するとともに、油相対浸透率の低下が見られた。最

適スラグサイズ、安定した油・水バンクサイズおよび界面活性剤スラグ回収率は初期ガス飽和率の関数となることが明らかとなった。

初期ガス飽和率の原油回収率への影響の原因について本論文では、界面活性剤スラグの吸着、相対浸透率、粘性力、毛細管圧力およびモビリティコントロールの各視点から議論し、分析している。さらに、初期ガスが安定した油・水バンクの形成に与える効果についても言及している。

Keywords

Tertiary oil recovery, Micellar solution, Initial gas saturation, Optimum slug size, Micellar slug adsorption