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Impact of Ultra-Low Interfacial Tension on Enhanced Oil Recovery of Ultra-Low Permeability Reservoir

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Abstract
Ultra-low permeability reservoirs have the characteristics of complex pore throat structure, generally higher injection pressure and lower oil recovery. By means of casting thin sections, pore structure of selected ultra-low permeability core was surveyed. The core was classified into low porosity, low permeability and without natural fractures. Vast majority of throats of the core varied in width from 2.5 μm to 15 μm. Core displacement experiments showed that surfactant flooding could have certain effect of reducing injection pressure and enhancing oil recovery. When interfacial tension was 5.93×10^{-2} mN/m, decompression rate reached 7.65%, and recovery was improved by 4.09%. And when interfacial tension was 4.9×10^{-5} mN/m, decompression rate reached 25%, and recovery was improved by 11.6%. The lower interfacial tension is, the better the effect of reducing injection pressure is, and the higher the extent of enhancing oil recovery is. In general, surfactants have a great application prospect on the oil field development of ultra-low permeability reservoir, and the interfacial tension should be reduced as far as possible.

Key words: Low permeability; Surfactant; Interfacial tension; Emulsion; Enhancing oil recovery

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INTRODUCTION
Ultra-low permeability reservoirs have the main characters of thin pore throats, large specific surface area, low permeability and strongly Jamin effect (Zeng *et al*., 2007). The seepage rule of ultra-low permeability reservoirs does not obey the Darcy's law, and there is a threshold pressure gradient (Zeng *et al*., 2010), which is different from that of middle and high permeable reservoirs (Yin *et al*., 2010). After injecting water, dispersed oil droplets remain in the pores of reservoirs, and cannot pass the minute pores. The oil phase of reservoirs flows by the way of small slugs or drops, instead of continuous flow. When the oil droplets pass narrow throats, the injection pressure rises due to resistance produced by Jamin effect. The water lock is easily formed after oil well operation, and the energy of ultra-low permeability reservoirs spreads slowly. So the displacement pressure of ultra-low permeability reservoirs is usually high, and water flooding is very difficult. Meanwhile, natural energy of ultra-low permeability reservoirs is insufficient. In short, the initial productivity is higher, production declines quickly and the ultimate oil recovery is low.

Surfactants can decrease interfacial tension of oil-water, improve the oil/water seepage characteristics, so reduce injection pressure and enhance oil recovery of ultra-low permeability reservoir. The mechanism of surfactant active mainly includes: reducing interfacial tension of oil-water, altering the wettability of rock surface (Adibhatia & Mohanty, 2007; Bortolotti *et al*., 2010; Seethepalli *et al*., 2004), emulsifying crude oil (Liu *et al*., 2006), increasing the surface charges, conglomerating oil drop, forming oil zone, changing the rheology of crude oil and so on. At present, scholars have done a lot of experimental studies about surfactants improving the development effect of low permeability reservoirs (Adams & Schievelbein, 1987; Sun *et al*., 2009). Manrique *et al*. (2006) found that current water flooding recovery was only 40-50% of the OOIP because of microscopic oil trapping and macroscopic bypassing. Torabzadeh and Handy (2006) found that surfactants could be used with injection fluids to increase recovery efficiency of immiscible displacements through reduction of interfacial tension, and the oil-water relative permeability increased by decreasing interfacial tension at given water saturations. Babadagli (2005) suggested the surfactant injection was recommendable in the pre-waterflooded unfractured zones as long as the proper surfactant type was selected. To use a surfactant solution for tertiary recovery, surfactant concentration, type and interfacial tension were important factors. Liu and Li (2006) found that reducing interfacial tension of oil-water of low permeability reservoirs could reduce additional capillary resistance, and increase relative permeability of water phase. Mohan (2009) studied the feasibility of oil recovery by surfactant flooding from an oil-wet carbonate reservoir. The unique features of the subject reservoir were high salinity and low permeability (2-5×10^{-3} μm^2). 80% OOIP was recovered using the surfactant which gave low interfacial tension (10^{-3} mN/m) in comparison to 60% from water flooding at similar pressure drops.

The study has showed reducing interfacial tension of oil-water is the most important mechanism of enhancing oil recovery (Edin *et al*., 2010), but it is not the only mechanism. Some people think that when interfacial tension is too low and emulsified oils are too small (Berger *et al*., 1988), the sweep efficiency of displacement fluid is not big and the recovery of ultra-low permeability core is not high. But others think that interfacial tension must reduce to 10^{-5} mN/m or even lower if necessary to activate the oils of ultra-low permeability reservoirs.

For ultra-low permeability core, the past study is less effort on the impact of ultra-low interfacial tension of oil-water on injection pressure and enhancing oil recovery. For this reason, in the first place, the distribution of pore structure, especially throats width, was studied by means of casting thin sections of ultra-low permeability core in this paper. Surfactant formulations of different levels of ultra-low interfacial tension were filtered out. The influence of ultra-low interfacial tension on reducing injection pressure and enhancing oil recovery of ultra-low permeability core was studied through the displacement experiments.

1. MATERIAL AND METHODS

1.1 Material

In this study, natural ultra-low permeability core of Shengli Oilfield was used, and formulated surfactants HFYQ-B were selected which contains 30% of active ingredients. We used the formation water of Shengli Oilfield, whose salinity was 1785 mg/L. The simulated oil was obtained by mixing diesel and crude oil of Shengli Oilfield with the proportion of 4:6, and its viscosity was 2.28 mPa·s at 50 °C. Many apparatuses, including TX-500 spinning drop interface tensiometer, reservoir simulation displacement equipment, electronic balance, etc., were applied in the experiments.

1.2 Providing Casting Thin Section

Natural ultra-low permeability core of Shengli oilfield was used to obtain casting thin section. Wash and dry the core, then cut it to get a cylindrical rock thin section whose thickness was about 2mm. The rock thin section was marked as core-1, while the remainder was marked as core-1'. Squeeze the blue organic resins into the rock thin section in condition of a constant vacuum. Polish it to get a casting thin section. Survey the pore structure of the section through a microscope and draw a throat distribution histogram of it.

1.3 Interfacial Tension Test

The surfactant HFYQ-B solutions of different concentrations with the formation water were prepared. Then interfacial tensions between the solutions and the simulated oil were measured by using the spinning drop interfacial tensiometer at 50 °C. The minimum value of dynamic interfacial tension was taken as evaluating indicator (Taylor *et al*., 1990). Surfactant formulations of different levels of ultra-low interfacial tensions were screened out.

1.4 Surfactant Flooding in Low Permeability Core

The basic data of core-1' are listed in Table 1.

Table 1
Basic Data of Core

Core No.	Length, cm	Diameter, cm	Gas log permeability, 10^{-3}μm^2	Water permeability, 10^{-3}μm^2	Pore volume, cm^3	Porosity, %
1'	8.03	2.50	0.52	0.07	4.05	13.5

The core whose gas log permeability was 0.52×10^{-3} μm^2, belonged to ultra-low permeability core. For the core-1', the impacts of ultra-low interfacial tensions of oil-water on reducing injection pressure and enhancing oil recovery were studied through core displacement experiments. Experimental temperature was 50 °C. And the flow chart is shown in Figure 1.

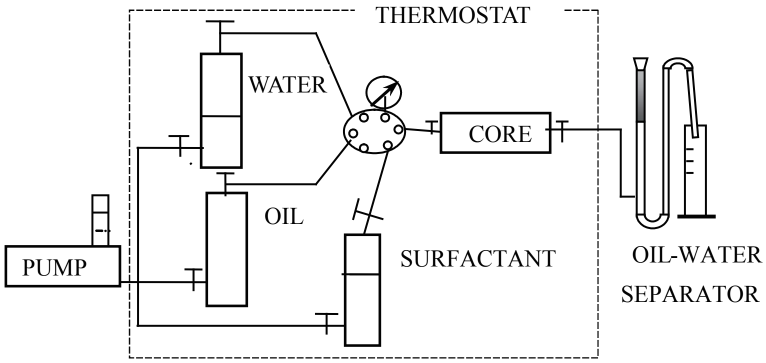


Figure 1
Flow Chart of Core Displacement Experiments

Experiment procedures were as follows:

(1) Weigh the core after drying it, then vacuumize and saturate it with formation water. Weigh again to calculate the pore volume of the core.
(2) Drive the core with formation water at a constant speed of 0.05 mL/min under a temperature of 50 °C.
(3) Drive the core with the simulated oil to irreducible water saturation, age 24 hours, record the volume of oil saturated, and calculate irreducible water saturation.
(4) Drive the core with the formation water at a constant speed of 0.05 mL/min, and stop experiment when water content was more than 98% at the outlet end. In this process, record pressure variation and cumulative oil production, and calculate the recovery of the first water flooding.
(5) Inject surfactant slug of certain interfacial tension into the core at a constant speed of 0.05 mL/min.
(6) The second water flooding was the same to the step (4).
(7) Wash and dry the core. Repeat the steps (1-6) of the experiment through changing interfacial tension of oil-water.

2. RESULTS AND DISCUSSION

2.1 Analyzing Casting Thin Section

The picture of casting thin section of core-1 is shown in Figure 2. Blue represented pore structure of the core.

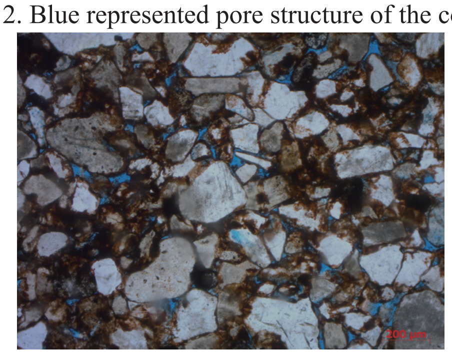


Figure 2
Picture of Casting Thin Section of Core-1

As shown in Figure 2, statistical analysis found that there were 124 pores in the casting thin section of core-1. Among them, there are 86 pores with diameters below 15 μm, 29 pores between 15 and 30 μm, and 7 pores between 30 and 45 μm in diameter, accounting for 69.35%, 23.387% and 5.645% of all the pores respectively. Yet, there are only 2 pores greater than 45 μm in diameter, which is about 1.61% of all the pores. The average pore diameter size is only 27.90 μm. The average ratio of pore to throat size is 0.63, the homogeneity index is 0.58, the sorting coefficients is 12.35, the area percent of pore of core is only 1.12%, and the average coordinate number is 0.35.

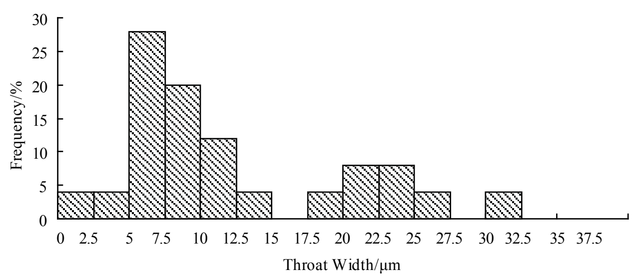


Figure 3
Throat Distribution Histogram of Core-1

The throat distribution histogram of core is shown in Figure 3.

As shown in Figure 3, the vast majority of throats varied in width from 2.5 μm to 15 μm. And only a few throats varied in width from 17.5 μm to 27.5 μm. The largest and the smallest diameter of throats are 30.8 μm and 1.14 μm respectively, and the average diameter is 12.36 μm.

Based on the above analysis, the core was characterized as low porosity, low permeability and without natural fractures.

2.2 Interfacial Tension Test

The interfacial tensions between the solutions and the simulated oil were measured at 50 °C. The relationship curve of interfacial tension with concentration is shown in Figure 4.

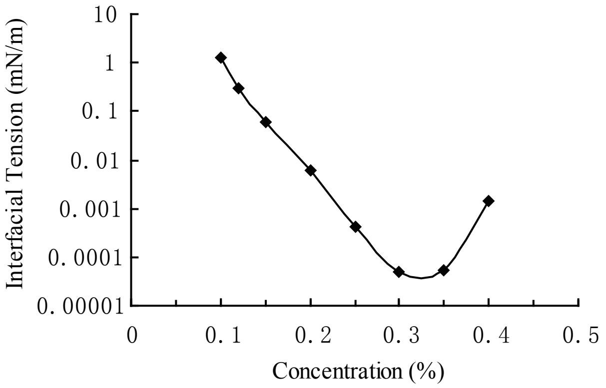


Figure 4
Relationship Curve of Interfacial Tension with Concentration

As can be seen from Figure 4, with increasing HFYQ-B concentration, interfacial tension rapidly decreased at first and then increased. With the concentration increased from 0.3% to 0.35%, interfacial tensions were as low as the order of magnitude of 10^{-5} mN/m. Analyzing its reason, it mainly is that the molecules adsorbing on the interface gradually increase with the increase of surfactant concentration, so the oil-water interfacial tension decreases rapidly. As the concentration of HEYQ-B continues to increase, surfactant molecules tend to be oriented arrangement at oil/water interface. As critical micelle concentrations (CMC) of surfactants in complex system are different, the contents of surfactants are different, and the distribution proportion of surfactants adsorbed at oil/water interface also changes continuously. When the distribution proportion of surfactants reaches a certain value, the interfacial tension reaches its lowest point. As the concentration continues to increase, some surfactants have formed micelles in solution, and adsorptions of the surfactants at the surface are no longer increase. And yet, adsorptions of other surfactants at the surface could still change. Because of the competing adsorption phenomena between the components, the distribution proportion of surfactants adsorbed at oil/water interface continue to change, and no longer remain its optimal value. So the oil/water interfacial tension is rising rather than falling.

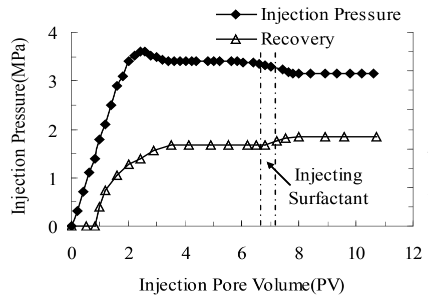
For above results, the surfactant formulations of different levels of ultra-low interfacial tension (10^{-2}-10^{-5} mN/m) are shown in Table 2.

Table 2
Surfactant Formulations of Different Levels of Interfacial Tension

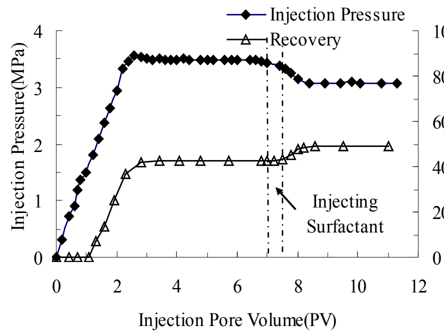
Formulations	Concentrations of surfactant, %	Interfacial tensions, mN/m
1	0.15	0.0593
2	0.20	0.0092
3	0.25	0.00071
4	0.30	0.000049

2.3 Surfactant Flooding in Low Permeability Core

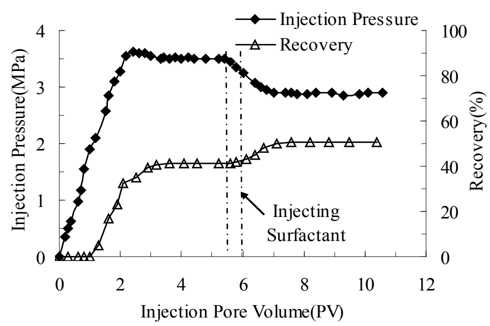
Under different ultra-low interfacial tensions of the selected surfactant formulations, the curves of injection pressure and recovery with injection pore volume in the processes of the first water flooding, injecting surfactant slug and the second water flooding are seen in Figure 5.



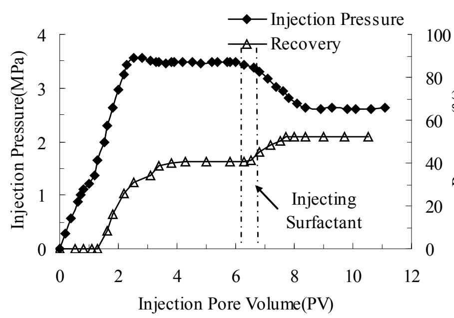
(a) With interfacial tension of 0.0593mN/m



(b) With interfacial tension of 0.0092mN/m



(c) With interfacial tension of 0.00071mN/m



(d) With interfacial tension of 0.000049mN/m

Figure 5
Curves of Injection Pressure and Recovery with Injection Pore Volume at Different Interfacial Tensions

As can be seen from Figure 5(a-d), the injection pressure rose sharply during the first water flooding, and the peak was achieved when the volume of injecting water reached 2~2.5 PV, then the pressure became gradually stable after showing a small drop. The injection pressure dropped slowly and then gradually tended to balance after injecting surfactant slug. In short, surfactant formulations with different ultra-low interfacial tensions could have certain effect of reducing injection pressure. On the side, at the beginning of the first water flooding, there was no oil at the outlet of core. When injecting a certain amount of water, the pressure increased to certain value, then the oil started coming out of the outlet and the recovery rose rapidly. The recovery changed unobvious after injecting 3 pore volume of the formation water. After injecting surfactant slug, the recovery rose in some extent and then stayed steady.

Analyzing its reason, the main characteristics of ultra-low permeability cores are small reservoir pore, fine throat, and high seepage resistance. During the process of the first water flooding, dispersed oil drops remain in reservoir pores and cannot flow through minute pores. The oil phase does not flow in a continuous state but in the state of small slug or dispersed drops. When oil drops or water drops flow through narrow throats, the injection pressure would increase because of Jamin Effect. The formation energy spreads slowly in low permeability reservoirs. These can cause low water intake capacity, high injection pressure, and low recovery efficiency. Surfactant can reduce interfacial tension and capillary resistance, make oil bead deform easily, and decrease the power on which oil droplets emit through the pore throat depending. It is easier for oil drop to change the shape of itself and flow through the throat. So surfactant can reduce injection pressure and enhance oil recovery of ultra-low permeability cores.

Figure 6 shows the two relation curves, including the curve between the decompression rate and interfacial tension, and another is the recovery and interfacial tension. The decompression rate is equal to the difference between stable pressure of the first water flooding and that of the second water flooding divided by that of the first water flooding.

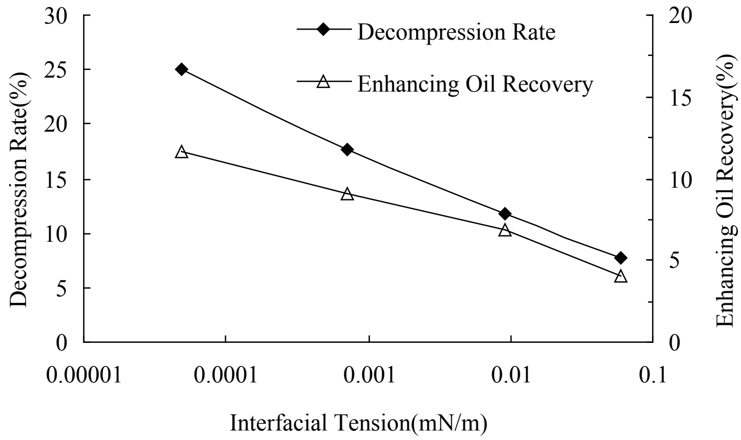


Figure 6
Impacts of Interfacial Tension on Decompression Rate and Enhancing Oil Recovery

As can be seen from Figure 6, when interfacial tension was 5.93×10^{-2} mN/m, decompression rate reached 7.65%, and recovery was improved by 4.09%. And when ultra-interfacial tension was 4.9×10^{-5} mN/m, decompression rate reached 25%, and recovery was improved by 11.6%. The effect of reducing injection pressure gradually strengthened and the extent of enhancing oil recovery gradually increased with the decreasing of interfacial tensions. Analyzing its reason, the lower interfacial tension is, the easier the deformation of residual oil is, the smaller the resistance caused by Jamin effect when oil beads travel through small throat. Thus, more and more residual oil is gradually emulsified and produced with lower interfacial tension. Meanwhile, owing to the reduction of residual oil, the flowing space of water phase increases gradually, so sweep efficiency is becoming larger, the relative permeability of water phase becomes higher, and injection pressure drops even further. In all, for ultra-low permeability core, the lower interfacial tension is, the better the effect of reducing injection pressure is, and the higher the extent of enhancing oil recovery is.

CONCLUSIONS

For the selected ultra-low permeability core whose gas log permeability was 0.52×10^{-3} μm^2, the vast majority of throats of core varied in width from 2.5 μm to 15 μm.

The injection pressure of the core rose sharply during the first water flooding,then the pressure became gradually stable after the volume of injecting water reached 2~2.5 PV. The pressure is higher about 3.5 MPa. There was no more oil at the outlet of the core after 3 PV. The recovery is lower about 40%.

The surfactant formulations with different ultra-low interfacial tensions could have certain effect of reducing injection pressure and enhancing oil recovery. And the lower interfacial tension is, the easier the deformation of residual oil is, the better the effect of reducing injection pressure is, the higher the extent of enhancing oil recovery is. When interfacial tension was 4.9×10^{-5} mN/m, decompression rate reached 25%, and recovery was improved by 11.6%.

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