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A Laboratory Study of Surfactant Flooding Performance Using a Modified Micromodel for Chemical Enhanced Oil Recovery (cEOR) Application: Capillary Desaturation Curve (CDC)

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Abstract. Previous studies show that surfactant flooding in enhanced oil recovery substantially increases oil recovery due to the reduction of interfacial tension and alters the wettability of reservoir rock. The capillary desaturation curve (CDC) is often used to represent surfactant flooding performance in the laboratory study, which correlates the relationship between residual oil saturation changes and capillary number. There are many equations to define the capillary number. However, one well-known is the ratio between viscous force (fluid viscosity and injection rate) and capillary force (interfacial tension between two immiscible fluids).

In this study, two surfactant commercials have been analyzed to determine the surfactant flooding performance regarding the reduction of residual oil saturation as the effect of changes in capillary number. To increase the capillary number, we modify the interfacial tension between surfactants and crude oil until reaching the ultra-low IFT region so that the capillary number can increase up to three-five orders of magnitude. Then, the reduction of residual oil saturation, which leads to increased oil production, has been analyzed during the changes in capillary number.

In addition, we use a transparent modified micromodel that enables us to monitor the fluid moves in porous media lively. Advanced digital image analysis (DIA) was then used to quantify the residual oil saturation in the micromodel.The study is divided into two parts; static test (fluid-to-fluid compatibility) and dynamic test (fluid-to-rock interaction). The static test includes CMC-IFT which determine the optimum concentration to get the lowest IFT between surfactant solution and crude oil. Finally, dynamic tests for surfactant flooding have been observed using a modified micromodel to visualize the fluid displacement in the porous media. The analysis of initial oil saturation, residual oil saturation, water saturation and surfactant saturation are determined and calculated accurately using digital image analysis.

The result shows that the interfacial tension between surfactant solutions and crude oil directly impacts reducing oil saturation, leading to higher oil recovery. However, the lowest IFT does not guarantee the highest oil recovery, which might not conform to the existing fundamental theory. The laboratory result shows that a particular capillary number increment is adequate for higher oil recovery.

The study uses a modified micromodel that enables us to monitor the fluid moves in porous media lively. In addition, this method is quite simple and low-cost efficient but powerful, accurate, and fast compared to the conventional coreflood test. We also added quartz and cement to mimic the native core from the reservoir so that the detailed fluid-to-rock interaction can be captured in the study.

Keyword(s): Chemical Enhanced Oil Recovery (cEOR); Surfactant; Capillary Number; Capillary Desaturation Curve; Micromodel.

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1 Introduction

Currently, most oil fields in Indonesia are in the maturation stage. Primary and secondary methods are not efficient enough to produce crude oil since the reservoir pressure is a too low and high water cut. Chemical EOR is one of the favourite methods to increase oil production in depleted reservoirs, especially surfactant injection. Surfactant flooding in enhanced oil recovery substantially increases oil recovery due to the reduction of interfacial tension and alters the wettability of reservoir rock. Residual oil saturation that is trapped in the pores is strongly governed by capillary pressure. To mobilize these trapped oils, we need to modify the viscous and capillary force in the system. The ratio between viscous force (fluid viscosity and injection rate) and capillary force (interfacial tension between two immiscible fluids) is often referred to as capillary number (N_c). Increasing the capillary number in the reservoir system will reduce the residual oil saturation that is trapped in the pore. The capillary desaturation curve (CDC) is often used to represent surfactant flooding performance in the laboratory study, which correlates the relationship between residual oil saturation changes and capillary number. In this study, two surfactant commercials have been analyzed to determine the surfactant flooding performance regarding the reduction of residual oil saturation as the effect of changes in capillary number. To increase the capillary number, we modify the interfacial tension between surfactants and crude oil until reaching the ultra-low IFT region so that the capillary number can increase up to three-four orders of magnitude. Then, the reduction of residual oil saturation, which leads to increased oil production, has been analyzed during the changes in capillary number.

$$N_c = \frac{\mu\nu}{\sigma} \tag{1}$$

Where,

N_c : Capillary number (dimensionless)
μ : fluid viscosity (Pa.s)
ν : fluid velocsity (m/s)
σ : interfacial tension (N/m)

2 Previous Studies

There are many studies of chemical performance in porous media for eor application. The coreflooding method is the most common method to analyze the chemical performance in terms of incremental oil recovery after a waterflood. However, this method has some limitations such as difficulty in visually representing the movement and mechanism of injection fluid. This limitation can be covered by micromodel flooding which enables us to observe visually the mechanism and other possibilities that happened during the chemical injection. This method represents 2D visualization of actual fluid that occurred.

Micromodel studies of surfactant flooding for enhanced oil recoveries have been reviewed by many researchers. Commonly, there are three mechanisms during surfactant flooding in eor application, which are reducing interfacial tension, wettability alteration, and microemulsion forming. Reducing the interfacial tension is one of the most important methods for surfactant flooding mechanism (Yang, et al., 2021). The reduced interfacial tension between water and oil can cause the oil droplet that is trapped in the pore to become smaller so that it can pass through the pore throat easily and increase oil production. Another mechanism for surfactant flooding is wettability alteration. In the oil-wet reservoir, displacement efficiency in the pore scale due to waterflood is very small. Residual oil saturation in the surface pore becomes difficult to be produced. Some surfactants can change effectively from an oil-wet system to a water-wet system. The third mechanism is forming of microemulsion as a result of the reaction between surfactant, water, and oil. In some cases, the presence of the microemulsion can change the flow pattern to become more stable because the viscosity of microemulsion is higher than water, even can be higher than oil. In other words, this microemulsion behaves like polymer flooding which improves the sweep efficiency.

Even though many studies have been conducted on surfactant flooding, it is very limited studies that discuss surfactant flooding performance in micromodel, especially in the specific topic of capillary desaturation curve. In this paper, we modify the micromodel by adding quartz sandstone and portland cement at a ratio of 4:1 to mimic the native cores. This enabled us to analyze not only fluid-to-fluid interaction but also rock-to-fluid interaction that could be possibly happened during surfactant injection.

3 Methodology

In this study, two anionic surfactant commercials have been analyzed to determine the surfactant flooding performance regarding the reduction of residual oil saturation as the effect of changes in capillary number. These two surfactants are Surfactant A and Surfactant B. For injection brine, we use synthetic brine with a salinity of 10,000 ppm (NaCl). The crude oil, with API Gravity 43.45 and viscosity of 0.90 cp at 66C from field X has been used for this experiment. The properties of crude oil are presented in the table below. All of the experiments are conducted at the room temperature.

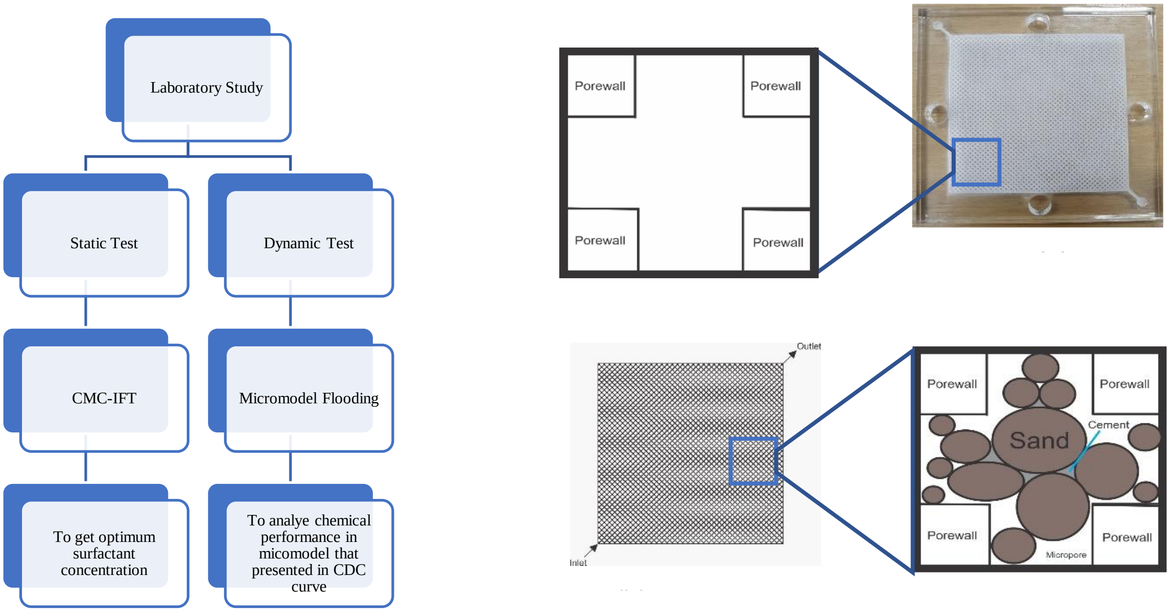


Figure 1. Workflow of the study (left) and modified micromodel (right)

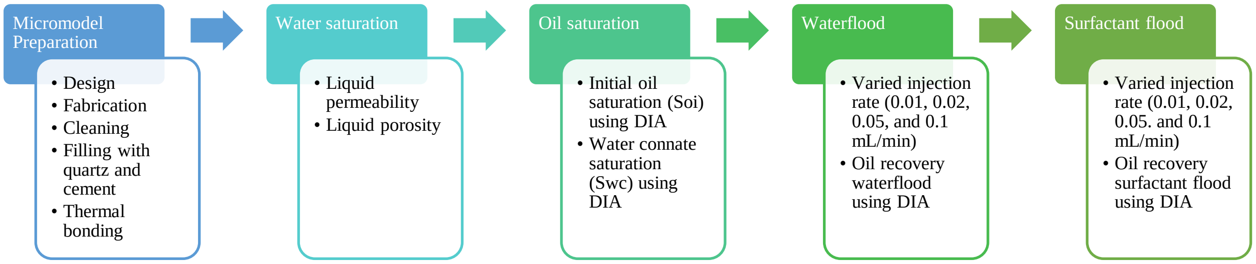


Figure 2. Workflow for micromodel flooding

4 Result and Discussion

4.1 Critical Micelle Concentration – Interfacial Tension (CMC-IFT)

The purpose of CMC-IFT test is to detemine the optimum surfactant concentration which resulted the lowest interfacial tension between surfactant solution and oil. This test is carried out by measuring interfacial tension of each surfactant solution at different concentrations, from 0.25 – 3.0 %w/w. We use Spinning Drop Tensiometer TX500D with 3000 RPM for 30 minutes with 2 minutes interval at room temperature. The interfacial tension between injection brine and oil (no surfactant added) is 10.1 mN/m.

Based on the result, Surfactant B has better result than Surfactant A in terms of reducing interfacial tension. The surfactant B can reduce the IFT until 5th orde magnitude, which is from 10.1 mN/m to 9.17x10$^{\wedge-4}$ mN/m. In other words, it is called as ultra-low IFT region since the IFT value is lower than 10$^{\wedge-2}$ mN/m. On the other hand, the Surfactant A doesn't reach ultra-low IFT region because the lowest IFT is only about 5,20x10$^{\wedge-2}$ mN/m. However, in terms of reducing interfacial tension, Surfactant A is good enough since it can reduce IFT until 3rd orde magnitude, from 10.1 mN/m to 5.20x10$^{\wedge-2}$ mN/m. Due to economical limits, we choose 1.5% and 2.0% w/w concentration for each surfactant to be continued in the micromodel flooding.

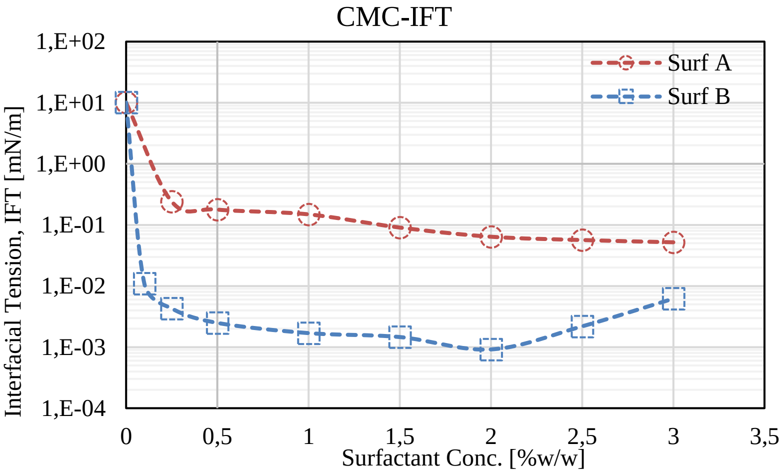


Figure 3. CMC-IFT results

4.2 *Micromodel Flooding*

The following table shows the micromodel properties that have been used in this experiment. In general, the properties of micromodel for all cases are similar. The bulk volume of micromodel is 1.45 cm^3 with pore volume ranging from 0.74 cm^3 – 0.844 cm^3. The porosity is in the range of 51.03% - 58.21% and permeability around 634.87 mD – 1264.31 mD.

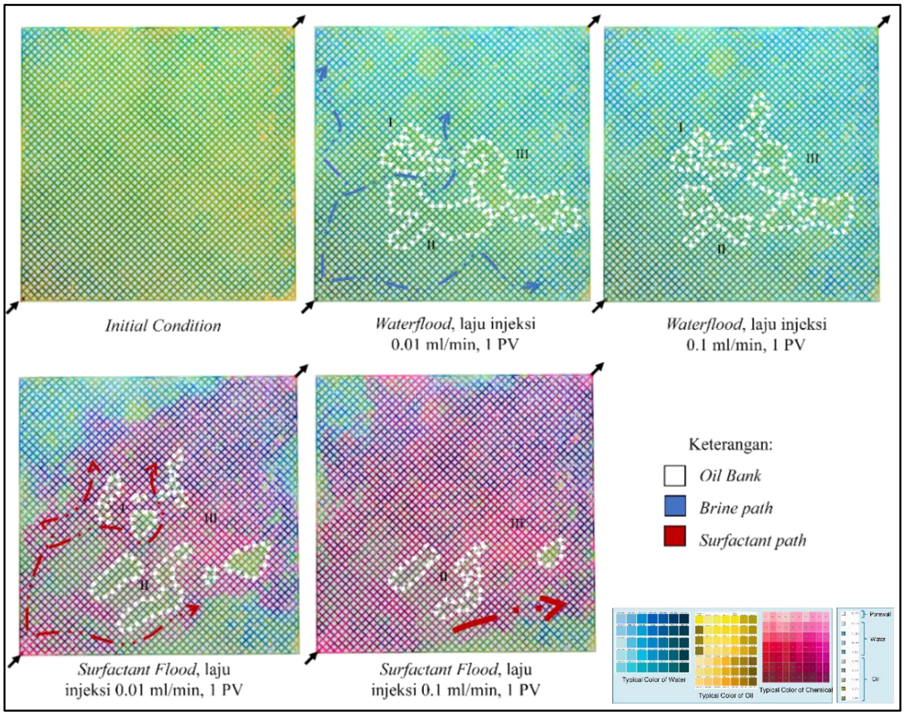
To quantify the oil and water saturation in the micromodel, we used advanced digital analysis with very high precision. Since there is a possible reaction during surfactant flooding that changes the colour of surfactant, water, and oil, we use a colour pallet to determine either water, oil, or chemical. Figure 4 shows the typical colour for each substance.

Figure 4 shows the typical result of micromodel flooding (for Case B: Surf A 1.5%). The upper left picture shows the initial condition which consists of water and oil. Then, the upper middle picture presents the micromodel condition after 1 pore volume injection waterflood with an injection rate of 0.01 ml/min. As can be seen in the figure, oil has been produced and replaced by water in some areas, especially in the area that is closer to the outlet. To help better visualization, we added a white line to help identify the oil bank. The upper right picture shows the micromodel condition after 1 pore volume injection of waterflood with an injection rate of 0.1 ml/min. There is still some oil bank left in the system, especially in the inlet and centre of the micromodel. The lower left picture presents is the condition of the micro model after 1 pore volume injection of surfactant flood with a 0.01 ml/min injection rate.

The oil bank that is left is reduced in the process and becomes smaller which indicates that oil production increases. It also happens in the last picture which shows the condition after 1 pore volume injection of surfactant flood at 0.1 ml/min injection rate.

Table 1. Micromodel properties

Deskripsi	*Micromodel* A, Surf A 2%	*Micromodel* B, Surf A 1.5%	*Micromodel* C, Surf B 2%	*Micromodel* D, Surf B 1.5%
Length (mm)	50	50	50	50
Width (mm)	50	50	50	50
Depth of Etching (mm)	0.58	0.58	0.58	0.58
Bulk Volume (cm^3)	1.45	1.45	1.45	1.45
Pore Volume (cm^3)	0.76	0.833	0.844	0.74
Porosity (%)	52.41%	57.45%	58.21%	51.03%
Absolute Permeability (mD)	789.85	1264.31	961.15	634.87



Initial Condition

Waterflood, laju injeksi 0.01 ml/min, 1 PV

Waterflood, laju injeksi 0.1 ml/min, 1 PV

Surfactant Flood, laju injeksi 0.01 ml/min, 1 PV

Surfactant Flood, laju injeksi 0.1 ml/min, 1 PV

Figure 4. Typical result of micromodel flooding

The figure above shows the result of capillary desaturation curve for all cases. In general, there is significant different result between Surfactant A and B in terms of reducing the oil saturation as function of capillary number. For Surfactant A, both 1.5% and 2.0% w/w concentration, it can reduce the oil saturation up to 50% after waterflood (from 1 to 50% residual oil saturation) eventhough the increment of capillary number only about 3 orde magnitude. Meanwhile, eventhough surfactant B 1.5% has increment of capillary number is quite high (until 5 orde magnitude), however in terms of reducing oil saturation is not that good enough.

This surfactant only can reduce oil saturation up to 34% (from 1 to 66% residual oil saturation). In addition, Surfactant B 2.0% can reduce the oil saturation up to 51% (from 1 to 49%).

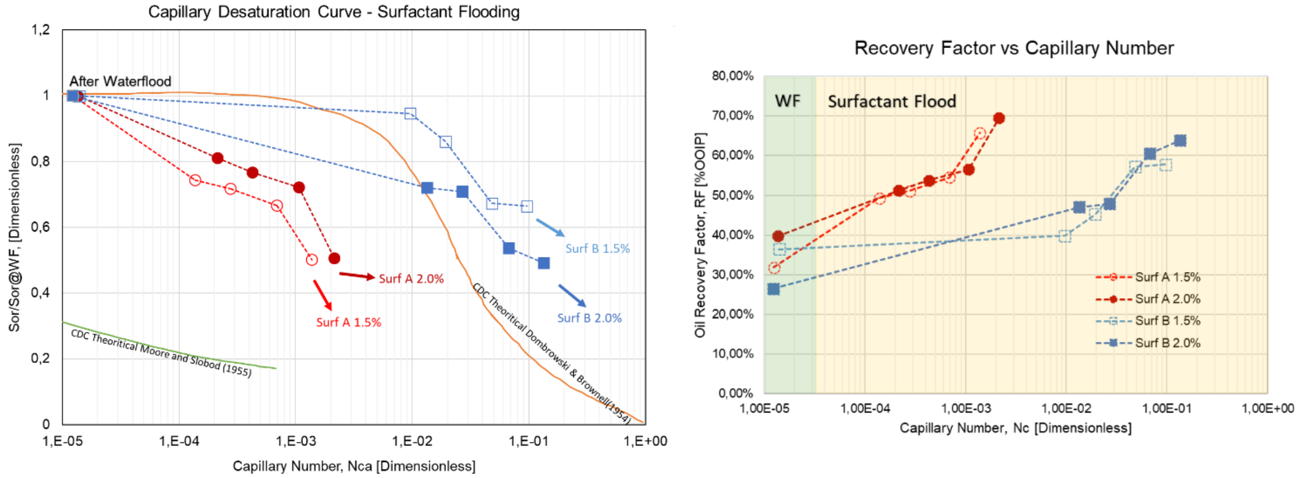


Figure 5. Result: capillary desaturation curve (left) and recovery factor (right)

5 Conclusion

5.1 The result shows that the interfacial tension between surfactant solutions and crude oil directly impacts reducing oil saturation, leading to higher oil recovery. However, the lowest IFT does not guarantee the highest oil recovery, which might not conform to the existing fundamental theory.

5.2 The laboratory result shows that a particular capillary number increment is adequate for higher oil recovery. In this case, the increment 3 orde of capillary number (or reducing IFT until 3 orde) is enough to reduce oil saturation.

5.3 The study uses a modified micromodel that enables us to monitor the fluid moves in porous media lively. In addition, this method is quite simple and low-cost efficient but powerful, accurate, and fast compared to the conventional coreflood test. We also added quartz and cement to mimic the native core from the reservoir so that the detailed fluid-to-rock interaction can be captured in the study.

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