Application of Surfactant-Polymer Flooding for Improving Oil Recovery in the Indonesian Oil Field

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Abstract. The goal of this research is to investigate the effect of surfactant and polymer found in the market and developed in the laboratory such as Sodium Ligno Sulfonat, Poly Vynil Alcohol (PVA) and Partially Hydrolyzed Polyacrylamide (HPAM) polymer on the oil recovery which can be used to optimize recovery and minimize residual oil in the reservoir by: lowering the oil / water interfacial tension and improving mobility ratio. The effectiveness of chemicals was tested through micro displacement using artificial reservoir as porous medium. The procedure of operation is as follows: initially the reservoir model was filled with brine until it was 100 % saturated. Then to represent oil migration, oil was injected into the medium until minimum water saturation (Swc) of about 30 % is reached. After this, the medium was flooded by the same brine until minimum oil saturation, Sor, was reached, which was about 10 %. The oil remaining in the reservoir model after this water flood was then subjected to the injection of various chemicals for additional oil recovery. A set of mathematical model of oil displacement from porous media using water and polymer flooding has also been developed, based on fundamental theories of two phase flow. Since the model includes the material balance of the water, surfactant and polymer, the concentration of the surfactant and polymer at any position and time can be predicted. The oil displacement experiments show that as much as 20 % to 60 % of remaining oil can be recovered by flooding it with the chemical developed in the laboratory. The results also show the oil recovery depends on chemical, chemical concentration, pressure and temperature in the model reservoir, and crude oil. It turns that the mathematical models proposed were in a good agreement with the experimental data.

1. Introduction

The increasing demand for petroleum-based fuels and petrochemicals, along with the diminishing supply of new sources for oil, has escalated interest in improving the extraction of oil from existing reservoirs. A new well produces crude oil with usually high oil saturation (about 70 to 90 %). On the other hand the old wells produce crude oil just with about 10 % saturation. After primary and secondary recovery, an average of 50 to 70 percent of the original oil in place is thought to have remained in the reservoirs. The residual oil can theoretically be recovered by enhanced oil recovery (EOR) which is indeed a very promising tool in the future [1].

EOR is an important process to produce more oil from the reservoir. Because of its importance much research has been directed towards the variables controlling the oil recovery. Currently, various researches in EOR technology is underway with intensity. One of the related researches that are given much attention is finding of chemicals for optimizing the enhancement of oil recovery. Even though many experiments have been done in this area, the applications in the field rarely succeeded. Expensive chemicals is certainly not the main reason for the failure, but more related to the process as application in the field is not properly guided by processes in the laboratory. There are many problems that need to be solved in the area of EOR basic research to allow results of research to be applied in the field.

EOR means the incremental oil recovery resulting from the injection of energy not normally present in the reservoir. EOR may be classified into two categories: secondary oil recovery and tertiary oil recovery. Secondary oil recovery refers to technique which is intended to maintain reservoir pressure by injecting gas or water. Tertiary oil recovery is any technique applied after secondary recovery process. Chemical flooding, classified as tertiary oil recovery, is an isothermal EOR process whose primary goals are to recover...
oil by lowering the oil - water interfacial tension (low IFT process) and improving mobility ratio (mobility control process). Some chemicals have been found favorable for the EOR processes. However, in order to determine the chemicals used in the experiment, some conditions had to be met such as: easily found in Indonesia, inexpensive, industrial waste, high recoverability, and not petroleum derivative. The research can be classified into two categories: (1) development of chemicals from local materials, and (2) oil displacement process. Development chemicals for EOR which are applicable in oil reservoirs have been completed. Several processes have been conducted to produce EOR chemicals such sodium ligno sulfonate surfactant and partially hydrolyzed poly acrylamide polymer (HPAM). A set of mathematical model that can be used to simulate the process of one-dimensional water and polymer flooding in that reservoir has also been developed. The empirical equation developed showed the effect of chemicals on the fractional flow.

2. Experimental
2.1. Chemical flooding

Natrium chloride solution added with surfactant and polymer developed in the laboratory has been used as EOR chemicals. The surfactant was sodium ligno sulfonate (SLS) whereas the polymers were Poly Vinyl Alcohol (PVA) and Partially Hydrolyzed Polyacrylamide (HPAM). Because of the high molecular weight the water soluble polymers used in this Enhanced Oil Recovery (EOR) technique, only a small amount of polymer will bring about a substantial increase in water viscosity. The SLS was developed in the laboratory. There were two steps of the development of surfactat, delignification of palm oil fruit brunch and sulfonation.

\[ C_t = C_{so} \left( \frac{k_1}{k_2 - k_1} \right) \left[ e^{-k_1 t} - e^{-k_2 t} \right] \]

where

\[ k_1 = \frac{C_{so}}{10} \left( \frac{C_{so}}{31.5} \right)^A \exp \left( -\frac{E_A}{T} \right) \]

\begin{tabular}{|c|c|c|c|}
\hline
x & y & Ar & E \\
\hline
k1 (hr) & -0.972 & 4.991 & 7.695 x 10^{-18} & 19983 \\
k2 (hr) & -0.972 & 4.991 & 7.695 x 10^{-18} & 20022 \\
\hline
\end{tabular}

Whereas the kinetic for the sulfonation is:

\[ \frac{d[SLS]}{dt} = k [\text{lignin}]^x [\text{HSO}_4]^{y} \]

\[ k = 96.9473 \times 10^{-3} \left( \frac{1}{\min} \right) \left( \frac{g}{L} \right)^{3.2044} \]

\[ \alpha = 4.2152 \]

\[ \beta = 8.7976 \times 10^{-3} \]

PVA was obtained from the market while hydrolysis of polyacrylamide under basic conditions was studied with emphasizing on the kinetic aspect. Polyacrylamide derived from polymerization of
acrylamide using mixed solvent precipitation method. Hydrolysis of polyacrylamide was carried out in batch reactor equipped with a stirrer, thermometer, condenser and heater. A solution of sodium hydroxide was put in to reactor and heated to the desired temperature. When the desired temperature was reached, polyacrylamide was introduced quickly in the reaction medium. During the process, the temperature was kept constant. Samples were taken from the reaction medium at a regular time then analyzed by acidic-alkalimetric method. The effect of temperature, concentration of sodium hydroxide and concentration of amide in water to k’, were studied in this investigation.

2.2. Experimental set-up for flooding

The effectiveness of the chemicals was tested through micro displacement using artificial porous medium. The flow rates of oil, water and surfactant or polymer were controlled using pressurized gas. The porous media used in the oil displacement process were Berea stones. Porosity of a rock depends on the pore or grain size distribution, in which the small grains can fill the space between larger grains. Porosity is a strong function of grain size distribution (sorting).

![Experimental set-up for oil displacement](image)

**Figure 2.** Experimental set-up for oil displacement

2.3. Operation procedure

The procedure is as follows: initially the reservoir model was filled with brine (1 to 3 % salt concentration) until it was 100 % saturated. Then, to represent oil migration, oil was injected into the medium until minimum water saturation (Swc) of about 30 % is reached. After this, the medium was flooded by the same brine until minimum oil saturation, Sor, which was about 10 %. The oil remaining in the reservoir after this water flood was then subjected to various injections of different chemicals for further oil recovery.

2.4. Mathematical model

A simplified mathematical model represents the behavior of migrating oil in the porous media has been developed. The model was developed based on the mass balance of oil, water (brine) and polymer. The purpose of this simulation is to test experimental data and mathematical model so that model parameters can be found which give minimum sum of squares of errors between the experimental data and simulation. The mathematical models are as follows:

### Equations for Water Flooding

\[
\begin{align*}
S_w + S_o &= 1 \\
\frac{\partial S_w}{\partial t} &= -\frac{\mu f_{wq} \frac{\partial S_w}{\partial x}}{\phi \frac{\partial S_o}{\partial x}}
\end{align*}
\]
Equations for Polymer Flooding
\[
\frac{\partial^2 C_p}{\partial x^2} - u \frac{\partial C_p}{\partial x} = \phi \frac{\partial^2 C_p}{\partial t^2}
\]  
(6)

\[
f_w = \frac{1}{1 + \left(1 - S_w \right)^{2}} \times \frac{S_u - S_{wp}}{\Omega_0 \phi \phi A}
\]  
(7)

\[
S = 1 - S_{wp} \frac{1}{S_u - S_{wp}} - a_2 C_p
\]  
(8)

\[
\Omega_0 = \Omega_{0f} - a_2 C_p
\]  
(9)

Equations for Sum Square of Errors (SSE) calculations
\[
V_{oil} = \phi \int_0^L \frac{\partial}{\partial x} \left[ 1 - S_w - (x,0) \right] dx
\]  
(10)

\[
V_{oor} = \phi \int_0^L \left[ 1 - S_w (x,t) \right] dx
\]  
(11)

\[
V_{op} = \frac{V_{oil} - V_{oor}}{V_{oil}} \times 100\%
\]  
(12)

\[
PVT = \frac{\mu A f}{\phi A L}
\]  
(13)

\[
SSE = \sum_{i=1}^N \left( \frac{V_{op}}{V_{op}} \right)_{calc} - \left( \frac{V_{op}}{V_{op}} \right)_{dataset} \right)^2
\]  
(14)

The initial and boundary conditions are:

**IC:** For water flooding
\[
t > 0 \quad 0 < x < L \quad S_w = S_{wo}
\]

For chemical flooding, the initial condition for water saturation is a function of position and is given by the final condition of the process, and
\[
t > t' \quad 0 < x < L \quad C_s = 0
\]

**BC:** For water flooding
\[
t > 0 \quad x = 0 \quad S_w = 1
\]

For chemical flooding, the water saturation depends on the water flood (from previous process), and
\[
t > 0 \quad x = 0 \quad C_p = \text{finite}
\]

\[
dC_p/dx = 0
\]

In this study, a finite difference method is used. All variables and spatial derivatives were averaged between two consecutive time steps. For the increment calculation, the length of porous media, \( L \), was divided into \( N \) equal interval of size \( dz \), and the time is divided into \( P \) intervals of \( dt \).

3. Results and Discussion

In the EOR process, after injection of water (water flooding), some oil is still left in the reservoir due to high viscosity or high interfacial tension (IFT) between oil and the reservoir rocks. Therefore, after injection of chemicals which has higher mobility ratio, more oil can be recovered. Figure 3 shows the process of water flooding followed by surfactant-polymer flooding. From the figure, it can be seen that after injection of water (2 % brine) some oil is still left in the reservoir. After injection of surfactant and polymer, more oil can be recovered.
Figure 3. Example of water, and polymer-surfactant flooding. (Berea stone permeability 385 mD; porosity 18 %)

In this experiment the temperature was kept constant at room temperature, the concentration of surfactant was 1 % and polymer were varied from 5,000 to 25,000 ppm for PVA and 1,000 to 3,000 ppm for HPAM. Table 1 shows the amount of oil can be recovered using surfactant and polymer either found in the market or developed in the laboratory, presented in percent of oil remain which cannot be recovered by water flooding. From the figure, it can be seen that as much as 35 % of remaining oil can be recovered by flooding it with the EOR chemicals. The figure demonstrates the oil recovery after water flooding in percent of originally oil in place (OOIP). The figure shows that the oil recovery increases when the chemical concentration is raised. The results of this experiments accord well with the studies conducted by DeBons et al. [3] which also showed the same phenomenon that if the concentration of chemicals or chemical blends is increased the amount of oil recovered will also raise. According to them, the oil recovery strongly depends upon the chemicals used after water flood. In their studies, done in the Berea sandstone, the oil recovery were between 12 and 79 % of oil remain.

Table 1. Result of surfactant-polymer flooding

| Core type | Permeability | Porosity | Recovery |
|-----------|--------------|----------|----------|
| Berea I   | 680 mD       | 25 %     | WF = 69 % OOIP <br>SF = 23 % SOI = 75 % SOR <br>Total recovery = 92 % OOIP |
|           | 385 mD       | 18 %     | WF = 46 % OOIP <br>SFP = 23 % SOI = 42 % SOR <br>Total recovery = 69 % OOIP |
| Berea II  | 185 mD       | 19 %     | WF = 47 % OOIP <br>SF = 7 % SOI = 13 % SOR <br>Total recovery = 54 % OOIP |
|           | 160 mD       | 23 %     | WF = 51 % OOIP <br>SFP = 28 % SOI = 57 % SOR <br>Total recovery = 79 % OOIP |

A more complex study on the predictive model for chemical flooding has been conducted by Lake [3]. In his investigation, the oil recovery is not only affected by the amount of chemicals injected but also affected by capillary number, heterogeneity, cross flow, surfactant sorption and wettability. Capillary forces cause large quantities of oil trapped in well swept zones of water flooded oil reservoirs. The capillary number, $N_{VC}$, is defined in equation 15, where $U_o$ is the linear velocity, $\mu$ is the viscosity and $\sigma$ is the IFT.
\[ \frac{N_{\text{cap}}}{\sigma_{\text{ow}}} \frac{U_0 \mu_w}{\sigma_{\text{ow}}} \]  

From that equation, it can be seen that the lower the IFT and the higher the viscosity, the higher the value of capillary number resulting in increasing of oil recovery. Higher concentration of surfactant will lower the IFT and on the other hand polymer will increase the viscosity more effectively and increasing the value of capillary number. High capillary number will ease the oil to be pushed out.

Mathematical models set-up based on fundamental concepts of two phase flow through porous media and proposed empirical equations turned out to be able to describe the EOR performances. Explicit finite difference approximation was adequate to solve the mathematical equations for EOR processes. Computer programs for solving the mathematical equations have been developed and turned out to be successful. The results of simulation using one dimensional model show good agreement between the experimental data and the simulation. From the same figure, it can be seen that the model can predict the behavior of water and polymer flooding. The behavior of the flow in the porous media in the water phase is shown in Figure 3. Figure 3 shows the process of water flooding followed by polymer flooding. From the figure, it can be seen that after injection of water some oil is still left in the reservoir. After injection of polymer, more oil can be recovered. The constants for equation 4 to 6 were found as: for water flooding \( n_1 = 0.750258, n_2 = 0.695647, M = 1.55545 \); and for polymer flooding \( a_1 = -1.4843, a_2 = 1.37935, D_{\text{es}} = 0.000831278 \), with the average error equal to 6.7%.

The experimental results of the variation of temperature show that the higher the temperature, the higher the oil recoveries after water flood. This is related to the change of oil viscosity with temperature as well as the effect of the polymer itself which reduces mobility of oil.

In the polymer injection, the polymer adsorbed by reservoir core is caused by clay content in the core. High adsorption of polymer by reservoir core is undesirable since it could decrease the ability of polymer to increase the mobility ratio which makes injection ineffective. Experiment to study the effect of clay on the oil recovery was done to get better understanding of the effect of clay content on oil displacement. The result showed that the lower the clay content in the reservoir rocks, the better of oil displacement can be achieved. Clay minerals can occur as pore-linings, pore-bridging, and/or pore-fillings in sandstone, so clay minerals can greatly reduce permeability by effective blocking pore throats of the fluid flow routes. Another important feature of clay mineral is their ability to swell and ability in cation exchange in the presence of water. The relationship between cation exchange capacity (CEC), clay content more than 5 (five) %, and permeability has also been examined. The CEC will increase relative to the increase of clay content.

4. Conclusion

Surfactant and polymer developed in the laboratory has been tested for its sweeping ability. The results show that this chemical has potential as EOR chemicals. The recoverability of the chemicals are in the range
of 50 to 60% of original oil in place (OOIP) or between 20 and 30% of the oil remain after water flooding. The sweeping processes depend on the chemical used, chemical concentration, temperature of the system, and crude oil. It turns that the mathematical models proposed were in a good agreement with the experimental data.

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6. Nomenclature
\[ \phi \] = Porosity, fractional
\[ \Omega \] = Water oil mobility ratio, dimensionless
\[ A \] = Sweeping area, cm²
\[ C \] = Concentration, g/cm³
\[ D \] = Diffusivity, cm²/s
\[ f \] = Fractional flow
\[ n \] = Constant
\[ q \] = Liquid flow, cm³/s
\[ S_w \] = Water saturation
\[ u \] = Linear velocity, cm/s

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