

INCREASING OIL RECOVERY THROUGH LOW-TENSION POLYMER FLOODING

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ABSTRACT

After completing a waterflood activity, the need of enhancing oil recovery (EOR) is essential. The selection of appropriate EOR methods that will be applied to particular field, as an effort to increase oil recovery, mainly depends on the reservoir characteristics and fluid behaviors. Chemical injections have been categorized as effective EOR methods in low oil gravity oilfields. These methods are considered as a very costly. However, low-tension polymer flood (LTPF) approach may address the cost problem by using low concentration of surfactant. LTPF is a mixture of low surfactant concentration and polymer which could result in the reduction of interfacial tension (IFT) to oil much lower.

Experiments on LTPF had been carried out at Lemigas' EOR laboratory using two different fluid and core samples from two different wells in addition of standard core samples. Before conducting the injection experiments, a sequence of studies has been done. These include the study of the polymer's rheology, filterability polymer tests, polymer-rock adsorption and desorption, IFT reduction against surfactant concentration, and optimum mixed surfactant-polymer. Surfactant solution could only reduce the IFT down to 6.0×10^{-2} dyne/cm. On the other hand, mixed surfactant-polymer reduced the IFT much lower, i.e. 2.4×10^{-4} dyne/cm. The results of coreflood experiments were very promising. LTPF, gave an additional oil recovery up to 63.57% of residual oil saturation after waterflood. No formation damage was observed through SEM and X-ray diffraction analyses. These laboratory findings suggested that the LTPF technology could be applied to oilfields.

I. INTRODUCTION

Intensive laboratory tests on chemical flood and followed by field projects have been done around the world.^{1,2} Polymers have been extensively used for enhanced recovery of crude oil: partially hydrolyzed polyacrylamide (HPAM) and xanthan gum polysaccharide (XGPS). The purpose of either polymer is to reduce the mobility of injected fluid during flow through the reservoir. The mechanisms of controlling mobility are by increasing the viscosity of injected fluid and also by decreasing the relative permeability of the reservoir rocks to water. This reduction in water mobility can create a piston like displacement and followed by improving fractional flow of oil into the wells.^{1,3}

On the other hand, surfactant is usually used in EOR processes to reduce IFT between oil and water. This reduction in the tension should be sufficient to either eliminate or significantly reduce the capillary forces, which have trapped the oil in the formation. The recovery of a residual oil by reduction of capillary forces depends upon the capillary number (N_c). Many experiments have proposed a number of more or less equivalent definitions of N_c . The following equation is the one that commonly used⁴:

$$N_c = k\Delta P/L\sigma$$

Where k is the permeability of a 100% brine saturation medium, ΔP is the pressure drop across the length L , and σ is the interfacial tension. The N_c curve is illustrated in Figure 1, where S_{or} is residual oil saturation and S_{or}^* is residual oil saturation at low IFT. The critical value of N_c is around $2 \cdot 10^{-5}$. Below this value, residual oil saturation (S_{or}) is relatively constant. However, above the critical value, S_{or} begins to decrease gradually.

Polymer flood is aimed to displace oil in the upswept zones with emphasis on areal sweep efficiency and much more macroscopic, then it leaves the microscopic displacement efficiency. In contrary, surfactant tends to be used in increasing microscopic displacement.^{5,6} By mixing of compatible surfactant and polymer in solution develops a low-tension viscous injection fluid that has both characteristics. In turn, this LTPF can improve both microscopic and macroscopic displacement efficiency.

The objectives of this work are to evaluate the magnitude of the decrease of IFT between oil and mixed compatible surfactant-polymer compared to the surfactant alone. Then, the following works are to examine the effectiveness of mixed surfactant-polymer in coreflood-

ing experiment at tertiary production stage using fluid and native core samples beside a standard core.

II. PREPARATION OF FLUID AND CORE SAMPLES

Samples of formation water, oil, and cores were taken from two different wells, namely Well-1 and Well-2. Well-1 consists of sandstone formation and Well-2 of limestone formation. LTPF tests were prepared for 5 times, which each experiment had a different design with respect to the fluid and cores used.

A. Preparation of Formation Water

Samples of formation water were first analyzed for their composition. These were done to know the mineral contents, especially divalent ions, in which the chemical floods are usually susceptible to these ions. However, both formation water samples contain very low of divalent ions, such as Mg and Ca ions. Formation water from Well-1 contains around 21.000 ppm of dissolved solid and Well-2 18.000 ppm. The formation waters were then filtered to reduce their content of large size particles, which may hamper the flooding process.

B. Preparation of the Crude Oil

The crude oil samples used were first analyzed for their physical and chemical characteristics, such as composition, specific gravity, viscosity, and density. These properties will be used to design the injected fluid. Viscosity of the oil from Well-1 is 1.25 cp at reservoir temperature (60 °C), and Well-2 about 1.42 cp. To avoid plugging by fine particles in the crude, this crude oil were also filtered before injected into the core.

C. Determination of Physical Characteristics of the Core

The standard core used was Classach sandstone from Scotland. A plug size suitable for the core holder, i.e. 3-inch length and 1.5 inch diameter, was prepared. In addition, the native cores from Well-1 and Well-2 were also plugged. The core plugs were then washed with methanol to remove water and then with toluene to remove oil from their pores. The cores were dried in an oven and their porosity and permeability were measured. The selected core samples were analyzed for their composition and rock mineral type by X-ray diffraction (XRD). The pore structure of the core, before and after the test, was analyzed by Scanning Electron Microscope (SEM). For the XRD and SEM analyses, a small portion of the core was taken from the front end, before and after flooding test. The purpose was to know any changes that may occur on the composition, mineral type, and pore structure of the core before and after LTPF.

III. POLYMER RHEOLOGY

Synthetic polymer powder used in these experiments was obtained from a market. The powder was diluted in both formation water samples with concentration variation of 1000, 1300, 1600, and 1900 PPM. Then, the filterability polymer solutions were done using 3 mm Millipore filter of SSWP. The straight line curves of cumulative injection against time indicating that all polymer solutions fulfill the condition to be used in coreflood experiments.

Polymer solutions commonly show pseudo plastic, non-newtonian behavior in capillary flow. The viscosity tends to reduce as shear rate increases. Bulk rheology was measured using Low Shear 30. The Low Shear 30 is a rotational rheometer based on the Couette principle. The highly sensitive torque measuring system ensures rapid response to change in torque value. It is, therefore, possible to observe the elastic behavior of a solution by determination of retardation and relaxation curves. In conjunction with a Contraves Rheoscan 30 an optimum combination of the measuring program to test a solution can be obtained. The results are presented in Figures 2 and 3. The bulk behavior is slightly different from rheology in porous medium. The flowing polymer is subjected to a range of shear rate as it passed through successive pores and pore throats. The average shear rate will depend upon the pore size distribution and the tortuosity of the medium, as well as the gross parameters such as Darcy velocity, permeability and porosity. The non-newtonian behavior of the polymer is very complicated.

The adsorption and desorption of polymer used for enhanced oil recovery processes is of considerable importance, since the loss of polymer affects both the technical and economic success of the operation. The processes could be reversible or irreversible, equilibrium or nonequilibrium, and isotherm. Adsorption of polymer to the rock surface was determined using bulk static adsorption. The results were in the range of average 0.3 mg/g for 1000 ppm polymer solution to 0.9 mg/gr for 1900 ppm. These adsorptions were considered as very low.

IV. INTERFACIAL TENSION REDUCTION

Surfactant used in this research was also commercial product. This surfactant is classified as nonionic surfactant and relatively more soluble in water. The reduction of IFT due to surfactant was determined using spinning drop interfacial tensiometer and additional equipment of refractometer ABBE. The IFT of oil-water, and oil-polymer solution were firstly measured. Table 1 illustrates the results. Furthermore, the IFT of surfactant solution-oil is

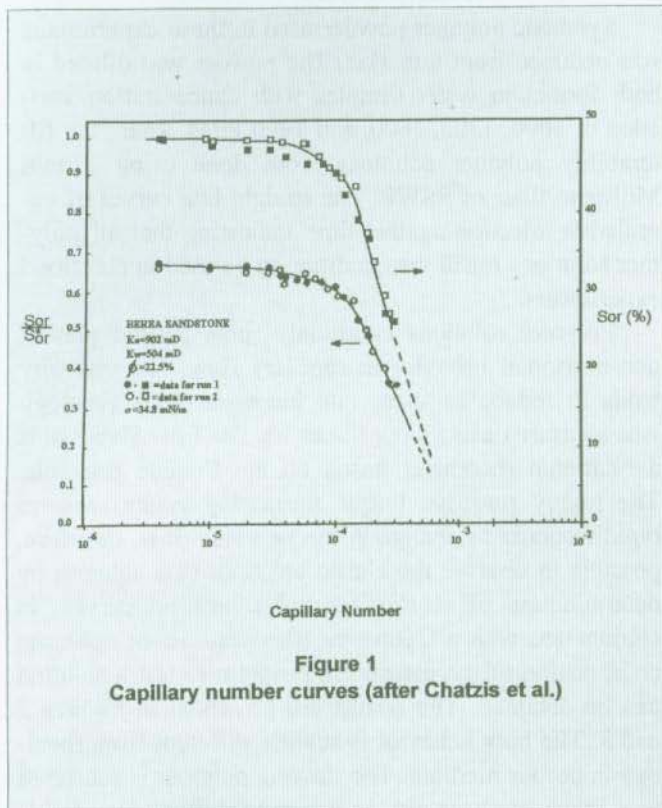


Figure 1
Capillary number curves (after Chatzis et al.)

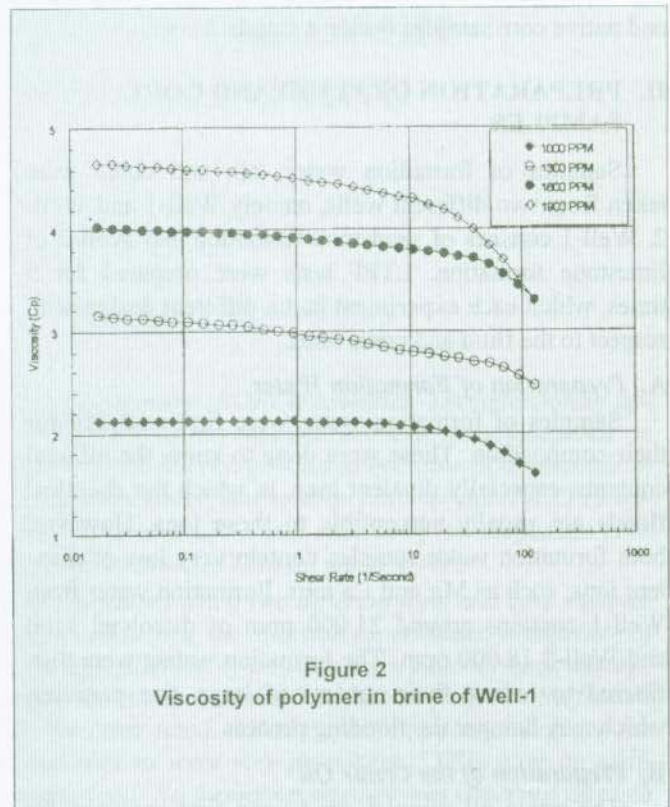


Figure 2
Viscosity of polymer in brine of Well-1

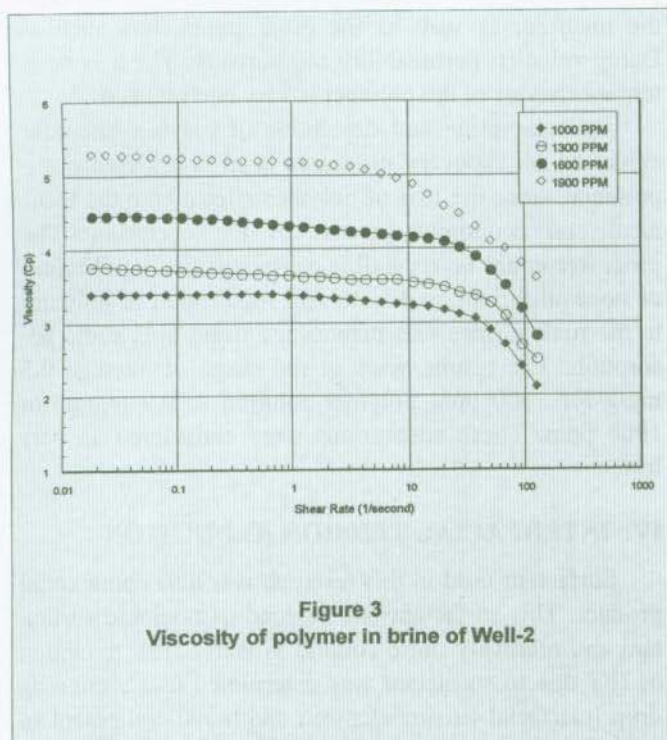


Figure 3
Viscosity of polymer in brine of Well-2

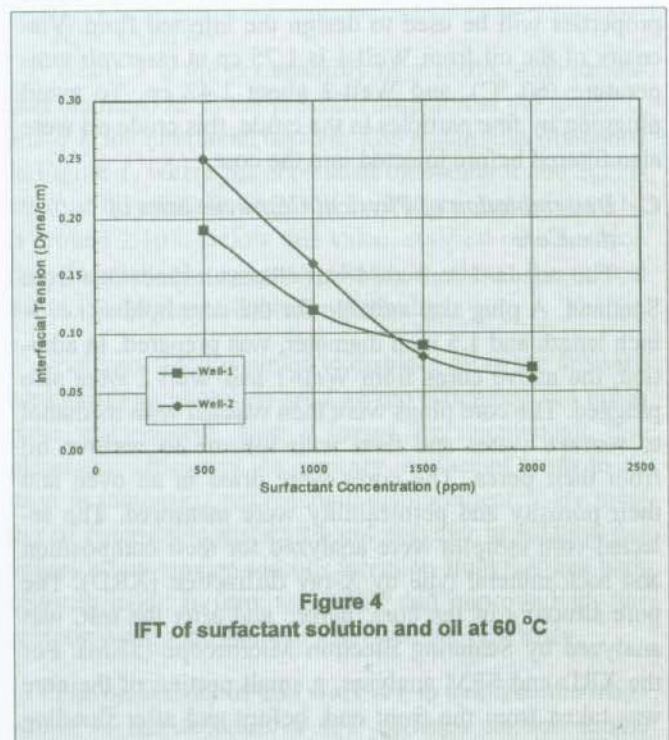


Figure 4
IFT of surfactant solution and oil at 60 °C

Table 1
IFT of oil phase and water phase (dyne/cm)

Fluid samples	Oil of well-1	Oil of well-2
Brine of Well-1	9.12	Oil of Well-2
Polymer of 1300 ppm	12.21	
Polymer of 1900 ppm	12.53	
Brine of Well-2		6.53
Polymer of 1300 ppm		5.58
Polymer of 1900 ppm		5.31

presented in Figure 4. These preliminary data have been used to make a comparison to the reduction of IFT between LTPF solutions and oil.

The LTPF systems consisted of a several mixtures of surfactant and polymer solution. These mixtures variation were made up to investigate the optimum interfacial tension reduction to oil. Firstly, polymer solution was prepared with concentration of about 1300, 1600, and 1900 ppm using formation water from Well-1 as well as Well-2. These solutions, then, were mixed with 250, 500, 1000, 1500, and 2000 ppm of surfactant. The LTPF formulation became; 250/1300, 500/1300 1000/1300, 1500/1300; 250/1600, 500/1600, 1000/1600, 1500/1600; 250/1900, 500/1900, 1000/1900, and 1500/1900. The IFT measurements were made using the similar spinning drop tensiometer equipped with temperature controller. The results were shown in Figures 5, and 6. Both figures illustrate the enhancement effect of additional surfactant into polymer solution that were very pronounced. The additional of surfactant decreased the overall IFT values, the curves fell down gradually with the additional of surfactant. However, when the optimum values were attained, the curves moved upward again. Based on these results, LTPF system of 1000/1600 and 1000/1900 were selected for core flooding experiments.

V. CORE FLOODING TESTS

The LTPF systems were prepared for core flooding experiment using a standard core, in addition of sandstone cores from Well-1, and limestone cores from Well-2. Formation water and oil were taken from Well-1, as well as Well-2, and filtered. These fluids were then placed into the tubes, inside a test rig.

A. Test Rig

The rig consisted of a 1.5-inch diameter and 3-4 inches length of Hassler type core holder. The core holder was given an overburden pressure of 1200 psig. It

was connected with three piston-equipped tubes, which contained the flooding fluid, i.e. formation water, crude oil, and LTPF solution. The tubes were provided with fluid regulating valves to enable the selection of fluid to flow into the core in the core holder. A computer controlled quizix pump was used to force the injection fluid into the tubes. Besides that a digital pressure indicator to control the flow of the fluid. In and out the coreholders, it was also provided with a number of pressure transducers to observe the fluid movement in core and to observe the pressure difference in each segments of the core. In order to maintain a stable pressure in the coreholder, it was equipped with a backpressure regulator. The fluid coming out of the core was directed to a separator and the liquid collected in a fraction collection so that both oil and water production can be measured as the function of time. The injection fluid taken, coreholder, backpressure regulator and other accessories were placed in a circulation oven, which was equipped with temperature control. The system of pressure and temperature were detected at various locations by means of calibrated thermocouples and transducers. The data collected during injection/flooding included pressure, flowrate, pressure difference, production and injection times were directly recorded in a computer.

B. Flooding Procedure

The water-saturated core was placed in the coreholder. The core sample was given confining pressure of at least twice the injection pressure, i.e. 1200 psig. The rig was heated to 60°C to simulate the reservoir temperature, and the pressure was 200 psig in the core. The core sample was first saturated with formation water to S_w 100% and its permeability was measured with respect to water (K_w). The core sample was then flooded with the oil, until it reached the irreducible water saturation, S_{wi} . The permeability to oil was then measured ($K_o@S_{wi}$) and was subjected to aging for 7 days to let the rock physical conditions back to the original state. The core was then flooded with formation water as a secondary recovery. Water injection was terminated when oil production approached zero, so that the core reached its residual oil saturation (S_{or}). Permeability measurement was then made on the core sample ($K_w@S_{orwf}$). At the next stage LTPF solution was injected in application of EOR up to 1 pore volume. Next, 6 formation water was injected to the extent of several pore volumes in order to stimulate oil production. The increase in oil production by LTPF was calculated as the oil recovery factor (RF), which is formulated as follows:

$$RF = \frac{S_{orwf} - S_{oripf}}{S_{orwf}}$$

where: S_{orwf} = oil saturation after waterflooding
 S_{orltpf} = oil saturation after LTPF.

The next stage again was to measure the permeability to water, $K_w@S_{orwf}$. From the measured K_w values, the permeability reduction factor (PRF) can be calculated according to the following formula:

$$PRF = \frac{K_w@S_{orwf} - K_w@S_{orltpf}}{K_w@S_{orwf}}$$

where $K_w@S_{orwf}$ = permeability to water after water injection

$K_w@S_{orltpf}$ = permeability to water after LTPF,

The change in the permeability during flooding was used to estimate the change in flow behavior during flooding which may be caused by fine particles or pore blocking. At the end of flooding, the core was removed from the core holder and a small portion was taken from the front end for SEM, to observe whether there was a change on rock composition, and to inspect the damage in the core. Beside the permeability measurement, the core was subjected to visual inspection and SEM analy-

sis, and quantitative X-ray analysis. These were done before and after LTPF injections.

C. Test Results on Standard Cores

LTPF system, the blend of 1000 ppm surfactant and 1900 ppm polymer, was used for only one time experiment on the Classack core. The core's porosity was about 18.64% and permeability of 200 mD. The injection of LTPF was initiated after waterflood. The chronology of operation is presented in Figure 7. The recovery factor was around 32.56% of S_{or} . The test results were shown in Table 2. The core character change was observed through three parameters. The first was the change in water permeability, before and after LTPF, as indicated by the value of PRF. The PRF was around 11.19%. The complete results are presented in Table 3.

This standard core consists of 97% quartz and only 3% feldspar, which is physically and chemically stable. The mineral contents of the core, before and after LTPF injection, are in general unchanged. The small percentages observed in some minerals might be caused by the variation in mineral distribution. SEM analysis was conducted before and after injection of LTPF. SEM images

Table 2
Enhanced oil recovery of LTPF

Core samples	Swi	Soi	Oil recovery of waterflood	Sor	Oil recovery of LTPF	
	(%PV)	(%PV)	(%OOIP)	(%OOIP)	(%Sor)	(%OOIP)
Classack-1	34.52	65.48	55.21	44.79	32.56	14.58
Sandstone-1	22.59	77.41	54.59	45.41	15.71	7.14
Sandstone-2	24.56	75.44	54.25	45.75	18.58	8.50
Limestone-1	54.70	45.30	74.42	25.58	49.82	12.74
Limestone-2	50.92	49.08	65.00	35.00	63.57	22.25

Table 3
Permeability reduction factor (PRF)

Core samples	Ka (md)	Kw (md)	Ko@swc (md)	Kw@sorwf (md)	Kw@sorltpf (md)	PRF (%)
Classack-1	200.00	121.49	90.81	20.19	17.93	11.19
Sandstone-1	18.08	4.69	3.30	1.43	1.10	23.08
Sandstone-2	15.75	6.50	3.00	1.40	1.12	20.00
Limestone-1	312.90	194.00	157.89	58.20	46.00	20.96
Limestone-2	268.30	165.00	90.91	30.29	24.00	20.77

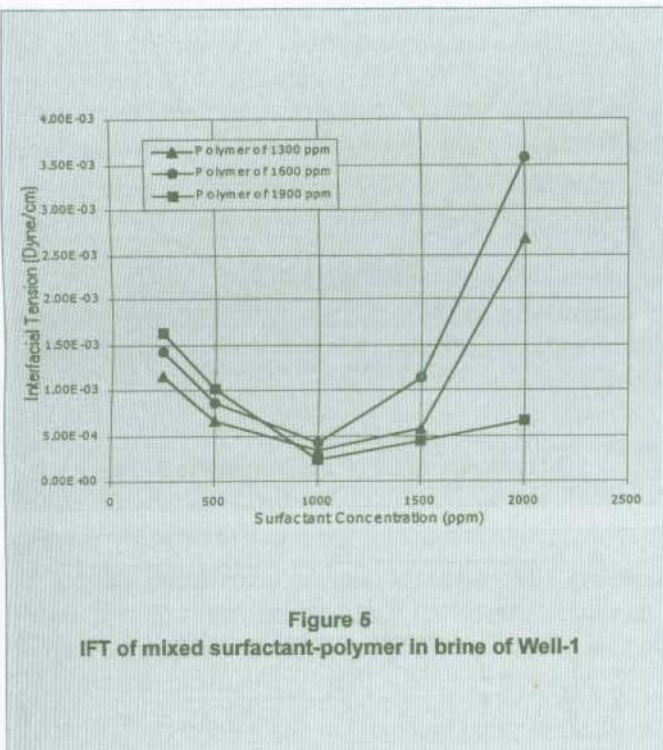


Figure 5
IFT of mixed surfactant-polymer in brine of Well-1

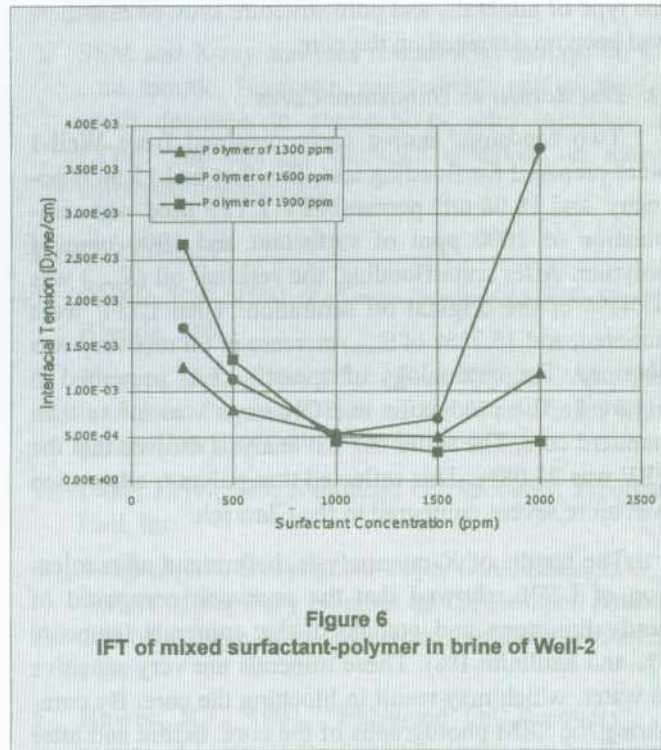


Figure 6
IFT of mixed surfactant-polymer in brine of Well-2

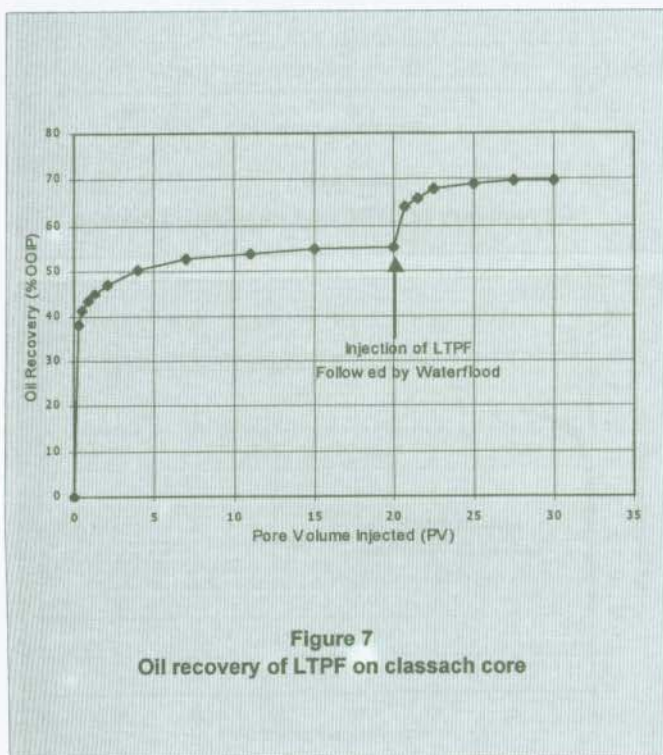


Figure 7
Oil recovery of LTPF on classach core

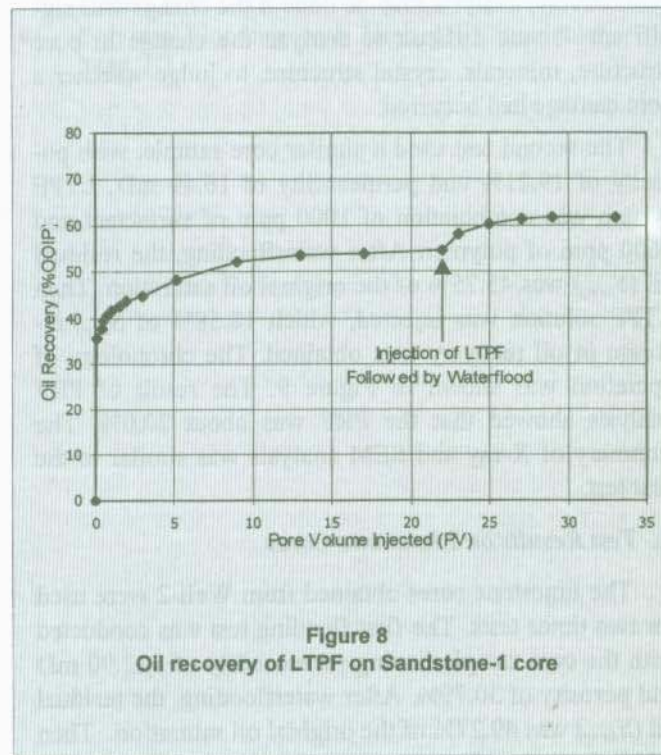


Figure 8
Oil recovery of LTPF on Sandstone-1 core

showed good pore structure with intergranular porosity. The results of the qualitative analyses, the compositions, the type of minerals, and pore structure showed that there had been no damaged on the core.

D. Test Results on Sandstone Cores

Two sandstone native cores obtained from Well-1 were prepared for flooding test. The first had 15.94% porosity and 18.08 mD permeability. LTPF used was combination of 1000 ppm of surfactant and 1900 ppm of polymer. After waterflooding, the residual oil (S_{orwf}) was 45.41% of the original oil saturation. Then LTPF were initiated, and 15.71% of S_{orwf} increase in oil recovery was obtained. The chronology of operation was presented in Figure 8. The production at EOR stage was lower than standard core. The result of PRF analysis showed that the PRF was 23.08%. This reflected that polymer adsorption was more severe compared to the Classach.

The results of X-ray analysis, before and after injection of LTPF, showed that the core was composed of sandy limestone and contained clay minerals (smectite 5% and kaolinite 1%). These minerals are very sensitive to water, which may result in blocking the core. By comparing the SEM photographs of the core, before and after injection of LTPF, it was difficult to analysis quantitatively the change that occurred on the case character. But, qualitatively, analysis may be done if the change was significant. It was difficult to analyze the change in pore structure, minerals, crystal structure, to judge whether a core damage had occurred.

The second test used a similar core sample, with porosity of 19.21% and permeability of 16.49 mD. LTPF system was combination of 1000 ppm of surfactant and 1600 ppm of polymer. After waterflooding, the residual oil (S_{orwf}) was 45.75% of the original oil saturation. Then LTPF solution was injected, which 18.58% of S_{orwf} increase in oil recovery was obtained. The chronology of operation was shown in Figure 9. The result of PRF analysis showed that the PRF was about 20.0%. The summary of X-ray and SEM analysis was similar to the first test.

E. Test Results on Limestone Cores

The limestone cores obtained from Well-2 were used for two times tests. The first flooding test was conducted with the core sample having permeability of 312.90 mD and porosity of 30.79%. After waterflooding, the residual oil (S_{orwf}) was 49.27% of the original oil saturation. Then LTPF system with composition of 1000 ppm of surfactant and 1900 ppm of polymer were injected. The production at EOR stage was very significant, 49.82% of

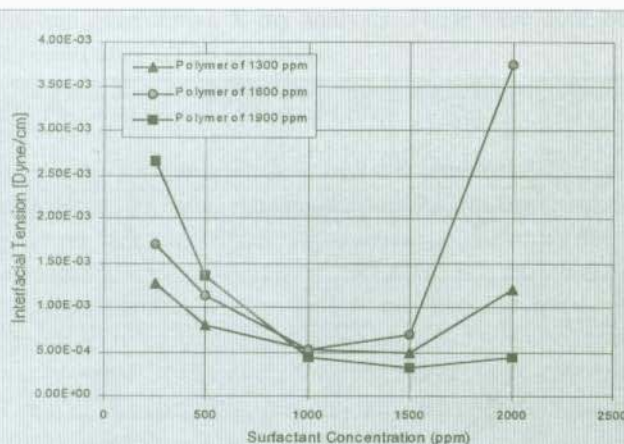


Figure 9
Oil recovery of LTPF on Sandstone-2 core

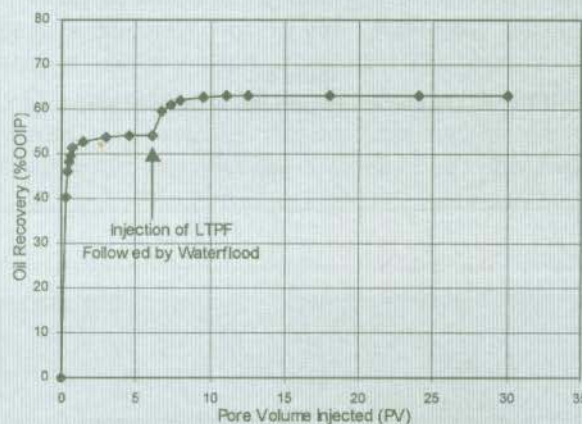


Figure 10
Oil recovery of LTPF on Limestone-1 core

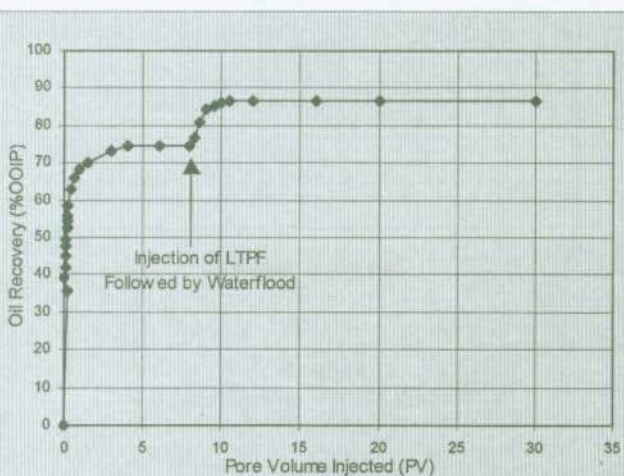


Figure 10
Oil recovery of LTPF on Limestone-2 core

Sorwf increase in oil recovery was obtained. The chronology of operation was presented in Figure 10.

LTPF used in the second test was a mixture of 1000 ppm of surfactant and 1600 ppm polymer. Rock properties were 31.75% of porosity and 268.30 mD of permeability. LTPF was initiated when waterflooding terminated. Recovery of oil was very high, i.e. 63.57% of S_{orwf} . Figure 11 illustrates the results. This suggested that LTPF was more suitable to be implemented in limestone reservoir rock.

Petrographic analysis indicated that the limestone contained pyrite (trace up to 2% of the rock volume) and dolomite (1-6% of the rock volume). This was confirmed by XRD analysis. Pyrite and dolomite are iron-bearing minerals which are only soluble in acid (HCl). However, PRF of both experiments was around 20%. These values usually tend to reduce the injectivity during flooding.

VI. CONCLUSION

1. LTPF system could not only reduce the IFT between displacing fluid and oil much lower than surfactant, but also maintain the viscosity high enough to control the preferred mobility ratio.
2. LTPF test using Classach standard core results in increasing oil recovery, 32.56% of S_{orwf} . The results obtained from two experiments on native sandstone cores are a little lower than Classach, i.e. 15.71% and 18.58%. However, the significant increase in oil recovery was demonstrated by the last two coreflood

experiment using limestone core samples. The incremental oil recoveries are 49.82% and 63.57% of Sorwf.

3. SEM and X-ray analyses revealed no damage on the core sample. However, permeability test showed a small decrease in permeability after injection of LTPF. The average decrease observed on native cores was around 20%.

REFERENCES

1. Sorbie, K.S., 1991, *Polymer-Improved Oil Recovery*, Blackie, Ltd.
2. Meyers, J.J., Pitts, M.J., Kon Wyatt, "Alkaline-Surfactant-Polymer Flood of the West Kiehl, Minnelusa Unit", *SPE/DOE* 24144.
3. Lake, L.W., 1989, *Enhanced Oil Recovery*, Prentice-Hall, Inc.
4. Delshad, M., Bhuyan, D., Pope, G.A., Lake, L.W.;; "Effect of Capillary Number on the Residual Saturation of a Three-Phase Micellar Solution", *SPE/DOE* 14911.
5. Hawes, R.I., 1991, "Enhanced Oil Recovery", *A course of Lectures for Lemigas, Indonesia* by British Geological Survey.
6. Holm, L.W., Robertson, S.D., "Improved Micellar-Polymer Flooding with High pH Chemicals", *SPE* 7583. □