DOI 10.1007/s10553-021-01298-9
Chemistry and Technology of Fuels and Oils, Vol. 57, No.4, September, 2021 (Russian Original No.4, July–August, 2021)

INNOVATIVE TECHNOLOGIES OF OIL AND GAS

RESEARCH ON FACTORS INFLUENCING WEAK ALKALI SURFACTANT POLYMER FLOODING SYSTEM

Jie Liu[1], Kai Zhang[1] ✉, Linyong Huang[1], Hui Li[2]

After 43 years of water drive development, the DG oilfield reached the stage of high recovery and ultrahigh watercut. At present, the efficiency of enhanced oil recovery (EOR) technologies, namely waterflooding, in the DG oilfield and the stable production are low. To develop and evaluate a new EOR mode, we have performed pilot tests comparing the waterflooding technique and the weak-alkali alkali/surfactant/polymer (ASP) flooding. Based on the laboratory tests, the formulation of the weak-alkali ASP flooding system has been developed. The objective of the new EOR method is to maintain the stability of the system under reservoir conditions. In this paper, we focus on the factors influencing the effectiveness of the proposed weak-alkali ASP system, including sodium and potassium ion concentrations, calcium and magnesium ion concentrations, water quality, and the shear viscosity of the solution. The results show that, depending on water quality and the ion concentrations, the interfacial tension of the developed weak-alkali ASP system can be maintained at an ultralow level below 10^{-3} mN/m. The influence of sodium and magnesium ion concentrations is slightly higher than that of potassium and calcium ion concentrations, respectively. Considering the cost-effectiveness of the new system, it is recommended that the solution be diluted with clean water mixed with oilfield sewage, and the calcium and magnesium ions be removed from the solution before preparation. When the core permeability is $95 \cdot 10^{-3}$ μm², the pore throat size has little effect on the molecular weight and viscosity of the system after shearing.

Keywords: nultrahigh watercut, weak-alkali ASP flooding, enhanced oil recovery, influencing factors.

1. Introduction

After four decades of water drive development, the DG oilfield has reached the stage of high recovery and ultrahigh watercut. At present, the effectiveness of water flooding in the DG oilfield is poor, and the resulting production rate of the enhanced oil recovery (EOR) methods is low. Therefore, to improve the recovery factor in the DG oilfield, a new EOR mode has been developed, followed by pilot field tests of binary flooding. The results prove that the new EOR technique can provide an effectiveness of

[1] College of Chemistry and Chemical Engineering, Hubei Key Laboratory for Processing and Application of Catalytic Materials, Huanggang Normal University, Huanggang 48000, China; [2] College of Earth Science and Resources, Chang'an University, Xi'an Shanxi 710064, China. *Corresponding author: Kai Zhang* ✉. *E-mail: 250610408@qq.com.* Translated from *Khimiya i Tekhnologiya Topliv i Masel*, No. 4, pp. 116–121, July–August, 2021.

10.2%. The application of the new technique is complicated by polymer blockage, low concentration of the produced fluid (less than 100 mg/L), and poor fluidity. Moreover, the adsorption capacity of the surfactant is comparatively high, and the mechanism of the surfactant is unclear. The above problems restrict the effective application of binary flooding technology. In the ASP flooding, the displacement fluid consists of the alkali, surfactant, and polymer solutions (thus abbreviated as ASP). Since the 1980s, ASP technology has been rapidly developing, both in China and abroad [1-2]. In China, in-depth scientific and technological research and numerous field tests have been carried out in the Daqing Oilfield and Shengli Oilfield. So far, the cumulative oil production stimulated by the ASP flooding in the Daqing Oilfield exceeded 18.3 million tons, accounting for 58.6% of the cumulative oil production, which is 10.7 million tons higher than that provided by conventional water flooding [3-10]. The results of both laboratory and field tests show that under similar injection pore volume conditions, the combination of the ASP flooding and water flooding can increase the recovery factor by more than 20%, which is more than 1.5 times higher than that by polymer flooding. Indeed, ASP flooding has since become a new production growth point in many oilfields, and the recovery factor can be increased up to 60%, showing broad application prospects of the technology [11-16]. Based on the previously published research, the authors have developed a new weak-alkali ASP system and studied the factors influencing the ASP system, including the impact of sodium and potassium ions, calcium and magnesium ions, water quality, and displacement activity.

2. Experimental section

2.1. Materials and instruments

The experimental water is clean water and treated re-injection sewage obtained from the DG Oilfield.

The chemical agent P2 polymer is partially hydrolyzed polyacrylamide (HPAM) with a relative molecular weight of 1000×10^4; it is a white powdery solid with 90% mass fraction produced by Daqing Refining and Chemical Company. The surface-active agent TX-3 is a laboratory-produced surfactant with an effective mass fraction of 50%. Weak alkali is Na_2CO_3 with a mass fraction of 98%. Sodium chloride and potassium chloride substances are solid powders supplied by Sinopharm Chemical Reagent Company, Ltd.

The experimental temperature is 55°C, which corresponds to the reservoir temperature.

The instruments include a TX-500c rotary drop interfacial tension meter, Brookfield DV-II+ viscosimeter, Ja2103N precision electronic balance, Jan-79 magnetic heating stirrer, JJ-1 electric stirrer, etc.

2.2. Influencing factors

In this paper, the effects of sodium and potassium ions, calcium and magnesium ions, water quality, and shearing on the viscosity and interfacial tension of the developed weak-alkali ASP system are investigated and the stability of the system evaluated.

3. Results and discussion

3.1. Effect of sodium and potassium ions on ASP system

The pretreated sewage from the DG oilfield is used to prepare a P2 polymer solution with a concentration of 2000 mg/L. The surfactant TX-3 concentration is 0.2%. The Na_2CO_3 weak alkali concentration is 1%. These three components constitute the ASP system. For experimental tests, ASP system solutions containing sodium chloride or potassium chloride in concentrations of 0.2%, 0.4%, 0.6%, 0.8%, 1%, 2%, and 3% are prepared, and the viscosity and interfacial tension of the sample solutions are measured.

3.1.1. Effect of sodium and potassium ion concentration on viscosity

The viscosity of the developed weak-alkali ASP system containing different concentrations of sodium and potassium ions has been measured, and the experimental results are shown in **Table 1**.

As can be seen from Table 1, when the sodium and potassium ion concentration is 0.2%, the viscosity of the ASP solution is 25.6 and 24.5 mPa·s, respectively. With increase in ion concentration, the solution viscosity decreases slightly. When the concentration of sodium and potassium ions is 3%, the viscosity decreases to 19.2 mPa·s, and the viscosity loss rate is 25% and 21.6%, respectively. The experimental results show that the effect of sodium ions on the ASP solution viscosity is slightly higher than that of potassium ions.

Table 1. Effect of Sodium and Potassium Ion Concentration on Viscosity

	Sodium ion concentration (%)							Potassium ion concentration (%)						
Viscosity (mPa·s)	0.2	0.4	0.6	0.8	1.0	2.0	3.0	0.2	0.4	0.6	0.8	1.0	2.0	3.0
	25.6	24.5	23.5	23.5	22.4	20.1	19.2	24.5	24.5	23.5	23.5	22.4	19.2	19.2

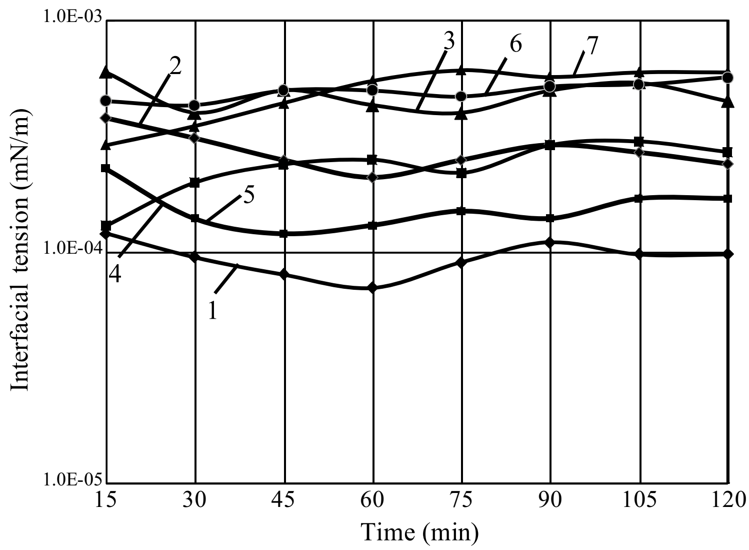

Fig. 1. Effect of sodium ion concentration on interfacial tension. 1) 0.2%; 2) 0.4%; 3) 0.6%; 4) 0.8%; 5) 1.0%; 6) 2.0%; 7) 3.0%

3.1.2. Effect of sodium ion concentration on interfacial tension

Figure 1 shows that with increase in sodium ion concentration, the interfacial tension of the weak-alkali ASP system after 2 h of measuring increases slightly. When the sodium ion concentration is 0.2%, 0.4%, 0.6%, 0.8%, 1.0%, 2.0%, and 3.0%, the interfacial tension is about $9.8 \cdot 10^{-4}$, $2.4 \cdot 10^{-4}$, $4.5 \cdot 10^{-4}$, $2.7 \cdot 10^{-4}$, $1.7 \cdot 10^{-4}$, $6.0 \cdot 10^{-4}$, and $5.7 \cdot 10^{-4}$ mN/m, respectively. The experimental results show that when the concentration of sodium ions ranges between 0.2% and 3.0%, the interfacial tension of the system can reach an ultralow level below 10^{-4} mN/m, depending on time. The experimental results also prove that the sodium ion concentration has little impact on the interfacial tension in the system.

3.1.3. Effect of potassium ion concentration on interfacial tension

Figure 2 shows that with increase in potassium ion concentration, the interfacial tension of the developed weak-alkali ASP system solution first increases slightly and then tends to be stable. When the concentration of potassium ions is 0.2%, 0.4%, 0.6%, 0.8%, 1%, 2% and 3%, and the time of measurements is 120 min, the interfacial tension of the ASP system is $1.5 \cdot 10^{-4}$, $2.7 \cdot 10^{-3}$, $1.4 \cdot 10^{-3}$, $1.0 \cdot 10^{-3}$, $1.8 \cdot 10^{-4}$, $6.3 \cdot 10^{-4}$, and $4.5 \cdot 10^{-4}$ mN/m, respectively. The experimental results show that when the potassium ion concentration ranges between 0.2% and 3.0%, the interfacial tension of the ASP system can reach an ultralow level below 10^{-3} mN/m. The experimental results also prove that the potassium ion concentration has little impact on the interfacial tension in the system. Nonetheless, comparing the effect of equal concentrations of the sodium and potassium ions, we can see that the impact of potassium ions is slightly higher than that of the sodium ions.

3.2. Effect of calcium and magnesium ions on ASP system

The P2 polymer solution is prepared with a polymer concentration of 2000 mg/L and water obtained from the pretreated sewage of the DG oilfield. The TX-3 surfactant concentration is 0.2%. The weak-alkali Na_2CO_3 concentration is 1.0%. The three components are mixed to produce the designed ASP system. Then sample solutions are prepared containing 0.01%, 0.02%, 0.03%, 0.04%, and 0.05% concentration of calcium chloride or magnesium chloride. Finally, the relationship between the viscosity and interfacial tension of the sample solutions and the time is measured.

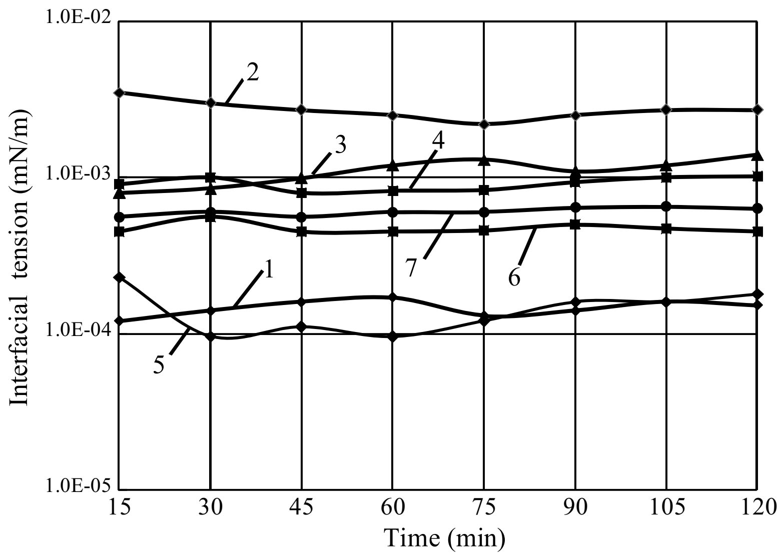

Fig. 2. Effect of potassium ion concentration on interfacial tension. 1) 0.2%; 2) 0.4%; 3) 0.6%; 4) 0.8%; 5) 1.0%; 6) 2.0%; 7) 3.0%

Table 2. Effect of Calcium and Magnesium Ion Concentration on Viscosity

	Calcium ion concentration (%)					Magnesium ion concentration (%)				
Viscosity (mPa·s)	0.01	0.02	0.03	0.04	0.05	0.01	0.02	0.03	0.04	0.05
	25.6	25.6	25.3	25.4	25.0	24.5	24.5	24.3	24.2	24.2

3.2.1. Effect of calcium and magnesium ion concentrations on viscosity

The viscosity of the ASP solutions with different concentrations of calcium and magnesium ions is measured, and the experimental results are shown in **Table 2**.

When the concentration of calcium and magnesium ions is 0.01%, the viscosity of the ASP solution is 25.6 and 24.5 mPa·s, respectively. With increase in ion concentration, the viscosity of the system remains unchanged. When the concentration of calcium and magnesium ions increases to 0.05%, the viscosity of the system is 25.0 and 24.2 mPa·s, respectively. The experimental results show that the impact of calcium ions on viscosity is slightly higher than that of magnesium ions.

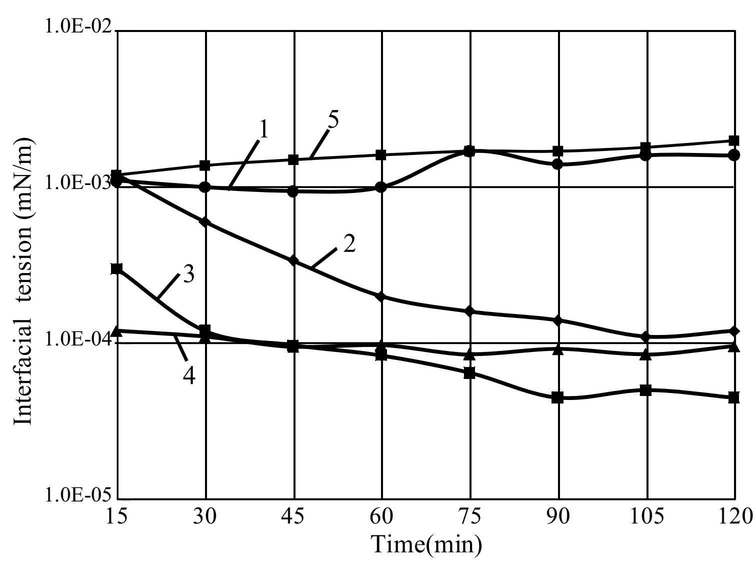

Fig. 3. Effect of calcium ion concentration on interfacial tension. 1) 0.01%; 2) 0.02%; 3) 0.03%; 4) 0.04%; 5) 0.05%

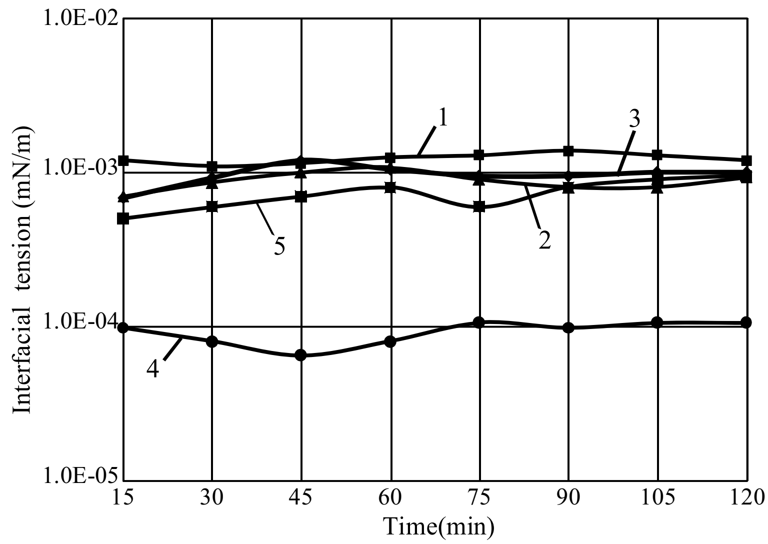

Fig. 4. Effect of magnesium ion concentration on interfacial tension. 1) 0.01%; 2) 0.02%; 3) 0.03%; 4) 0.04%; 5) 0.05%

3.2.2. Effect of calcium ions on interfacial tension

As shown in **Fig. 3**, when the calcium ion concentration increases from 0.01% to 0.04%, the interfacial tension of the ASP decreases slightly. However, when the calcium ion concentration is 0.05%, the interfacial tension of the solution increases. When the concentration of calcium ions is 0.01%, 0.02%, 0.03%, 0.04%, and 0.05% and the time is 120 min, the interfacial tension is $1.6 \cdot 10^{-3}$, $1.2 \cdot 10^{-4}$, $4.5 \cdot 10^{-5}$, $9.6 \cdot 10^{-5}$, and $2.0 \cdot 10^{-3}$ mN/m, respectively. The results show that when the calcium ion concentration ranges between 0.01% and 0.05%, the interfacial tension of the developed weak-alkali ASP system can reach an ultralow level below 10^{-3} mN/m. As can be seen, the calcium ion concentrations within the tested range have little impact on the interfacial tension of the complex weak-alkali system.

3.2.3. Effect of magnesium ions on interfacial tension

Figure 4 shows that when the concentration of magnesium ions increases from 0.01% to 0.05%, the interfacial tension of the ASP system solution decreases slightly. When the magnesium ion concentration is 0.01%, 0.02%, 0.03%, 0.04%, and 0.05% and the time is 120 min, the interfacial tension is $1.2 \cdot 10^{-3}$, $9.3 \cdot 10^{-4}$, $1.0 \cdot 10^{-3}$, $1.1 \cdot 10^{-4}$, and $9.5 \cdot 10^{-4}$ mN/m, respectively. The results suggest that when the magnesium ion concentration ranges between 0.01% and 0.05%, the interfacial tension of the system can reach an ultralow level below 10^{-3} mN/m.

Figures 3 and 4 show that equal concentrations of calcium and magnesium ions have a different impact on interfacial tension of the ASP system, and the influence of magnesium ions is slightly higher than that of the calcium ions.

3.3. Effect of water quality on ASP system

To evaluate the effect of water quality on the ASP system parameters, three types of polymer solutions are prepared using water of different quality: clean water, a mixture of clean water and the DG oilfield injection sewage at 4:6 ratio, and the DG oilfield injection sewage. The P2 polymer concentration is 2000 mg/L, the TX-3 surfactant concentration is 0.2%, and the Na_2CO_3 weak alkali concentration is 1.0%. The three components are formulated to produce the developed weak-alkali ASP system. Then the viscosity and interfacial tension of the solutions of different water quality are measured.

Figure 5 shows that the quality of water used in the solutions has a great influence on the viscosity of the developed ASP system. With increase in salinity, the viscosity of the system gradually decreases. Moreover, for all three types of solutions, the viscosity decreases with time. After 40 days, the viscosity of the clean water solution, clean water/sewage solution, and oilfield sewage solution changes from high to low and is 24.1, 16.0, and 13.2 mPa·s, respectively. Thus, the viscosity retention rate for the three types of solutions is 66.4%, 59.9%, and 51.6%, respectively.

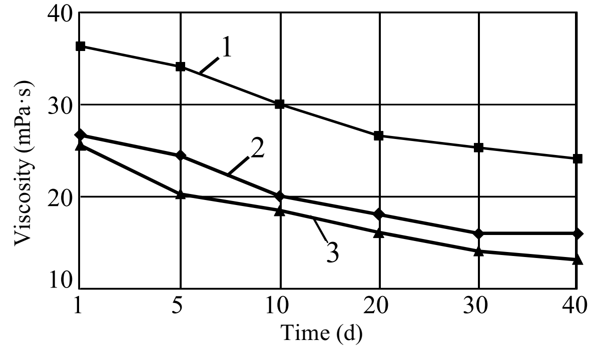

Fig. 5. Effect of water quality on viscosity. 1) clean water; 2) a mixture of clean water and oilfield injected sewage (4:6); 3) oilfield injected sewage

Based on the experimental results and considering the oilfield requirements and cost reduction, we suggest that water used in the ASP system be diluted with the pretreated oilfield sewage. Considering the negative influence of calcium and magnesium ions, the ions should be removed from the solvent before preparing the P2 polymer solution.

3.4. Effect of shearing in a pore throat on ASP system

When the system is subjected to high-speed shearing, it suffers a rapid decrease in the molecular weight and viscosity of the solution. The phenomenon can affect the viscoelasticity of the developed ASP system, thus reducing the swept volume expanding effect. To study the impact of shearing, we have prepared a sample solution containing the DG oilfield injecting sewage as the solvent and P2 polymer in a concentration of 2000 mg/L. The TX-3 surfactant concentration is 0.2%. The Na_2CO_3 concentration is 1.0%. The three components are formulated to constitute the ASP system. Then, we simulate the ASP system shearing in a pore throat and study the effect of shearing on the molecular weight and the viscosity of the system.

Figure 6 shows that before shearing, the solution viscosity of the weak-alkali ASP system is 25.6 mPa·s. After the sample is subjected to shearing for 20 s, the relative molecular weight of the polymer decreases to $715 \cdot 10^4$, and the viscosity decreases to 14.2 mPa·s. After that, the ASP solution is used for displacement in the natural core with a permeability of $95 \cdot 10^{-3}$ μm^2. The results show that after the displacement the relative molecular mass is reduced to $639 \cdot 10^4$, and the viscosity decreases to 13.2 mPa·s, indicating that shearing not only affects the molecular weight of the polymer but causes shrinkage of the polymer coil size. Thus, the polymer can easily pass through the pore throat. When the core permeability is $95 \cdot 10^{-3}$ μm^2, the pore throat radius has little effect on the molecular weight and viscosity of the system.

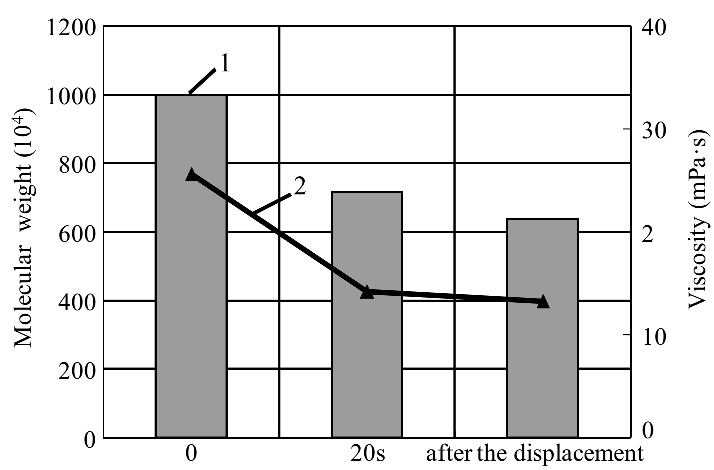

Fig. 6. Effect of shearing before and after the displacement in a natural core on molecular weight and viscosity. 1) molecular weight; 2) viscosity

4. Conclusions

1. The effect of sodium ions on the viscosity of the developed weak-alkali ASP system is slightly higher than that of potassium ions. When the concentration of sodium and potassium ions ranges between 0.2% and 3.0%, the interfacial tension of the system is below 10^{-3} mN/m. The effect of calcium ions on the viscosity of the system is slightly higher than that of magnesium ions. When the concentration of magnesium ions is between 0.01% and 0.05%, the interfacial tension of the system is below 10^{-3} mN/m. Comparing the solutions with equal concentrations of calcium and magnesium ions, it can be seen that the influence of magnesium ions on the interfacial tension in the system is slightly higher than that of calcium ions.

2. The influence of water quality shows that the viscosity of the ASP system depends on the salinity of the solvent used for preparing the solutions. The viscosity of a weak-alkali ASP system diluted with clean water is 24.1 mPa·s; in the case of the clean water/oilfield sewage in the ratio of 4:6, the viscosity is 16 mPa·s; when the oilfield sewage is used for the solution, the viscosity is 13.2 mPa·s; the corresponding viscosity retention rate is 66.4%, 59.9%, and 51.6%, respectively. The effect of the solvent type on the interfacial tension of the ASP system is similar, and in all cases, the interfacial tension can reach an ultralow level below 10^{-3} mN/m. Based on the results and considering the cost-effectiveness of the ASP system preparation, it is recommended that the developed weak-alkali ASP system be prepared with a mixture of clean water with oilfield sewage, and calcium and magnesium ions be removed from the solution prior to the system preparation.

3. The process of displacement in the natural core is simulated by experimental tests. The results show that after the displacement the molecular weight of the system is reduced to $639 \cdot 10^4$ and the viscosity decreases to 13.2 mPa·s. The decrease in polymer molecular weight after shearing occurs simultaneously with decrease in molecular coil size after shearing, which enables the polymer molecules to pass through the pore throat. When the core permeability is $95 \cdot 10^{-3}$ μm^2, the pore throat size has little effect on the molecular weight and the viscosity of the ASP system after shearing.

Acknowledgments

The authors thank Prof. C. T. Au for valuable suggestions.

REFERENCES

1. K. Wyatt, M. J. Pitts, and H. Surkalo, “Mature waterfloods renew oil production by alkaline-surfactant-polymer flooding,” *SPE Eastern Regional Meeting*, Lexington, Kentucky, USA (2002).

2. M. Pratar and M. S. Gauma, “Field implementation of alkaline-surfactant-polymer (ASP) flooding: a maiden effort in India,” *SPE Asia Pacific Oil and Gas Conference and Exhibition*, Perth, Australia (2004).

3. D. Wang and Y. Hao, “Results of two polymer flooding pilots in the central area of Daqing oil field,” *SPE Annual Technical Conference and Exhibition*, Houston, Texas, USA (1993).

4. D. Wang, Z. Zhang, J. Cheng, et al., “Pilot test of alkaline-surfactant-polymer flooding in Daqing Oilfield,” *SPE Res. Eng.*, **12**, 229-233 (1993).

5. C. Wang, B. Wang, X. Cao, et al., “Application and design of alkaline-surfactant-polymer system to close well spacing pilot Gudong Oilfield,” *SPE Western Regional Meeting*, Long Beach, California, USA (1997).

6. Z. Qu, Y. Zhang, X. Zhang, et al., “A successful ASP flooding pilot in Gudong Oilfield,” *SPE/DOE Improved Oil Recovery Symposium*, Tulsa, Oklahoma, USA (1998).

7. H. Gu, R. Yang, S. Guo, et al., “Study on reservoir engineering: ASP flooding pilot test in Karamay Oilfield,” *SPE International Oil and Gas Conference and Exhibition in China*, Beijing, China (1998).

8. D. Wang, J. Cheng, et al., “Summary of ASP pilots in Daqing Oilfield,” *SPE Asia Pacific Improved Oil Recovery Conference*, Kuala Lumpur, Malaysia (1999).

9. J. Vargo, J. Turner, et al., “Alkaline-surfactant-polymer flooding of the Cambridge Minnelusa Field,” *SPE Rocky Mountain Regional Meeting*, Gillette, Wyoming (1999).

10. J. Zhang, K. Wang, F. He, et al., “Ultimate evaluation of the alkali/polymer combination flooding pilot test in Xing Long Tai Oilfield,” *SPE Asia Pacific Improved Oil Recovery Conference*, Kuala Lumpur, Malaysia (1999).

11. M. J. Pitts, P. Dowling, K. Wyatt, et al., “Alkaline-surfactant-polymer flood of the Tanner Field,” *SPE/DOE Symposium on Improved Oil Recovery*, Tulsa, Oklahoma, USA (2006).

12. X. Wan, M. Huang, H. Yu, et al., “Pilot test of weak alkaline system ASP flooding in secondary layer with small well spacing,” *International Oil & Gas Conference and Exhibition in China*, Beijing, China (2006).

13. K. A. Elraies and I. M. Tan, “Design and application of a new acid-alkali-surfactant flooding formulation for Malaysian reservoirs,” *SPE Asia Pacific Oil and Gas Conference and Exhibition*, Brisbane, Queensland, Australia (2010).

14. D. Wang D, H. Xia, S. Yang, et al., “The influence of visco-elasticity on micro forces and displacement efficiency in pores, cores, and in the field,” *SPE/EOR Conference at Oil & Gas West Asia*, Muscat, Oman (2010).

15. Y. Zhu, Q. Hou, H. Yuan, et al., “Synthesis and properties of petroleum sulfonates for weak alkali ASP/alkali-free SP combination flooding,” *SPE Asia Pacific Oil and Gas Conference and Exhibition*, Brisbane, Queensland, Australia (2010).

16. A. Sharma, A. Aziz-Yar, B. Clayton, et al., “The design and execution of an alkaline-surfactant-polymer pilot test,” *SPE Improved Oil Recovery Symposium*, Tulsa, Oklahoma, USA (2012).