

Laboratory Study of an Anti-Temperature and Salt-Resistance Surfactant-Polymer Binary Combinational Flooding as EOR Chemical

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ABSTRACT: Experimental studies were conducted to enhance the oil recovery by a surfactant-polymer binary combinational flooding system. The surfactant-polymer binary combinational flooding was obtained by mixing the surfactants with the poly(AM-NVP-AS)-1 which was an anti-temperature and salt-resistance tercopolymer and successfully synthesized via free radical polymerization using acrylamide (AM), N-vinyl pyrrolidone (NVP), allyl sulfonate (AS) as raw materials. The initiator was redox system including water-soluble azo compound (AIBA-2HCl) and sodium bisulfite (NaHSO₃). Petroleum carboxylate dodecyl dibasic carbonylic acid sodium (C12DAS) and carboxyl betaine dodecyl dimethyl betaine (C12DB) were selected in this article. Compared with the surfactant-HPAM, the surfactant-poly(AM-NVP-AS)-1 binary combinational system showed higher apparent viscosity and lower interfacial tension at high temperature and salinity conditions as the result of a better capacity of anti-temperature, salt-resistance, and swept volume. The recovery could enhance over 17% based on the core flooding test under the mineralization of 10,000 mg/L at 65°C. © 2013 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* **2014**, *131*, 39984.

KEYWORDS: surfactant-polymer binary combinational flooding; enhanced oil recovery; interfacial tension; anti-temperature; salt-resistance

Received 11 May 2013; accepted 18 September 2013

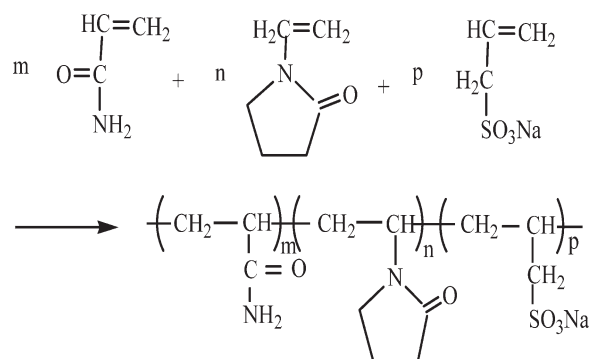
DOI: 10.1002/app.39984

INTRODUCTION

Polymer flooding pilot tests¹ and commercial field tests² have been successfully conducted in oil field. Now commercial application on a large scale is in process. It is generally thought that polymer flooding can increase oil recovery by improving swept volume and the mobility ratio of water to oil. In many oil fields, polymer flooding can improve oil recovery by 10% of original oil in place (OOIP) over water flooding. To further improve oil recovery and displacement efficiency, alkali-surfactant-polymer and micellar-polymer flooding pilot tests have been conducted in Daqing and Shengli oil field for instance, and all achieved satisfying technological results. Compared with the polymer, the cost of chemical flooding was greatly reduced due to the slight amount of the surfactant. Clark, et al.³ published articles to present the technology of ASP in early time. Then, Song,⁴ Wang,^{5,6} and French⁷ et al. recorded that more than 15% OOIP incremental recovery was achieved by ASP over water flooding in some oil fields. Thus, this technology has gradually become one of the crucial technologies on the sustainable development of oil fields.⁸ However, there was

some problem in the application of ASP flooding. The use of alkali caused the dispersion of the formation clay, the migration and formation of alkali scale, resulting in decreased permeability of formation. Alkali reduced the polymer viscosity and viscoelasticity, especially the flexibility as a result of making sweep efficiency lower simultaneously. The alkali made the recovery solution an emulsion of water in oil with high viscosity, which may affect the well capacity and greatly increase the difficulty of demulsification. Therefore, further studies should be made on the surfactant-polymer flooding with less or even no alkali of ASP. Relevant researches have already been conducted in the laboratory and have obtained approved achievement so far.

A lot of studies have indicated that the initial surfactant-polymer binary combinational flooding refers to the active water being injected as slugs to reduce the interfacial tension between oil and water, and then the polymer slug being injected to control mobility.⁹⁻¹¹ It was proposed to mix high concentration surfactants with polymer to form blending solution for enhancing oil recovery subsequently. Surfactant micelle microemulsion-polymer miscible flooding was the one which



Scheme 1. The synthesis of poly(AM-NVP-AS).

had the best displacement efficiency among the all. The SP flooding pilot tests were technically successful in foreign countries like the United States and domestic sites such as Daqing oil field. However, due to the high cost of large usage of surfactants, this technology has not been extended.

Recently, many researches such as the solution character, the interface rheology, and interfacial viscosity of surfactant-polymer system have been done by domestic researchers.^{12–14} But the aspect of field application tests were less reported, especially about high temperature and salinity reservoirs. Residual oil saturation has been dropped sharply in the oil pilot tests¹⁵ via low interfacial tension of surfactant-polymer binary combinational displacing agent in sand layer of McCleskey, Texas Ranger oilfield of U.S. Oryx Energy Company in Eastland County, and the increased oil was equivalent to 25% of irreducible oil after water flooding.

As a new flooding method, surfactant-polymer flooding system could maximize the viscosity and elasticity of the polymer which was higher than that of the ASP system, resulting in the increase of the swept volume and the mobility ratio of water to oil and the improvement of the displacement efficiency. Through selecting suitable surfactant and polymer, a system could be obtained which performs both viscoelastic behavior and low interfacial tension which could decrease the negative impacts of emulsion processing and producing ability, while eliminating the alkali scale phenomenon thoroughly. Based on the preliminary evaluation and the economical feasibility, therefore, in the near future, a much larger scale of SP flooding field tests to be performed in Oil Field is foreseeable.

Inspired by the predecessors' methods, herein, we hope to obtain a novel anti-temperature and salt-resistance surfactant-polymer binary combinational flooding to search for a new highly efficient EOR chemical based on AM copolymer and surfactant synergy aiming to reach the level of practicability (see Scheme 1).

EXPERIMENTAL

Materials

Acrylamide (AM) was obtained commercially and purified by crystallization from a water–ethanol mixture. Sodium hydrate (NaOH), N-vinyl pyrrolidone (NVP), allyl sulfonate (AS), NaHSO₃, water-soluble azo compound (AIBA·2HCl), OP-10, tetradecyl trimethyl ammonium bromide (C14TAB), dodecyl

dibasic carboxylic acid sodium (C12DAS), dodecyl dimethyl betaine (C12DB), NaCl, MgCl₂·6H₂O, CaCl₂, and other chemicals were commercially available, and used directly without further purification. Water was doubly distilled and deionized by passing through an ion exchange-column. All other chemicals were of analytical grades unless otherwise noted.

Synthesis of the Copolymer AM-NVP-AS

The AM-NVP-AS copolymer was synthesized by free radical polymerization. Monomers in appropriate feed composition as well as NaHSO₃-AIBA·2HCl initiator (indicated loading, and 1/1 mol ratio) were taken along with deionized water in a three necked flask assembled with a nitrogen inlet. The reactor was kept in water bath with magnetic stirring arrangement. Copolymerization was performed at the indicated temperature under N₂ atmosphere for an indicated time. The polymer was then isolated by precipitation with acetone or water–ethanol and dried in vacuum oven at 60°C for 7 h to yield the corresponding copolymer.

Preparation of the Surfactant-Polymer Binary

Combinational Flooding

The poly(AM-NVP-AS)-1 was dissolved to 5000 mg/L by the saliniferous water with its components being listed in Table I, and then it was diluted into 1500 mg/L to be spared. Petroleum carboxylate and carboxyl betaine were compounded in appropriate ratio of 4 : 1, and mixed with the polymer. The resulting solution was adjusted to pH 7 and placed for 20–40 min to form stable oil in water emulsion, namely the surfactant-polymer system (SP1 system).

Measurements and Characterization

Copolymerization reactions were performed under an atmosphere of nitrogen in flame glassware with magnetic stirring unless otherwise indicated. The infrared spectrum was recorded on a Perkin Elmer RX-1 Spectrophotometer (Beijing Rayleigh Analytical Instrument) using a KBr disk. The ¹H-NMR was recorded on a Bruker 400 MHz nuclear magnetic resonance spectrometer (Bruker Daltonics, U.S.A.). The apparent viscosities of copolymer and SP system solutions were measured using a Brookfield DV-III Ultra Programmable Rheometer (Brookfield Engineering Laboratories, U.S.A.). Interfacial tension measurements were performed on a Texas-500 Rotating Drop Interfacial Tension Meter (America).

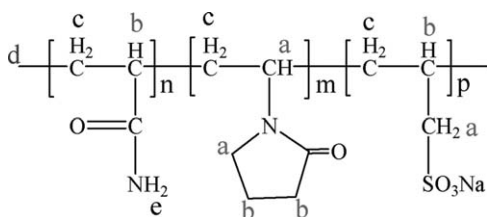
RESULTS AND DISCUSSION

IR Spectra and ¹H-NMR Spectra Analysis

The structure of copolymers AM-NVP-AS was confirmed by IR and ¹H-NMR spectroscopy as shown in Figure 1. In the

Table I. The Component of the Saliniferous Water

N.O.	Salt	Salt concentration (g/L)
1	NaCl	6.19
2	KCl	0.049
3	NaHCO ₃	0.2625
4	Na ₂ SO ₄	0.0542
5	CaCl ₂	1.579
6	MgCl ₂ ·6H ₂ O	1.9351



Scheme 2. The structure of the poly(AM/NVP/AS)-1 with marked positions of hydrogen.

Figure 1(a), the major functional groups identified in the spectrum included N—H stretching vibration (3426.41 cm^{-1}), C=O deformation of the saturate (1659.16 cm^{-1}). The peak at 2928.32 cm^{-1} and 2787.66 cm^{-1} indicated the presence of $-\text{CH}_2-$ groups stretching vibration. The peak at 1052.02 cm^{-1} and 1186.42 cm^{-1} suggested that the $-\text{SO}_3-$ groups stretching vibration, while the peak at 1411.95 cm^{-1} and 1450.37 cm^{-1} showed the existence of pyrrolidone annulations stretching vibration.

The $^1\text{H-NMR}$ spectra of the poly(AM/NVP/AS)-1 was shown in Figure 1(b). The peak at 3.37 ppm was assigned to the $-\text{CH}-$ proton of $[-\text{NCH}_2\text{O}-]$. The chemical shift value at -3.31 ppm identified the $-\text{CH}_2-$ protons on pyrrolidone annulations next to the N (the position of a in Scheme 2). The chemical shift value at 3.37 ppm was due to the $-\text{CH}_2-$ of $[-\text{SO}_3\text{Na}]$. The protons of the aliphatic $-\text{CH}-$ of polymeric chain and $-\text{CH}_2-$ on pyrrolidone annulations, the position of b in Scheme 2, appeared at 2.21–1.77 ppm. The protons of the aliphatic $-\text{CH}_2-$ of polymeric chain (position c) appeared at 1.44–1.24 ppm. A characteristic peak due to the $-\text{CH}_3$, which was the terminal group of poly(AM/NVP/AS)-1 (position d) was observed at 0.89–0.85 ppm.

As expected, IR and $^1\text{H-NMR}$ spectra confirmed the presence of different monomers in the copolymer AM-NVP-AS. Both of the spectrum of poly(AM/NVP/AS)-1 indicated that these monomers have been successfully connected to the polymer chain as expected.

The Optimization of the Poly(AM/NVP/AS)-1 Synthesis Conditions

On the basis of the single factor experiments, the orthogonal trail was used in optimization of the synthesis conditions.¹⁶ The experiments considered the following factors: the feed ratio of AM and NVP, the addition of AS and initiator, the monomer concentration, reaction temperature, and reaction time. All factors and levels in orthogonal trails were in Table II with the amount of AS being fixed at 5% as well as 8 h reaction time. It was available to get optimized conditions for C3, D1, B2, and A2 by orthogonal experiment: the feed ratio of AM and NVP was 15 : 1, and initiator was 1.5% with 30% monomer concentration in 30°C .

The Properties Comparison Among Poly(AM/NVP/AS)-1 and Other Polymers

Before the preparation of the surfactant-polymer system, the properties of poly(AM/NVP/AS)-1 have been compared with poly(AM/NVP/AS)-2 (It was obtained by the initiator of $\text{NaHSO}_3-(\text{NH}_4)_2\text{S}_2\text{O}_8$) and HPAM. From Figure 2(a–d), it is

obvious that the poly(AM/NVP/AS)-1 was better in increasing viscosity, anti-temperature, salt-resistance, and high shear-resistance property.

Optimization of the Surfactant-Polymer System Conditions

The Selection of Surfactant. With the existence of surfactant, the interfacial tension of the polymer system could be reduced sharply. In this article, samples chosen, respectively, from the cationic, anionic, nonionic, and zwitterionic surfactant, and the surfactants were tested and compared carefully (Figure 3). Based on an extensive literature review and the experiment results, due to the interactive synergy among all surfactants, the effect of two or multiple surfactants was much better than that of a single one.^{17,18} Therefore, the C12DAS and C12DB were selected to compound and the ratio was 2 : 1.

According to Figure 3, it is apparent that the interfacial tension of C14TAB, C12DAS, and OP-10 were almost stable after reached the lowest; however, the interfacial tension of zwitterionic surfactant C12DB dropped to the lowest firstly and then raised to a certain value, and finally tended to stable. Meanwhile, the compounded system had the same trend, and it had the lowest interfacial tension and the minimum area is the

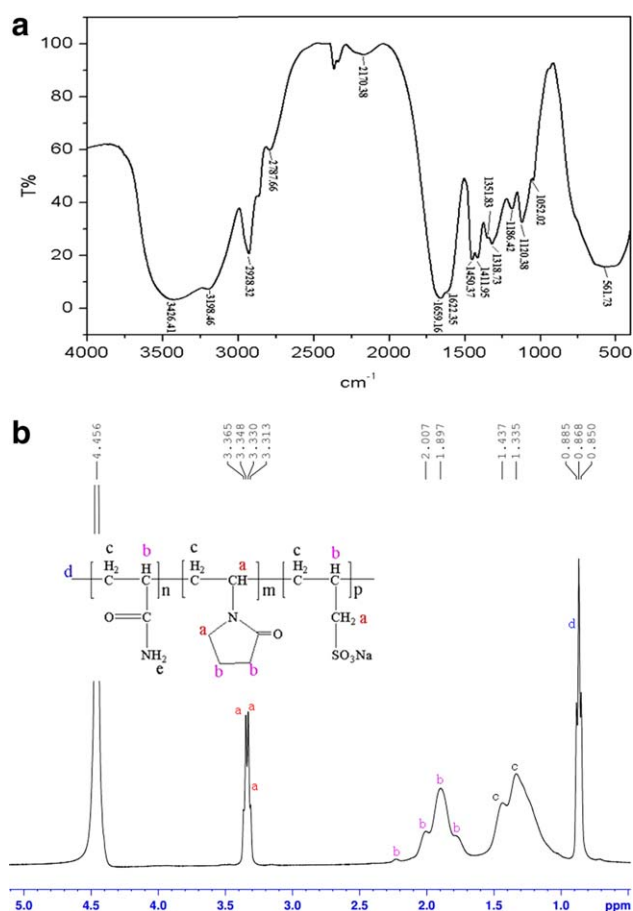


Figure 1. (a) IR spectrum of terpolymer AM-NVP-AS. (b) $^1\text{H-NMR}$ spectrum of terpolymer AM-NVP-AS in D_2O . [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table II. $L_9(3^4)$ Orthogonal Experiment Table of Polymerization Conditions

N.O.	A AM : NVP	B The amount of initiator (%)	C The monomer concentration (%)	D reaction temperature (°C)
1	10 : 1	0.5	20	30
2	10 : 1	1.0	25	40
3	10 : 1	1.5	30	50
4	15 : 1	0.5	25	50
5	15 : 1	1.0	30	30
6	15 : 1	1.5	20	40
7	20 : 1	0.5	30	40
8	20 : 1	1.0	20	50
9	20 : 1	1.5	25	30

^aAll reactions were performed for 8 h, pH = 7.0, AS: 5 wt %.

^bTested all copolymer solutions at 2000 mg/L by Brookfield DV-III viscometer at 65°C.

widest as well. Therefore, the combined system of C12DAS and C12DB was adopted.

The Combined Ratio of Dodecyl Dibasic Carboxylic Acid Sodium (C12DAS) and Dodecyl Dimethyl Betaine (C12DB). The effect of different ratios of C12DAS and C12DB was investi-

gated [Figure 4(a)]. It was found that the best results could be obtained by measuring the interfacial tension (IFT) as the ratio of C12DAS to C12DB was 3 : 1 of 500 mg/L, and the corresponding IFT reached the 10^{-3} mN/m order of magnitude (about 9.8×10^{-3} mN/m). The final choice of the ratio was 4 : 1 after considering the interfacial tension and the price of the surfactants.

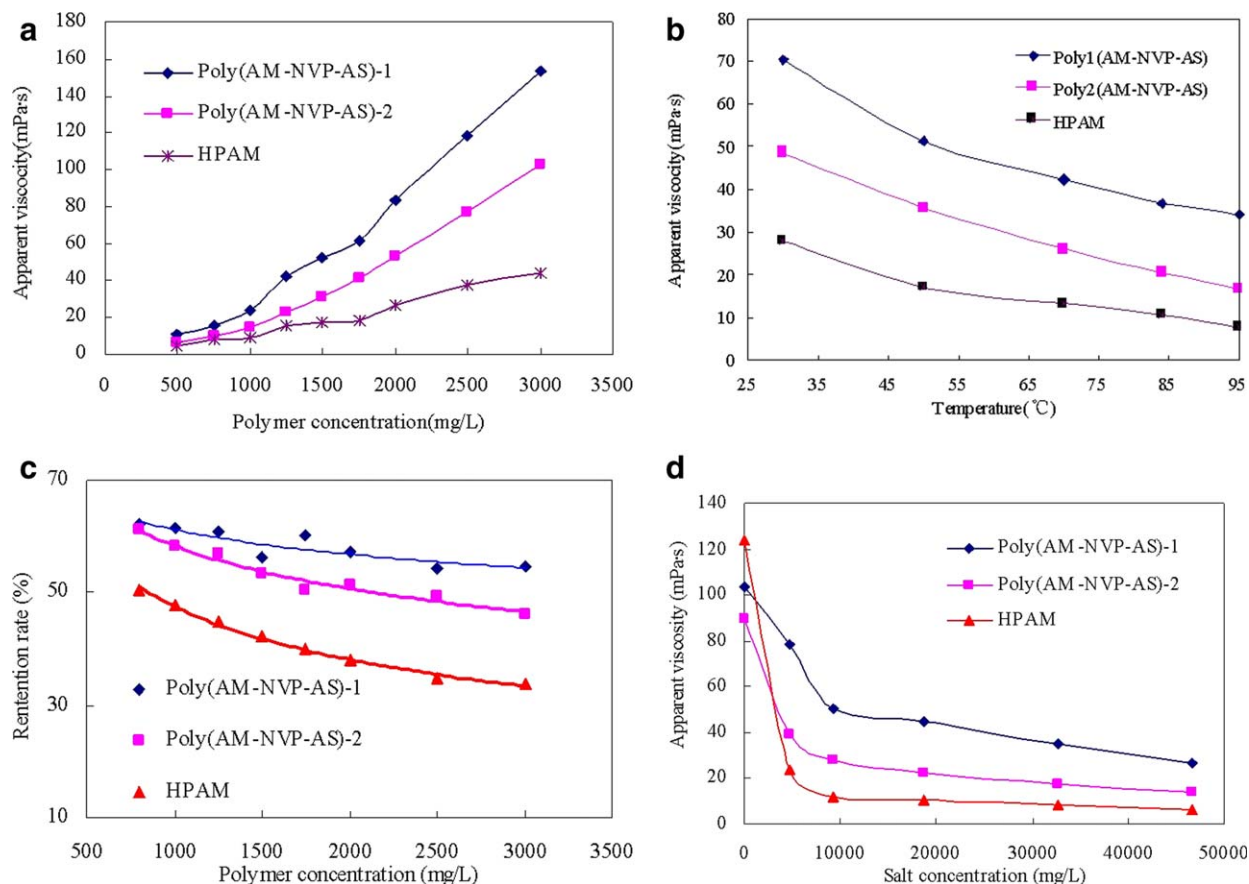


Figure 2. (a) The apparent viscosity of different concentrations for polymers. (b) The apparent viscosity of polymers in different temperature. (c) The relationship of the polymers concentration and the retention rate. (d) The relationship of the ion concentration and the apparent viscosity (all copolymer solution were tested at 2000 mg/L by Brookfield DV-III rheometer at 7.34 s^{-1} and 65°C using 00[#] and 61[#] rotor). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

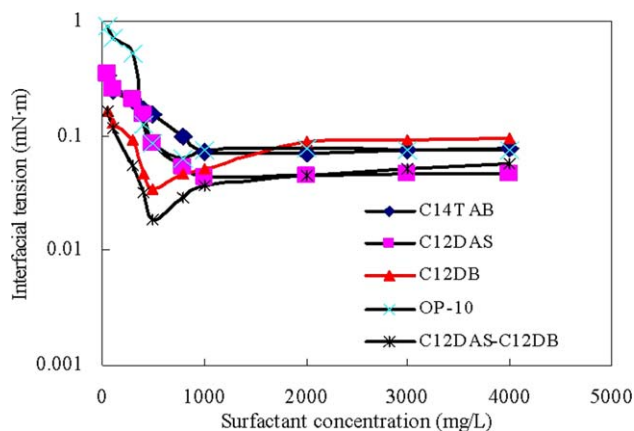


Figure 3. The relationship of different surfactant's concentration and interfacial tension (all surfactant solutions were tested by Texas-500 Rotating Drop Interfacial Tension Meter at 500 mg/L and 80°C). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The Concentration of the Surfactant. Having realized the most promising ratio of C12DAS to C12DB, it was found that the best concentration of C12DAS and C12DB was 500 mg/L with the ratio of 4 : 1 [Figure 4(b)]. Low IFT (about 9.9×10^{-3} mN/m) was obtained as the concentration of 400–600 mg/L. Besides, the results could not be improved when adding more surfactant. We may explain that the micelle was dispersed when the surfactant was in low concentration, and with the increase of the micelle, the micellar aggregation resulted in the decrease of the interfacial tension. After the micelle concentration reached the critical micelle concentration (cmc), the excess surfactants caused a certain negative impact on the interfacial tension although theoretically that should be kept in a stable state.

The Concentration of Polymer. The effect of different concentration of poly(AM/NVP/AS)-1 to SP1 system was investigated from 800 to 2500 mg/L [Figure 5(a)], it was indicated that it had similar trends of different surfactant (300, 500, 1000 mg/L) and the best polymer concentration was 1500 mg/L. From Figure 5(a) we could see, the impact of polymer concentration on the interfacial tension was greater in low concentration, and vice versa. It is because of AM-NVP-AS molecules enriched in the aqueous phase that more active components were brought into the aqueous phase, leading to the change of the surfactant partition coefficient in oil phase/aqueous phase. After being added to the solution, the polymer was adsorbed mainly at the oil–water interface, which resulted in the decrease of the surfactants' adsorption area, and increasing the interfacial tension as well.

The Dynamic Interfacial Tension. The dynamic interfacial tension (DIFT) refers to that the oil–water interfacial tension changes with the time. It reflects the time required by the oil–water interfacial tension reaching the lowest (t_{\min}), and the relationship between the adsorption characteristics and the adsorption amount of the surfactants at the oil–water interface. Hence, the investigation of surfactant-polymer solution DIFT is meaningful. Different polymer concentrations obtain

various t_{\min} . The higher the concentration is, the shorter the time is required.

This article investigated individual surfactants and surfactant-polymer solution DIFT [Figure 5(b)]. The experiment results demonstrated that before added the polymer, the oil–water interfacial tension declined slowly over time, and then dropped to the lowest (600 s) and stabilized finally. After adding the polymer, the oil–water interfacial tension first remained unchanged, and then decreased to the lowest over time, and increased finally.

The phenomenon due to the reduction of oil–water interfacial tension is actually a dynamic process of surfactants adsorption on the oil–water interface. The change of interfacial tension with time is dominated by the corresponding dynamics, and the surfactants accumulate upon the interface when the adsorption rate is faster than the desorption rate, resulting in a drop of interfacial tension. The polymer increases the viscosity of the surfactant-polymer solution, and increases the surfactants' desorption time on the oil–water interface as well, hence, the t_{\min} was increased. Simultaneously, the increase of surfactant adsorption on the interface may form a high concentration

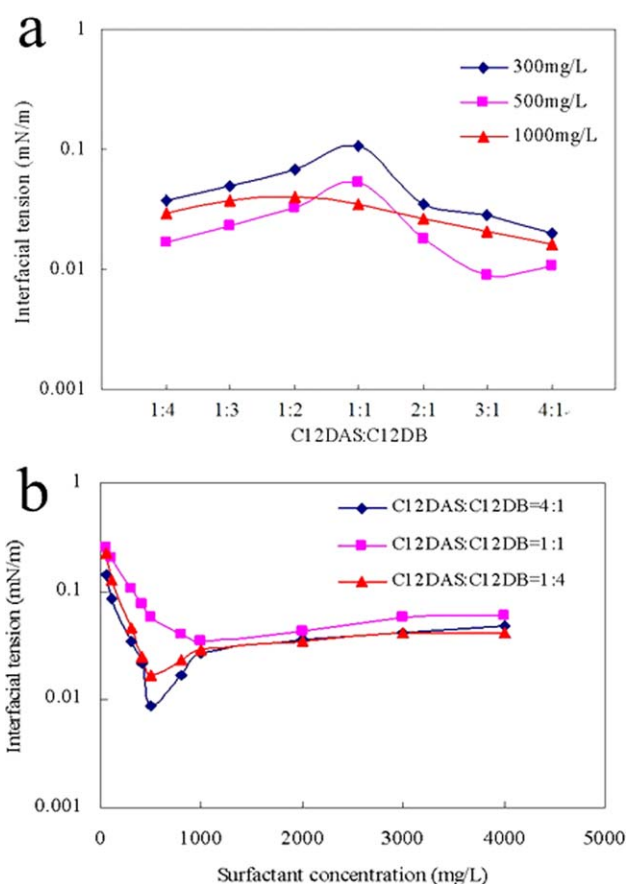


Figure 4. (a) The effect of surfactants compounded ratio to interfacial tension. (b) The relationship of concentration and the interfacial tension (all surfactant solutions were prepared using the salinity water of 10,000 mg/L [NaCl], pH = 7. All surfactant solutions were tested by Texas-500 Rotating Drop Interfacial Tension Meter at 65°C). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

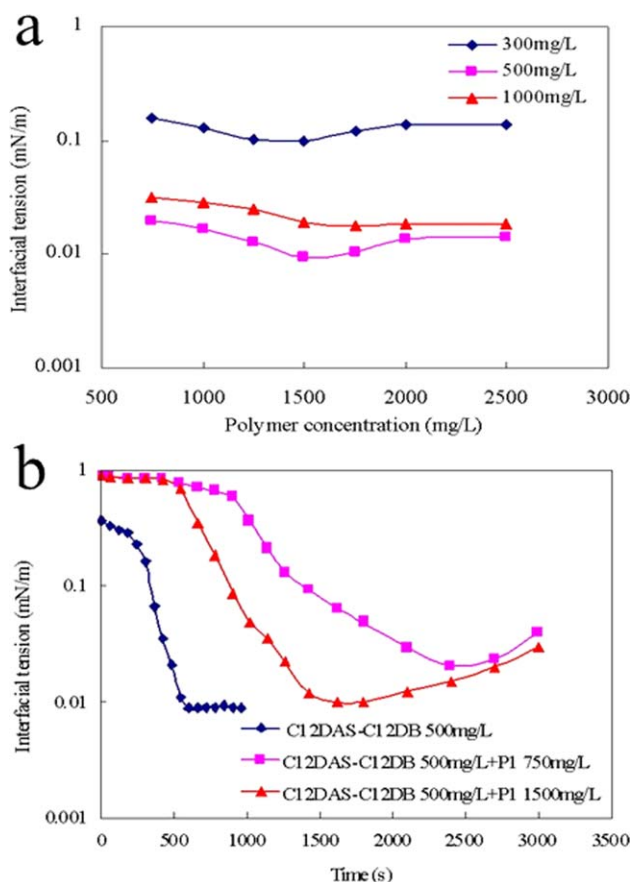


Figure 5. (a) The effect of the polymer concentration to interfacial tension. (b) The effect of the time to interfacial tension (all polymer solutions were prepared using the salinity water of 10,000 mg/L [NaCl], pH = 7, C12DAS : C12DB = 4 : 1. All solutions were tested by Texas-500 Rotating Drop Interfacial Tension Meter at 65°C). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

gradient, and leading to the increase of the desorption rate which may result in the decrease of the concentration as well as the increase of interfacial tension again.¹⁹ Therefore, it should be placed 25–30 min after the SP1 system prepared.

Degree of Mineralization Rate. The salinity tolerance of compounded surfactants solution (300, 500, and 1000 mg/L) was investigated with 100–12,000 mg/L NaCl (Figure 6). Figure 6 illustrated that the surfactant solution obtained the lowest IFT (about 9.9×10^{-3} mN/m) at 10,000 mg/L NaCl (500 mg/L). The minimum in interfacial tension occurs when the partition coefficient is about unity on both sides of interface (two-phase system),²⁰ or when the surfactant partition coefficient between residual oil phase and the remaining aqueous phase was one (three-phase system), and then, the salinity achieved optimal degree. No matter the salinity is higher or lower than the optimal value, it may make the distribution coefficient of surfactant molecules deviate from the state of one, resulting in increasing the interfacial tension. When the concentration of salt (sodium chloride) exceeded the limit, it would not only raise the interfacial tension also precipitate the carboxylate as well as enlarge the adsorption of the surfactant and increase the consumption.

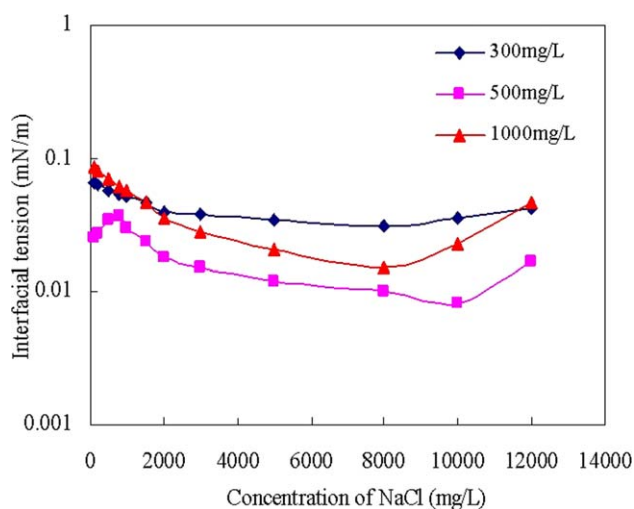


Figure 6. The effect of the mineralization (sodium chloride) to interfacial tension (conditions: pH = 7, C12DAS : C12DB = 4 : 1. All solutions were tested by Texas-500 Rotating Drop Interfacial Tension Meter at 65°C). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Performance Evaluation of the Surfactant-Polymer Binary Combinational Flooding

The rheological properties of polymer solution are closely related to its solution properties. Meanwhile, the polymer solution rheological properties are the integrated embodiment of its micro phase structure and functions.^{21,22}

To know better of the SP1 system, three systems—poly (AM/NVP/AS)-1, surfactant-poly (AM/NVP/AS)-1 (SP1), and surfactant-HPAM were taken account of evaluation in this part.

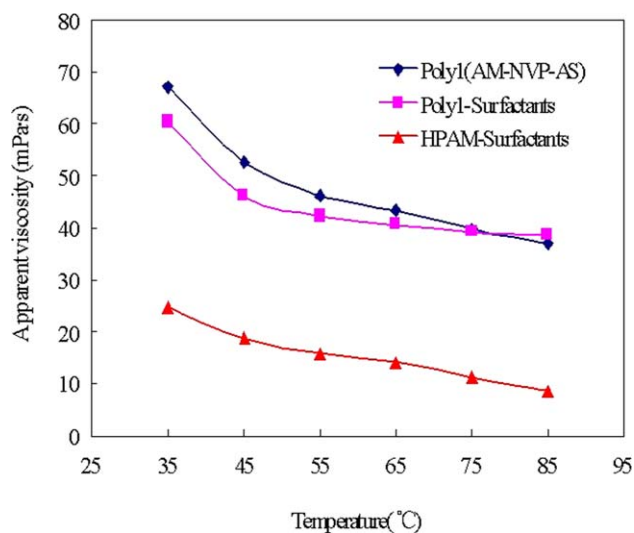


Figure 7. The relationship of temperature and apparent viscosity (conditions: pH = 7, polymer concentration 1500 mg/L, surfactant concentration 500 mg/L, salinity 8000 mg/L, C12DAS : C12DB = 4 : 1. All systems were tested by Brookfield DV-III rheometer at 7.34 s^{-1} and 65°C using 00[#] rotor). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The Temperature-Tolerance. Compared with surfactant-HPAM which has been widely used in EOR, the SP1 system showed better thermal stability. The thermal stability of the three systems was studied by aging at different temperature (35–85°C, Figure 7).

Interestingly, it was found that all three systems had analogous trends although poly(AM/NVP/AS)-1 had higher viscosity. However, the SP1 system exhibited better temperature-resistance and absolute value of apparent viscosity than poly(AM/NVP/AS)-1 at 85°C, about 65% of the solution apparent viscosity was retained. The phenomenon was likely attributed to the effect of temperature. When the temperature was lower, intramolecular group associations were dominant. As the temperature increased, a large number of associating groups aggregated together to form reversible, physical, supermolecular structures by strong Van der Waals interactions, and the polymer chains entangled with each other via hydrogen-bond interactions in the aqueous solution.²³ But the intermolecular interaction is unstable, especially under high temperature, even degradation and molecular chain fractures are likely to occur, resulting in the apparent viscosity reduction.

The Salt-Resistance. The SP1 system was finally applied in the processes of oil recovery, and the underground water contained amount of inorganic ions like Na^+ , Ca^{2+} , and Mg^{2+} that would be a great influence on the properties of the SP1 system in the aqueous solution. In Figure 8(a–c), with an increasing cations concentration in the polymer solution, the stretched polyelectrolyte chain started coil up due to a reduction in intra-anionic electrostatic repulsion. At a certain salt concentration, the amount of cations present was sufficient to complete the shrinking. Hence, beyond that certain salt concentration, the addition of salt could not change the corresponding apparent viscosity more, and this is typical of a nonelectrolyte.²⁴

For SP1 system, it showed that the apparent viscosity was gradually increasing slightly at extremely low NaCl concentration [Figure 8(a)] may be explained by the salt-solubilization, the theory of ionic charge resonance. And the apparent viscosity of SP1 system could be up to 78.3 mPa s even when the NaCl was 12,000 mg/L; viscosity retention rate was 78.8%. The SP1 system solution also showed moderate property against CaCl_2 and the apparent viscosity could reach 50 mPa s when the concentration of CaCl_2 increased to 1500 mg/L with the viscosity retention rate of 50.3% [Figure 8(b)]. However, anti- MgCl_2 revealed that the apparent viscosity was only 49.7 mPa s in 800 mg/L solution and 45.3 mPa s in 1500 mg/L with the viscosity retention rate of 40.6% [Figure 8(c)].

Flooding Experiment. To study and analyze the feasibility of the SP1 system to enhance oil recovery, this article took the HPAM-surfactant into comparison. The viscosity of simulation crude oil was 70.34 mPa s at the shearing rate of 7.34 s^{-1} and 65°C. The one-dimensional sand packed model of 250 mm in length and 25 mm in diameter with the porosity of 22.5% and permeability of $846.1 \times 10^{-3} \mu\text{m}^2$ was used for the experiments.²⁵ Core flooding displacement process was shown in Figure 9(a). The results have been shown in Figure 9(b). The diagram indicated that the SP1 system could enhance the oil recovery 17.3%

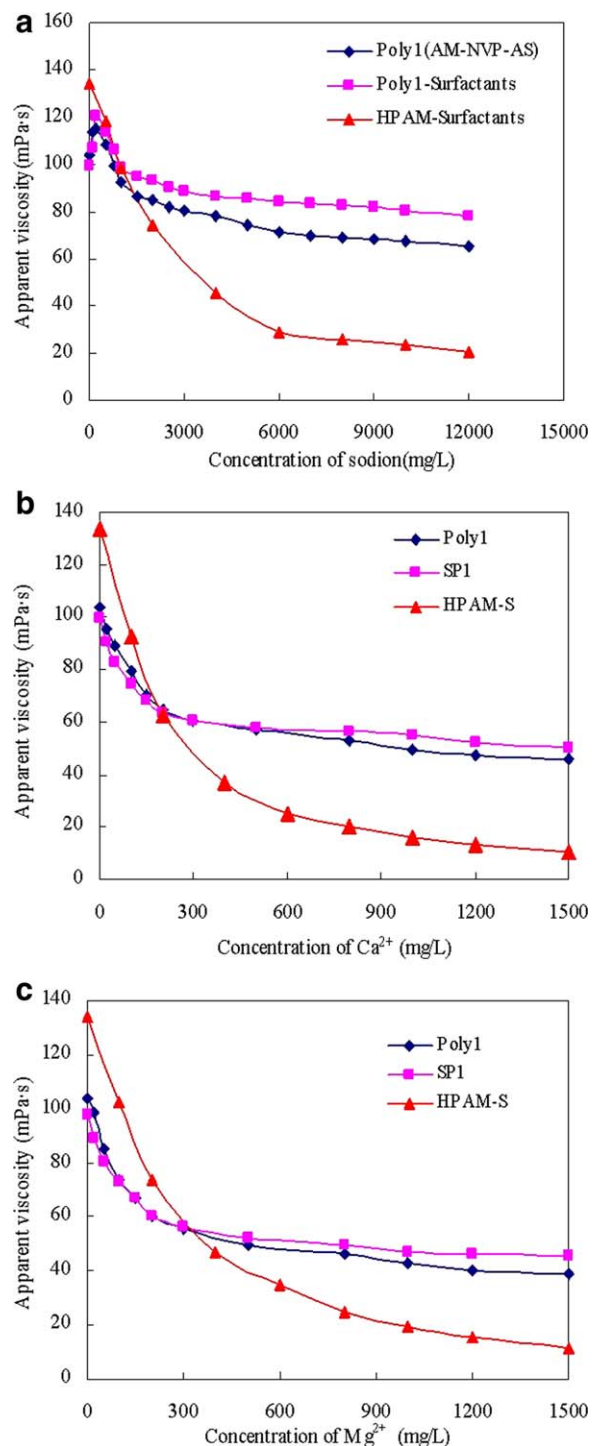


Figure 8. (a) The effect of NaCl concentration on apparent viscosity. (b) The effect of CaCl_2 concentration on apparent viscosity. (c) The effect of MgCl_2 concentration on apparent viscosity (conditions: pH = 7, polymer concentration 1500 mg/L, surfactant concentration 500 mg/L, C12DAS : C12DB = 4 : 1. All systems were tested by Brookfield DV-III rheometer at 7.34 s^{-1} and 65°C using 00# and 61# rotor). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

compared with the water flooding. The result indicated that the SP1 system reveals a better ability of EOR than the ordinary polymers like HPAM under same conditions.^{26,27}

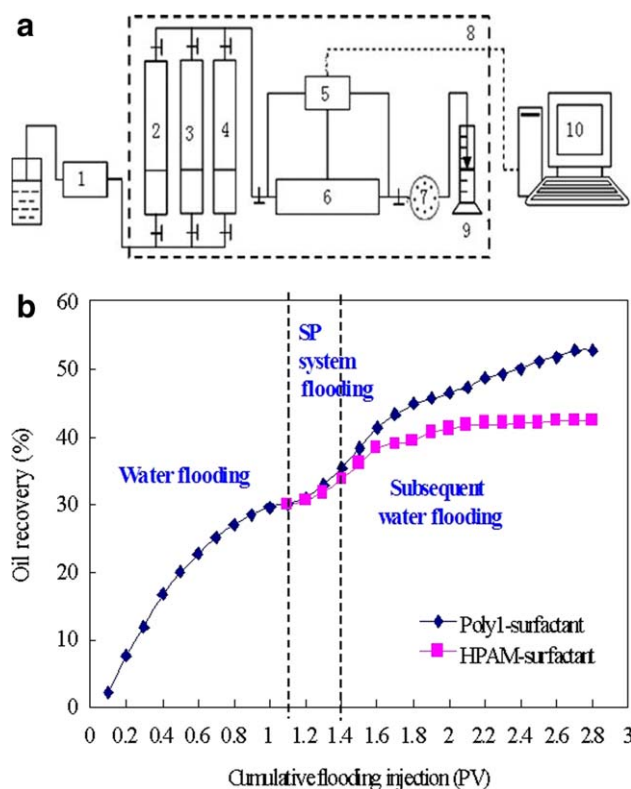


Figure 9. (a) The one-dimensional Sand-packed Model for EOR. (b) The relationship of cumulative flooding injected and oil recovered (conditions: pH = 7, polymer concentration 1500 mg/L, surfactant concentration 500 mg/L, C12DAS : C12DB = 4 : 1. All the core flooding were tested at 65°C). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

CONCLUSIONS

This article has introduced a new surfactant-polymer binary combinational system as a flooding. The polymer poly(AM/NVP/AS)-1 was achieved creatively by water-soluble azo compound (AIBA·2HCl) and sodium bisulfite (NaHSO₃), which had much better properties than the one poly(AM/NVP/AS)-2 by (NH₄)₂S₂O₈-NaHSO₃. Compared with surfactant-HPAM which has been widely used in EOR, this water-soluble surfactant-poly(AM/NVP/AS)-1 system revealed an excellent capability of solubility, temperature tolerance and brine compatibility. The results of core flooding test showed EOR was up to 17.3% when mineralization attained 10,000 mg/L at 65°C. Based on the results above, the surfactant-polymer binary combinational system might be a good candidate as an EOR chemical for high-temperature reservoirs with high-density brine fluid. And the further investigation on the applications of the corresponding surfactant-polymer binary combinational flooding is ongoing.

ACKNOWLEDGMENTS

This work was supported by the Open Fund (PLN1212) of State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (Southwest Petroleum University) and the Specialized Research Fund for the Doctoral Program of Higher Education

(20125121120011) and the key program for Undergraduate Extra-curricular Open Experiment (KSZ1246) of Southwest Petroleum University: synthesized and characterized of the polyamidoamine dendrimers polymer.

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