



King Saud University
Arabian Journal of Chemistry

www.ksu.edu.sa
www.sciencedirect.com



ORIGINAL ARTICLE

Study of polyacrylamide-surfactant system on the water–oil interface properties and rheological properties for EOR

S.Z. Mahdavi ^{a,b}, J. Aalaie ^{b,*}, T. Miri ^{a,*}, S.M.R. Razavi ^c, M.R. Rahmani ^{b,d}

^a Department of Chemical Engineering, Faculty of Engineering, Arak University, Arak 38156-8-8349, Iran

^b Chemical, Polymeric & Petrochemical Technology Development Research Division, Research Institute of Petroleum Industry (RIPI), P.O. Box 14665-137, Tehran, Iran

^c Young Researchers and Elite Club, South Tehran Branch, Islamic Azad University, Tehran, Iran

^d Department of Chemical Engineering, Babol Noshirvani University of Technology, Babol, Iran

Received 16 February 2016; accepted 18 May 2016

KEYWORDS

Polyacrylamide;
Surfactants;
Phase behavior;
Micro emulsion;
Rheological behavior;
Properties of water/oil interface

Abstract Nowadays, due to the remarkable oil reduction in oil fields, enhanced oil recovery (EOR) techniques have been considered by a large number of scientists and company. Situ oil extraction is normally done by these techniques with high efficiency. In this particular study, five different surface active agents (surfactant), two kinds of oil with various API, two kinds of sulfonated polyacrylamide, two different electrolyte solutions with various TDS and two distinctive alcohols were tested and evaluated. An optimal formulation in terms of the properties and quantity of materials has to be used in order to enhance oil recovery, achieved by investigation of surface tension and the phase behavior of mentioned substances. Rheological behavior of polymer flooding and surfactant was studied. Employing this formulation, the maximum micro emulsion of oil in water occurred. Due to the synergy between surfactant and alcohol (as a co-surfactant), relatively lower amounts of surfactants were used which led to the dip in the cost of operation, and ultimately the efficiency of operation improved.

© 2016 The Authors. Production and hosting by Elsevier B.V. on behalf of King Saud University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

One of the well-known approaches to chemically enhanced oil recovery (CEOR) is the chemical applications. Chemicals are used for above purpose such as surfactants, alkalis, polymers, and sometimes alcohols as co-surfactants that often inject into the reservoir as surfactants, polymers, alkalis/surfactants (AS), alkalis/surfactants/polymers (ASP), and surfactants/polymers (SP) systems. The alkalis and surfactants decrease interfacial tension between oil and water, and polymers raise the viscosity of solution. In addition to that, polymers can

* Corresponding authors.

E-mail addresses: aalaiej@ripi.ir (J. Aalaie), t-miri@araku.ac.ir (T. Miri).

Peer review under responsibility of King Saud University.



Production and hosting by Elsevier

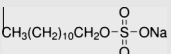
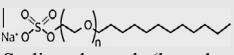
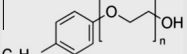
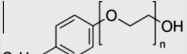
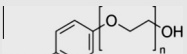
<http://dx.doi.org/10.1016/j.arabjc.2016.05.006>

1878-5352 © 2016 The Authors. Production and hosting by Elsevier B.V. on behalf of King Saud University.

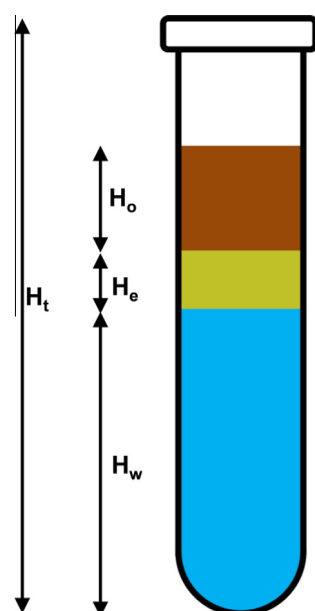
This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Please cite this article in press as: Mahdavi, S.Z. et al., Study of polyacrylamide-surfactant system on the water–oil interface properties and rheological properties for EOR. Arabian Journal of Chemistry (2016), <http://dx.doi.org/10.1016/j.arabjc.2016.05.006>

Table 1 Some properties of surfactant.

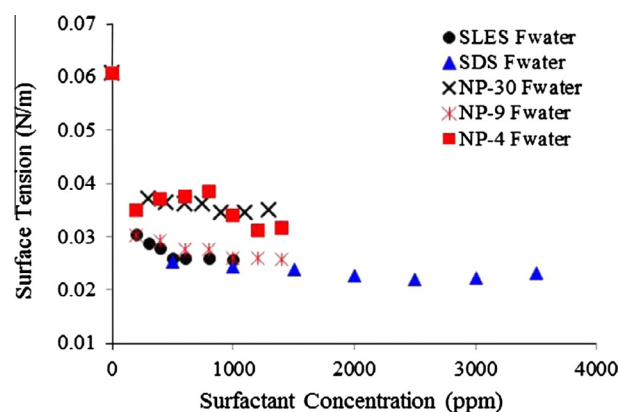
Surfactant and molecular structure	Abbreviation	HLB	Cat
$\text{CH}_3(\text{CH}_2)_{10}\text{CH}_2\text{O}-\text{S}(\text{O})_2\text{ONa}$  Sodium lauryl sulfate	SDS	40	Anionic
 Sodium laureth (lauryl ether) sulfate $n = 2-3$	SLES	41.2	Anionic
 Nonylphenol polyethylene glycol ether 30M $n = 30$	NP 30	17.1	Nonionic
 Nonylphenol polyethylene glycol ether 9M $n = 9$	NP 9	12.9	Nonionic
 Nonylphenol polyethylene glycol ether 4M $n = 4$	NP4	8.9	Nonionic

improve sweep efficiency (Alvarado and Manrique, 2010; Ramirez, 1987; Austad and Taugbol, 1995; Abidin et al., 2011; Kjøniksen et al., 2008). Micellar solutions produced by surfactants decline capillary forces between oil and water and lead to the movement of the remaining oil (Austad and Taugbol, 1995). Polymer injection includes the injection of the polymer solution into the reservoir. When the polymers are mixed with water, water viscosity increased and oil swept by flooding solution was intensified and accordingly CEOR was increased. Polyacrylamides and polysaccharides are two sorts of polymers which are widely used in oil recovery (Alvarado and Manrique, 2010; Ramirez, 1987). Alkaline often generates extremely tight emulsion which is difficult to break; the wastewater treatment is much more difficult, and it also causes additional scale deposition issue. It is therefore, economically risky and operationally intensive in EOR operations, even though ASP often show great promise from laboratory core-flood experiments and some field tests (Co et al., 2015).

**Figure 1** Method of measuring phase behavior.

Surfactants work in SP flooding to lower the IFT between trapped oil and brine and to aid mobilization and contribute to the formation of oil banks. IFT reduction lowers capillary forces and allows for the oil bank to flow more freely without renewed trapping (Gao et al., 2010; Hirasaki et al., 2011).

Polyacrylamides reduce the mobility ratio of injected fluid by means of decreasing the permeability of the reservoir rock and they can dissolve in water as well. Polysaccharides also decline the mobility of injected fluid by way of increasing viscosity and decreasing the permeability that occurs in small area of reservoir rock. Polysaccharides are sensitive to temperature and bacteria. Therefore, in the presence of bacteria they destroy quickly. Moreover, the viscosity of the polymer solution falls sharply when the polymer is subjected to the high temperature. In comparison, polyacrylamides are resistant to temperature and bacteria (Kjøniksen et al., 2008). In 1973, Hill et al. were among the first people who began working on surfactants. They demonstrated that when the surface tension between oil and water was decreased, oil recovery improved; also surfactant adsorption and wettability of reservoir rock were main factors which were investigated in their study. Lyons and his team evaluated the effects of petroleum sulfonate (a kind of surfactant) on several oil samples, and as a consequence, the interfacial tension between oil and water declined to 10^{-3} dyne/cm and some of the remaining oil was extracted (Lyons, 2010).

**Figure 2** The comparison of surface tension of surfactants with different concentrations.

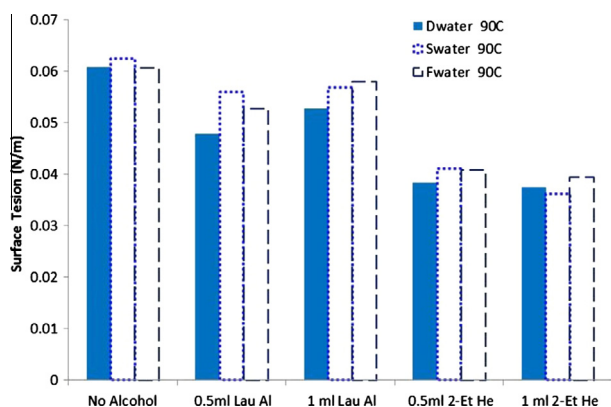


Figure 3 The effects of adding 2-ethylhexanol (2-Et He) and lauryl alcohol (Lau Al) on the surface tension of distilled water, S formation water, and F formation water (after 24 h, at 90 °C).

The EOR methods and flooding solutions are not the same, for different wellbores. In fact, for each well, depending on the conditions and characteristics of the well, situation is completely distinctive. In CEOR process for polymer/surfactant flooding, first the kind and amount of surfactants, polymers, and alcohols are determined and various methods such as surface tension, interfacial tension, thermal stability, PH stability, and bacterial destruction were investigated. The next step was allocated for evaluation of simple and interfacial rheological behavior in order to determine flow regime in different conditions. Simple rheological behavior of polymer solution is very important, although interfacial rheological behavior between water and oil is very important in order to determine flow regime at various conditions. Water–oil emulsion is viscoelastic fluids with complex rheology that has shear thinning behavior and sometimes they show thixotropic behavior. Finally before actual water flooding test, in order to ensure the performance of water flooding, pilot tests and core injections test are usually carried out (Ma et al., 2010; Dickinson, 1992; Jamaloei et al., 2012; Guo et al., 2006; Schramm, 2005; Tadros, 1976; Hadi et al., 2016).

In this study, the effects of polyacrylamide-surfactant samples on the properties of the oil–water interface have been studied. Alcohols were used as co-surfactants in order to improve the performance of system. Phase behavior and interfacial tension between oil and water were investigated. Finally, an optimal formulation in terms of property and quantity of materials was achieved. Two anionic surfactants (SDS

and SLES) and 2-ethylhexanol alcohol as mentioned above as an auxiliary agent were used. An eye-catching micro emulsion was prepared using low concentration of surfactants. The costs of enhanced oil recovery reduce, thereby decreasing the concentration of surfactant. In fact, this is a cost-effective method. It is worth noting that the combinations of some surfactants and co-surfactants along with polymers in order to CEOR have not been used up to now so, the method used in the present study is a novel approach.

2. Materials and methods

2.1. Materials

Sodium Dodecyl sulfate (SDS, 99.5%) and Sodium Lauryl Ether Sulfate (SLES) were purchased from Sigma–Aldrich (The US) and Kimyagaran Emrooz Chemical Industries Co. (Iran), respectively. Nonyl phenol Ether 30M and 9M (NP30 and NP9) and Nonyl phenol Ether 4M (NP9) were received from Kimyagaran Emrooz Chemical Industries Co. (Iran) and Merck (Germany). Table 1 summarizes some properties of these surfactants. Sulfonated polyacrylamide (MW = 8×10^6 Dalton) (SP825) and sulfonated polyacrylamide (MW = 6×10^6 Dalton) (V30) which contains N-vinylpyrrolidone groups were prepared from the SNF company (France). 2-propyl alcohol (99.5%) was purchased from Merck (Germany). Lauryl alcohol (99.1%) and 2-ethylhexanol (99.1%) were provided from P & G Chemical (The US) BASF (The US), respectively. Two types of crude oil (light oil-API 32 and heavy oil-API 20) were obtained from Iranian oil fields, and light oil and heavy oil were defined as F and S, respectively. The formation water associated with each of these oils was also known by the same definition. The water with F formulation has TDS 12900 and TDS 50000 belonging to water with S formulation.

2.2. Methods

2.2.1. Mixing method

For mixing the electrolyte solution and sulfonated polyacrylamide along with surfactants and alcohols, the compounds

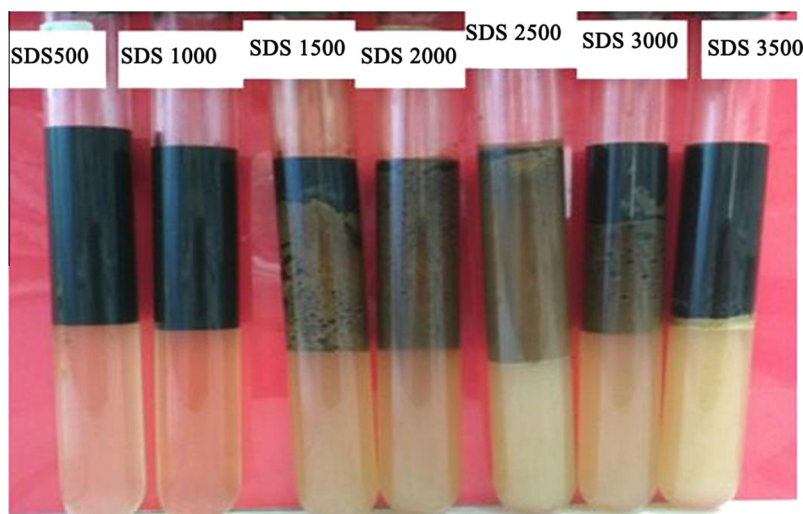


Figure 4 Phase behavior of water and F oil in the presence of SDS surfactant after 24 h exposure to the heat treatment (90 °C) (the written numbers represent surfactant concentration (ppm) within the total volume of water and oil).



Figure 5 Phase behavior of water and S oil in the presence of SDS surfactant after 24 h exposure to the heat treatment (90 °C) (the written numbers represent surfactant concentration (ppm) within the total volume of water and oil).

of vessel were stirred (70 rpm) for one hour at ambient temperature. At last, the obtained solution was added to the oil sample with equal proportion and mixed for one hour using a magnetic stirrer. When the mixing process finished, the contents of vessel were poured into the long glassy tube and placed into the oven for 24 h at 90 °C. By this method two phases will be separated from each other stably and the height of each phase can be measured. It should be noted that different periods of time (24, 48, 96, and 120 h) were tested and no significant changes were observed among results, so 24 h was selected as the optimum time for experiments.

2.2.2. The method of measuring surface tension

The interfacial tension is defined as the cohesive forces among molecules at liquid surface. Actually, the outer layer that is in contact with another surface acts as an elastic sheet. There are a large number of methods and devices in order to calculate interfacial tension including the following: wilhelmy, du Nouy ring, pendant drop, spinning drop, plate and so on. After equilibrium, surface tension of prepared solutions was measured using IFT machine by pendant drop method (Tadros, 1976; Salager, 1977).

2.2.3. The method of calculating and measuring the phase behavior

There are plenty of methods such as light scattering, turbidity test, visual observations, flow behavior in order to calculate the amount and type of emulsions (Bera et al., 2011; Reimer et al., 2005; Khosravani et al., 2013; Khan and Shah, 2008; Samanta et al., 2010). The height of total mixture was determined as H_t and represents the volume of total mixture. The height of water phase (the lower phase which is a bit turbid and may be due to the permeation of oil into water and formation of microemulsion) was determined as H_w . The height of microemulsion phase was determined as H_e , which can easily be recognized due to the color difference in comparison with

the oil phase and it is between the oil and water phases. Ultimately, the height of the oil phase which is at the top of glassy tube was determined as H_o . It should be noted that in some cases due to complete emulsion formation which is our main aim, the height of oil phase will be very low and even in some cases it will disappear.

The mentioned heights symbolize improvement, formation, and the amount of emulsions. In some cases, they represent quality and amount of micelles of emulsion which was formed. Fig. 1 depicts the mentioned heights and various phases.

2.2.4. Rheological behavior of polymer and surfactant solution

A rheometer was produced by Anton Paar Co., Austria, with different modules was used for determination of flow curves.

3. Result and discussion

In this section, first of all the formation and stability of the microemulsion in the electrolyte mixture containing surfactants, sulfonated polyacrylamide, and crude oil were examined. Afterward, the effects of various factors such as the surfactant concentration, surfactant combination, and addition of alcohol as co-surfactants to the samples (to improve the microemulsion characteristics) were discussed. The phase behavior of the samples will be evaluated and in the end, a formulation for the use in enhanced oil recovery will be achieved. Also rheological behavior of polymer and surfactant solutions was studied.

3.1. Phase behavior and emulsion formation

The decrease in surface tension between the aqueous phase and the oil phase is required to form the emulsion; this can be achieved using surfactants. After the critical concentration of surfactants, micelles will be formed and consequently the emulsion will be formed. So that in this particular surfactant



Figure 6 The phase behavior of water and F oil in the presence of SP825B polymer and the combination of SLES/SDS surfactants after 24 h exposure to the heat treatment (90 °C) (the written numbers represent surfactant concentration (ppm) within the total volume of water and oil).

concentration, the IFT between oil and water will be declined extremely and thus two phases will permeate to each other and finally the emulsion will be formed. Interfacial tension test (IFT) was applied in order to investigate the interfacial tension. The pendant drop method for calculating IFT, is a drop suspended from a needle in a bulk liquid or gaseous phase. The shape of the drop results is different because of the relationship between the surface tension or interfacial tension and gravity. In the pendant drop method, the surface tension or interfacial tension is calculated from the shadow image of a pendant drop using drop shape analysis, when one drop was hanging the camera takes a photograph and after by using the computer's program (math equation) and Geometry drop, can measure the IFT (Nelson et al., 1984; Arashiro and Demarquette, 1999).

IFT of surfactants within the electrolyte solutions was compared with each other in order to select surfactants and combine them.

As can be seen in Fig. 2, the anionic surfactants in comparison with non-ionic surfactants decrease the IFT further.

Another interesting issue is the behavior of NP30 in comparison with other members of its group (NP4 and NP9). Although NP30 compared with two other surfactants decreases the IFT further, the emulsion formed by NP30 is more stable than others which were confirmed using phase behavior test. In fact, the emulsion formed by NP30 was remarkably stable against heat treatment and the passing of time. Conversely, the emulsion formed by NP4 and NP9, vanished over the time, or by exposing to the high temperature and after 7 h the emulsion disappeared thoroughly. It may be attributed to the performance of combining the electrolyte solution with two surfactants (NP4 and NP9). In fact, two mentioned surfactants show upper critical solution temperature (UCST) behavior. For this reason, NP4 and NP9 were not consumed and three other surfactants were used instead.

3.1.1. The effects of secondary agent (alcohols) on surface tension

The effects of adding 2-ethylhexanol (2-Et He) and lauryl alcohol (Lau Al) on the surface tension of distilled water, S forma-



Figure 7 The phase behavior of water and F oil in the presence of SP825B polymer, the combination of SLES/SDS surfactants and 2-ethylhexanol alcohol after 24 h exposure to the heat treatment (90 °C) (the written numbers represent surfactant concentration (ppm) within the total volume of water and oil).

tion water, and F formation water are demonstrated in Fig. 3. As can be seen in Fig. 3, the presence of both types of alcohol within three samples, leads to the reduction in surface tension. However, the effects of 2-ethylhexanol on reduction in IFT were much stronger than the lauryl alcohol. One of the reasons which can be cited for this is that the alcohol molecules fill the cavities among the monomers of surfactant. The co-surfactant is organized with its OH group lying among the polar group of surfactant and neighboring water molecules and the hydrocarbon group lying among the polar chain of the surfactant. The energy of interaction per molecule with water of alcohol and surfactant is not constant amount and decreases due to self-association mechanism through intermolecular hydrogen bonding, which reduces the ability of the OH group of the alcohol to form hydrogen bonds with water (Resende et al., 2008; Nguele et al., 2016).

On the one hand, it leads to the stability of emulsion and on the other hand, it leads to the decrease in the number of monomers at interface of two phases. Therefore, the critical concentration will be declined.

3.1.2. Phase behavior of water and oil reservoirs of F and S in the presence of polymers and surfactants

3.1.2.1. The effects of surfactant (SDS) concentration on phase behavior. As mentioned earlier, surfactants by reducing the interfacial tension between oil and water can form oil and water emulsion and finally the increase in the recovery oil will be observed. The phase behavior of prepared mixture by using F and S Oil in the presence of surfactants was investigated in order to study the effects of type and concentration of different surfactants on emulsion formation SDS, SLES and NP30 surfactants in some concentrations result in the formation of water in oil emulsion, albeit NP4 and NP9 surfactants do not show any significant influence on the phase behavior. In addition, it was observed that all the surfactants (SDS, SLES and NP30) in a limited range of concentration (critical micelle concentration) can increase the amount of water in oil emulsion and outside the scope their influences exponentially decrease (Fig. 4).

S oil is a kind of relatively heavy crude oil (with API 20), and the concentration, acidity and opacity of S oil are greater



Figure 8 The phase behavior of water and F oil in the presence of V30 polymer, the combination of SLES/SDS surfactants and 2-ethylhexanol alcohol after 24 h exposure to the heat treatment (90 °C) (the written numbers represent surfactant concentration (ppm) within the total volume of water and oil).

than F oil. It should be noted that investigation of phase behavior of S oil was a bit difficult. With regard to high concentration of S oil and the impossibility of detecting water in oil emulsion, the phase behavior studies of water and S oil were restricted to the outstanding samples prepared using F oil and additives (Fig. 5).

3.1.2.2. The effects of surfactant and polymer combination on the phase behavior. The effects of polymer presence and combination of SLES/SDS and SLES/NP30 surfactants on phase behavior of water and F oil are demonstrated in Fig. 6. According to the figure, when SP825B polymer was just added to the sample, no significant changes in phase behavior of water and oil were observed; however, in the presence of polymer along with combination of surfactants, the great changes in phase behavior of water and oil were occurred, and formation of water in oil emulsion could be distinguished. For instance, the noticeable water in oil emulsion was formed using 1000 ppm SP825B polymer, 300 ppm SLES surfactant and 1000 ppm SDS surfactant. Despite the formation of water in oil emulsion in the presence of all additives, the remarkable increase in the volume of emulsion was only occurred for some samples.

3.1.2.3. The effects of secondary agent (alcohols) on phase behavior. The effects of two types of alcohols (2-ethylhexanol and lauryl alcohol) along with polymer and combination of SLES/SDS and SLES/NP30 surfactants on phase behavior of water and oil were studied to optimize and improve characteristics of the samples and especially to reduce surfactant concentration. The results of studies are shown in Figs. 7–9. As can be seen, the presence of 2-ethylhexanol alcohol along with the combination of SLES/SDS surfactants for two samples containing SP825B polymer leads to the formation and significant improvement of water in oil emulsion volume. However, the improvement of emulsion volume for samples containing the mentioned alcohol along with the combination of SLES/NP30 surfactants is not considerable. It is worth noting that, the presence of lauryl alcohol along with the combination of SLES/NP30 surfactants can have remarkable influences on phase behavior of water and oil; however, the presence of lauryl alcohol along with the combination of SLES/SDS surfactants cannot have any prominent effects on phase behavior of samples.

In Fig. 9, the effects of adding surfactants, co-surfactants and polymer on the improvement of process are exhibited (see Fig. 10).



Figure 9 The phase behavior of water and F oil in the presence and absence of polymer, the combination of SLES/SDS surfactants and 2-ethylhexanol alcohol after 24 h exposure to the heat treatment (90 °C) (the written numbers represent surfactant concentration (ppm) within the total volume of water and oil).

3.2. Rheological behavior of polymer flooding and surfactant was studied

3.2.1. The effect of polymer concentration

To evaluate the effect of polymer concentration on rheological properties of polymer systems, flow behavior has been studied in the presence of a surfactant and different polymer concentrations. The viscosity variation of a polymer system containing SP825B polymer and SLES as surfactant is illustrated in Fig. 11.

As shown in this Fig. 11 by increasing the polymer concentration the viscosity of polymer systems increases. This behavior could be due to the rise in molecular twisting and increment of the number of ion groups in a polymer system. However, by increasing the shear stress polymer molecules are elongated in the shear direction, which consequently reduces the viscosity of the system.

Moreover, it is observed that in higher polymer concentration the oscillation in rheological results is lower (Aalaie and Youssefi, 2012). Based on this observation in order to generate

proper rheological graphs, in later tests, a polymer concentration of 7000 ppm is applied.

3.2.2. The effect of co-surfactant (alcohols) on flow profile

In Fig. 12 the viscosity behavior of polymer systems containing surfactants and alcohols is compared with the viscosity behavior of polymer systems containing SP825B polymer. It is observed that in the presence of SP825B polymer, mixture of SDS/SLES as surfactants and 2-ethylhexanol alcohol and mixture of SLES/NP30 as surfactants and lauryl alcohol, the system viscosity is slightly higher than the viscosity of the initial polymer system without alcohol. Due to the better performance of SDS/SLES system, this system has been selected for further investigations.

3.2.3. The effect of water formation on flow behavior of polymer systems

To evaluate the effect of formation water temperature on flow behavior of polymer systems, rheological behavior of systems was investigated in different temperatures. Due to instrumen-



Figure 10 The phase behavior of water and S oil in the presence and absence of polymer, the combination of SLES/SDS surfactants and 2-ethylhexanol alcohol after 24 h exposure to the heat treatment (90 °C) (the written numbers represent surfactant concentration (ppm) within the total volume of water and oil).

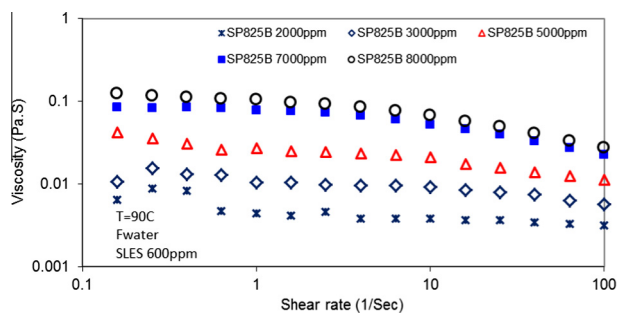


Figure 11 Effect of increasing polymer concentration on solution's viscosity (F water SLES:600 ppm, temperature: 90 °C).

tal constraints, maximum temperature of 90 °C was selected. Fig. 13 shows the effect of temperature on flow profile of polymer systems containing SP825B polymer and SLES/SDS as surfactants. As it is illustrated in this figure, as temperature increases the viscosity of polymer systems decreases, and this behavior might have different reasons such as weakening hydrogen bond between water and polymer molecules, increasing the chance of polymer chains collision in higher temperatures, increasing the movement of polymer chains, reducing the contact duration of adjacent chains and reducing average intermolecular forces. In next graph, the flow profiles of

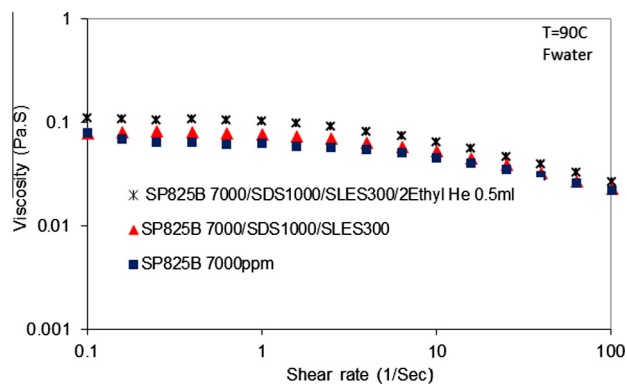


Figure 12 Effect SDS/SLES and 2 Ethyl He on SP825B polymer in F water (SP825B:7000 ppm, temperature: 90 °C).

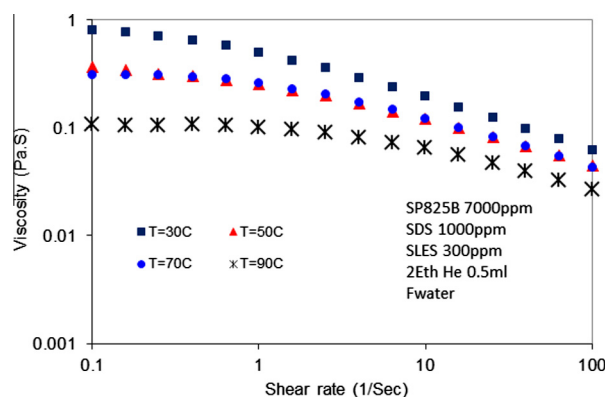


Figure 13 Effect of temperature on viscosity in SP825B polymer, SDS/SLES and 2-ethylhexanol solution (F Water).

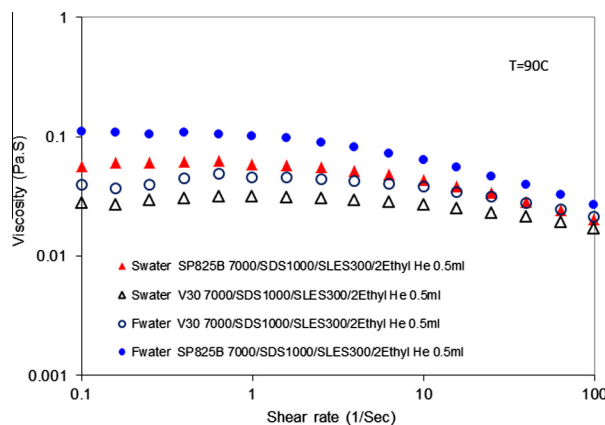


Figure 14 Effect of salinity on solution's viscosity (polymer concentration: 7000 ppm, temperature: 90 °C).

different formation water formulations are illustrated (Samanta et al., 2010).

3.2.4. The effect of formation water's salinity on rheological behavior

To evaluate the effect of water salinity on the viscosity behavior of the polymer system, the flow behavior of systems was

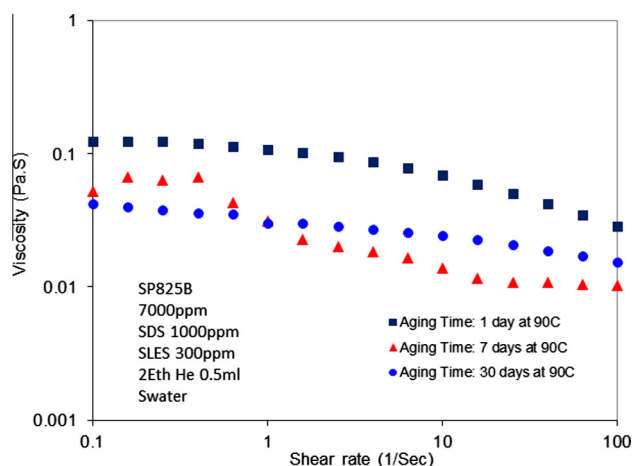


Figure 15 Effect of aging time on solution's viscosity (SP825B polymer's concentration: 7000 ppm, S Water).

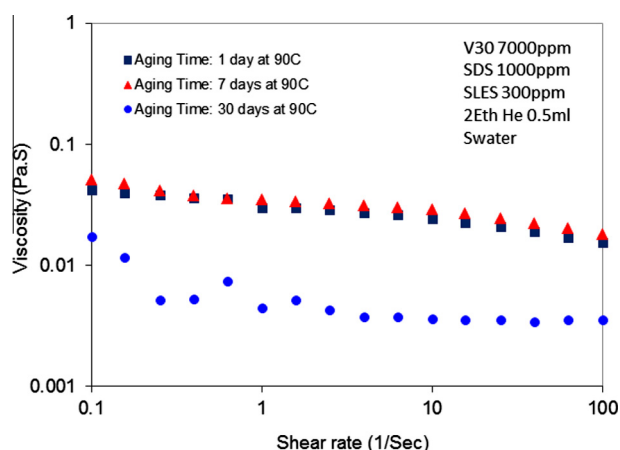


Figure 16 Effect of aging time on solution's viscosity (V30 polymer's concentration: 7000 ppm, S Water).

studied in the presence of formation waters F and S. The comparison of flow behaviors of polymer systems containing V30 polymer in two formation waters F and S shows that by increasing the water salinity from 12,900 ppm (F) to 50800 ppm (S) the system viscosity is reduced.

This phenomenon might be due to the higher number of Polyvalent cations in the S formation water. By surrounding the sulfate groups and reducing the repulsion force between them, polyvalent cations affect the opening of the polymer chains, which consequently cause viscosity reduction in a polymer system (Samanta et al., 2010). Moreover, by comparing the flow behavior of polymer systems based on V30 and Sp825B polymers in S water, it is observed that the polymer system based on SP825B has higher viscosity (see Fig. 14).

3.2.5. The effect of aging time on flow curve of selected polymer systems

To investigate the retention time and its influence on the viscosity of the system, selected formulations containing

7000 ppm of two polymer types with 1000 ppm SDS and 300 ppm SLES with 0.5 ml 2-ethylhexanol alcohol were tested in three time intervals of 1 day, 1 week and 1 month. It was observed that as retention time increases the viscosity decreases. This behavior might be due to destruction of polymer chains, opening of chain ties by time or other reasons which are shown in Figs. 15 and 16.

4. Conclusion

In the present study, the phase behavior, IFT and rheological behavior of formation water along with surfactants and co-surfactants, various polymers and oil were evaluated. In fact this evaluation was conducted in order to achieve an optimum formulation in terms of performance and economical operation of enhanced oil recovery from the reservoirs. In accordance with the results obtained in this research, it can be concluded that combination of surfactants due to the synergy among surfactants can have a positive effect on the process. In addition, the application of alcohols can also have a positive influence on the process when the chain length of alcohol and surfactant is exactly equal. So the desired emulsion can be achieved by fewer amounts of surfactants. It was confirmed that application of polymers does not have any significant influence on emulsion formation. In fact, polymers were used to increase the viscosity of solution and moreover to sweep the oil into the samples. Over time, viscosity of solution decreases. Although reason of this event is not so clear, it can be due to several parameters such as interchange reaction of polymer chains, change of polymer configuration or due to this fact that polymer chains lose their coil form. The viscosity decreases with increment of salinity due to the interactions between ions of electrolyte solution and ions of polymer chains. Flow behavior and rheological curves show the shear thinning behavior. Ultimately, the formulation that showed the outstanding results was formed from the combination of SLES/SDS surfactants along with 2-ethylhexanol alcohol. The mentioned formulation could economically be applied even in the presence of polymers for enhanced oil recovery.

References

- Aalaie, J., Youssefi, M., 2012. Study on the dynamic rheometry and swelling properties of the polyacrylamide/laponite nanocomposite hydrogels in electrolyte media. *Macromol. Sci. Phys.*, 1027–1040
- Abidin, A.Z., Puspasari, T., Nugroho, W.A., 2011. Polymers for enhanced oil recovery technology. *Proc. Chem.*, 11–16
- Alvarado, V., Manrique, E., 2010. Chapter 8 – EOR's current status. In: *Enhanced Oil Recovery*. Gulf Professional Publishing, Boston, pp. 133–156.
- Arashiro, Emerson Y., Demarquette, Nicole R., 1999. Use of the pendant drop method to measure interfacial tension between molten polymers. *Mater. Res.* 2 (1), 23–32.
- Austad, T., Taugbol, K., 1995. Chemical flooding of oil reservoir low tension polymer flood using a polymer gradient in the three-phase region. *Colloids Surf.*, 87–97
- Bera, Achinta, Ojha, Keka, Mandal, Ajay, Kumar, T., 2011. Interfacial tension and phase behavior of surfactant-brine-oil system. *Colloids Surf. A: Physicochem. Eng. Aspects* 383, 114–119.
- Co, Larry, Zhang, Zijie, Ma, Qisheng, Watts, Gary, Zhao, Lin, Shuler, Patrick J., Tang, Yongchun, 2015. Evaluation of functionalized polymeric surfactants for EOR applications in the Illinois basin. *J. Petrol. Sci. Eng.*
- Dickinson, E., 1992. Interfacial interactions and the stability of oil-in-water emulsions. *Pure Appl. Chem.*
- Gao, P., Towler, B., Li, Y., Zhang, X., 2010. Integrated evaluation of surfactant-polymer floods. In: *SPE EOR Conference at Oil & Gas West Asia, Muscat*.

- Guo, J. et al, 2006. The effect of alkali on crude oil/water interfacial properties and the stability of crude oil emulsions. *Colloids Surf. A*, 213–218.
- Hadi, Saboorian-Jooybari, Dejam, Morteza, Chen, Zhangxin, 2016. Heavy oil polymer flooding from laboratory core floods to pilot tests and field applications: halfcentury studies. *J. Petrol. Sci. Eng.*
- Hirasaki, G.J., Miller, C.A., Puerto, M., 2011. Recent advances in surfactant EOR. *Soc. Pet. Eng. J.* 16, 889e907.
- Jamaloei, B.Y., Kharrat, R., Asghari, K., 2012. The influence of salinity on the viscous instability in viscous-modified low-interfacial tension flow during surfactant-polymer flooding in heavy oil reservoirs. *Fuel*, 174–185.
- Khan, A.M., Shah, S.S., 2008. Determination of critical micelle concentration (Cmc) of sodium dodecyl sulfate (SDS) and effect of low concentration of pyrene on its Cmc using ORIGIN software. *Chem. Soc. Pak.*, 30
- Khosravani, S., Alaei, M., Rashidi, A.M., Ramazani, A., Ershadi, M., 2013. O/W emulsions stabilized with g-alumina nanostructures for chemical enhanced oil recovery. *Mater. Res. Bull.* 48, 2186–2190.
- Kjønksen, A.-L. et al, 2008. Modified polysaccharides for use in enhanced oil recovery application. *Eur. Polym. J.*, 959–967
- Lyons, W.C., 2010. Chapter 5 – enhanced oil recovery methods. In: *Working Guide to Reservoir Engineering*. Gulf Professional Publishing, Boston, pp. 279–310.
- Ma, L. et al, 2010. Microstructure changes induced by capillary condensation in catalyst layers of PEM fuel cells. *Int. J. Hydrogen Energy* 3 (22), 12182–12190, 5.
- Nelson, R.C. et al, 1984. Cosurfactant-enhanced alkaline flooding. *SPE*.
- Nguele, Ronald, Sasaki, Kyuro, Said-Al Salim, Hikmat, Sugai, Yuichi, Widiatmojo, Arif, Nakano, Masanori, 2016. Microemulsion and phase behavior properties of (dimeric ammonium surfactant salt – heavy crude oil – connate water) system. *J. Unconventional Oil Gas Resour.* 14, 62–71.
- Ramirez, W.F. (Ed.), 1987. Chapter 5 One-Dimensional Optimization of the Micellar/Polymer EOR Process. *Developments in Petroleum Science*. Elsevier, pp. 123–166.
- Reimer, Johan, Nilsson, Markus, Chamorro, Marta Álvarez, Söderman, Olle, 2005. The water/n-octane/octyl- β -D-glucoside/1-octanol system: phase diagrams and phase properties. *J. Colloid Interface Sci.* 287, 326–332.
- Resende, Kélia Xavier, Corrêa, Marcos Antonio, de Oliveira, Anselmo Gomes, Scarpa, Maria Virgínia, 2008. Effect of cosurfactant on the supramolecular structure and physicochemical properties of non-ionic biocompatible microemulsions. *Brazilian J. Pharm. Sci.* 44.
- Salager, J.L., 1977. *Physico-Chemical Properties of Surfactant-Water-Oil Mixtures: Phase Behavior, Microemulsion Formation and Interfacial Tension*. The University of Texas at Austin, USA, p. 253.
- Samanta, A. et al, 2010. Effects of alkali, salts, and surfactant on rheological behavior of partially hydrolyzed polyacrylamide solutions. *Chem. Eng.*, 4315–4322
- Schramm, L.L., 2005. *Emulsions, Foams, and Suspensions Fundamentals and Applications*. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 341.
- Tadros, T.F., 1976. 17 – Stability of oil-in-water emulsions in polymer-surfactant complexes. Paraffin-water emulsions in mixtures of poly-(vinyl alcohol) with cetyltrimethyl ammonium bromide or sodium dodecylbenzene sulphonate. In: Smith, A.L. (Ed.), *Theory and Practice of Emulsion Technology*. Academic Press, pp. 281–299.