ORIGINAL PAPER - PRODUCTION ENGINEERING

Influence of lauryl betaine on aqueous solution stability, foamability and foam stability

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Abstract

In gas flooding, one of the major problems in implementing foam as a gas mobility control method is the stability of foam. Foam booster when blended with surfactant could improve the foam stability. However, the influence of foam booster on the conventional foam stability and foamability at elevated temperature and presence of inorganic electrolytes is not yet explicit due to limited studies in this area. The objective of the present work was to evaluate the influence of a foam booster on aqueous solution stability, foamability and foam stability when blended with surfactant at different ratios at an elevated temperature in the presence of brine composed of monovalent and divalent ions. Three different surfactants AOS $C_{14–16}$ (alpha-olefin sulfonate), SDS (sodium dodecyl sulfate) and a locally manufactured surfactant 'Surf X' were chosen as base surfactants. An amphoteric surfactant lauryl betaine was chosen as a foam booster in this study. The aqueous solution stability was visually evaluated, whereas the bulk foam experiments were conducted in a commercial foam analyzer apparatus. It was found that not all solutions were stable when lauryl betaine was blended. Lauryl betaine did not improve the foam generation time. The foam stability was improved; however, not all solutions were able to generate stable foam. 'Surf X' was able to generate more stable foam as compared to AOS and when blended with lauryl betaine it also required less amount of lauryl betaine to generate stable foam.

Keywords Divalent ions · Foamability · Foam stability · Lauryl betaine · Surfactant

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Introduction

Foam is a dispersion of gas in a liquid phase such that the liquid is in continuous phase having some of the gas trapped inside the thin liquid films known as lamellae (Hiraski 1989). The surfactant molecules are present at the gas liquid interface, and thereby stabilize the foam films (Katgert 2008; Yekeen et al. 2017a). In gas flooding, the challenge associated with injected gas is poor volumetric sweep efficiency, because of low viscosity and density of gas compared to oil (Memon et al. 2016). Foam has higher apparent viscosity and can control the mobility of the gas by substantially hinder the gas flow in porous media, which forces gas to sweep pores that it would not have reached without foam (Farajzadeh et al. 2012). In short foam divert gas toward zones having lower permeability, it limits viscous fingering and also reduces overriding of gas in high permeability zones of reservoir (Yekeen et al. 2018; Chevallier et al. 2019). There are two main methods by which foam can be generated in porous media, surfactant alternating gas (SAG) and

co-injection of surfactant and gas (Jensen and Friedmann 1987; Farajzadeh et al. 2012).

As an enhanced oil recovery (EOR) method, a major concern with the application of foam is the stability of foam (Yekeen et al. 2018). The selection and concentration of proper foaming agents are one of the main parameters that determines the success of foam flooding (Rafati et al. 2012). Compared to an individual component, studies have shown that when foam booster is used as an additive they may improve the foam properties (Van Der Bent 2014; Cui, 2014; Osei-Bonsu et al. 2015; Sakai and Kaneko 2004). Betaines are known for their foam enhancing properties (Sakai and Kaneko 2004; Farajzadeh et al. 2012).

Previous studies have shown that zwitterionic betaine surfactants have the ability to improve stability of the foam films in the absence and presence of oil (Basheva et al. 2000; Cui 2014). Gao et al. 2017 in their research shown that the addition of betaine improves the foam stability. It was observed that more stable foam was generated when lauryl betaine was added to the NI (Neodol 67-7PO sulfate and IOS_{15-18}) 4:1 blend (Li et al. 2012). Lauryl betaine is an amphoteric surfactant that is thermally stable relative to cocamidopropyl-betaine (Cui 2014). It was also observed in some other studies that blending lauryl betaine does improve the foam properties (Conn et al. 2014; Singh and Mohanty 2016). The blend tested by Singh and Mohanty (2016) consisted of (1:1) AOS and LB with brine having salinity 1.2 wt% without the presence of divalent ions,. whereas Conn et al. (2014) study was limited to 1:1 of main surfactant (AOS) and lauryl betaine as foam booster with a total concentration of 1 wt%, in the presence of NaCl brine.

The presence of divalent ions can cause the surfactant to precipitate in the formation because of the intolerance of many surfactants to the divalent ions. So it is important to test surfactant solutions for foam studies in the presence of divalent ions. However, when mixed with different surfactants, the influence of lauryl betaine on aqueous solution stability, foamability and foam stability in the presence of divalent ions at high temperature has not been extensively investigated in previous studies.

This experimental evaluation studied the influence of lauryl betaine on aqueous solution stability, foamability and foam stability when blended with surfactant at different ratios in the presence of brine containing divalent ions at 60 °C. In this work AOS C_{14-16}, SDS and a locally manufactured surfactant 'Surf X' chosen as base surfactant was systematically blended with lauryl betaine (foam booster) at different ratios in a brine containing NaCl and $CaCl_2$. Except the foam stability test which was conducted at only 60 °C, all other tests were conducted at 25 °C and 60 °C. The aqueous solution stability was visually evaluated, whereas the foamability and foam stability experiments were conducted in a commercial Foamscan

apparatus. In bulk foam tests, half-life (foam stability) and foamability were investigated. In this study, a comparative understanding of the influence of lauryl betaine (which we here after called LB) on aqueous solution stability, foamability, foam stability when blended with base surfactant was studied to generate a stable foam solution that can be further tested in porous media.

Materials and methods

Materials

AOS C_{14-16} (Alpha-olefin sulfonate) was obtained from STEPAN Chemical Co. 'Surf X' a locally developed surfactant, SDS (sodium dodecyl sulfate) from Sigma Co. and Fentacare BS12/Lauryl Betaine (additive), received from Solvay Chemicals Co. The brine was prepared with deionized water and with the concentration of 3.0 wt% of NaCl from Merck Co., 0.20 wt% $CaCl_2$ from R&M Chemicals. The total brine salinity was 3.2 wt%. Pure N_2 gas was used in this study as the sparging gas. The injection rate was 50 ml/min for all the solutions. All the solution contained total concentration of 0.5 wt% active surfactant. The concentration used in this study was well above the critical micelle concentration. The CMC value of AOS at 3.0 wt% NaCl brine was 0.003 wt% (Laskaris 2015).

The details of the surfactant solutions tested in this study are given in Table 1. Label A 100, S 100 and X 100 denotes to AOS, SDS and 'Surf X', respectively, without the LB blend, whereas A 91, S 91, X 91 shows 9:1, A 73, S 73, X 73 shows 7:3 and A 64, X 64, S 64 shows 6:4 blends of AOS, SDS and 'Surf X' with LB, respectively.

Table 1 Surfactant solutions and LB blend used in the experiments

Sample no.	Label	Base surf	Foam booster	Ratio (Surf/LB)
1	A100	AOS	–	–
2	A 91	AOS	LB	9:1
3	A 73	AOS	LB	7:3
4	A 64	AOS	LB	6:4
5	X 100	Surf X	–	–
6	X 91	Surf X	LB	9:1
7	X 73	Surf X	LB	7:3
8	X 64	Surf X	LB	6:4
9	S 100	SDS	–	–
10	S 91	SDS	LB	9:1
11	S 73	SDS	LB	7:3
12	S 64	SDS	LB	6:4

Experimental procedure

This research is divided into two main phases. In the first phase, the aqueous stability testing of the surfactant solution was conducted. In aqueous stability testing, there were two types of test. First one is the precipitation testing (in this test the solutions were checked for any type of precipitation) and second is the thermal stability testing (in this test, phase separation was checked). First the individual surfactants were tested. In the second part, the foam booster (LB) was added at different ratios as mentioned in Table 1. The surfactant solutions were stored at different temperatures (25 °C and
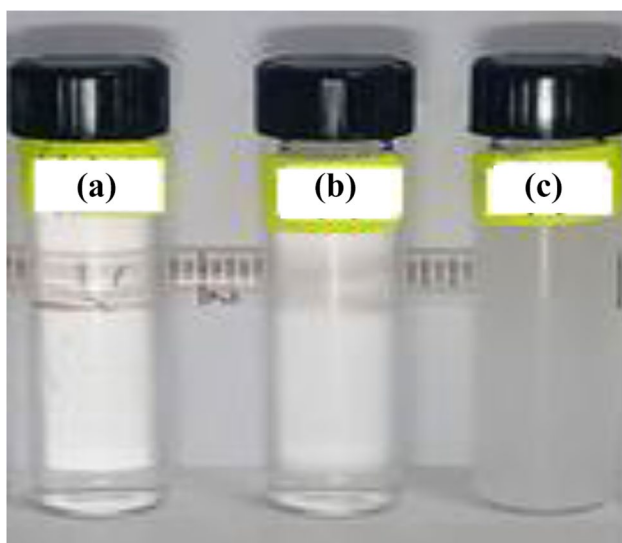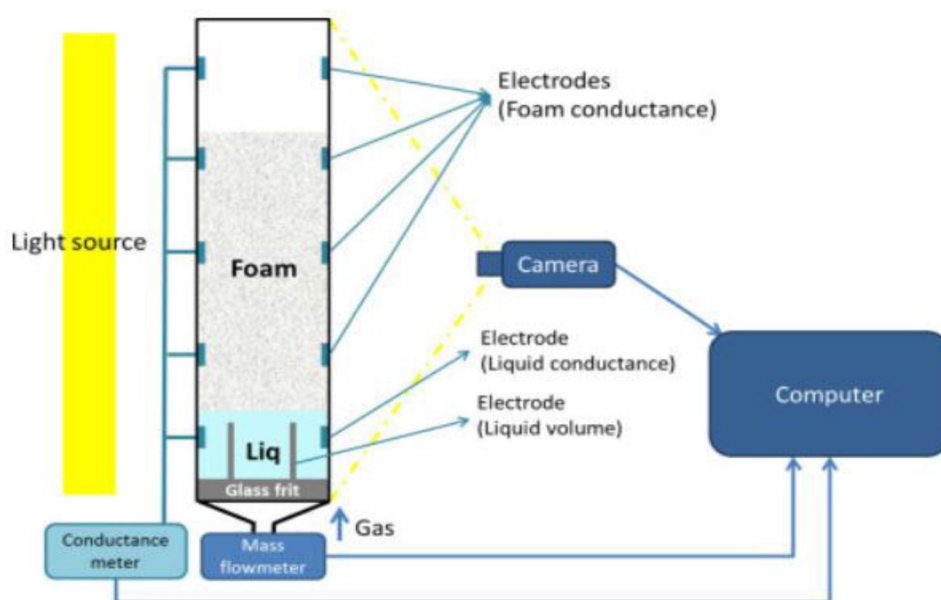

Fig. 1 Results of surfactant aqueous solution stability, **a** a clear stable solution, **b** a slightly blurry solution, **c** a cloudy/precipitated solution

60 °C) for 2 weeks, which were than visually inspected. A surfactant solution is considered stable, if the solution is homogeneous, contain single phase and clear. If the surfactant solution that is used for injection is not in single phase and clear will have significant phase trapping, formation plugging, and loss of surfactant solution to adsorption in the formation will occur. As shown in Fig. 1 if the solution was clear or slightly blurry, it was considered aqueously stable. If a solution was cloudy or if a solution has precipitates, then it was considered unstable and was not used for further testing.

In the second phase, the bulk foam experiments were carried out using Foamscan apparatus (Teclis instruments) ®. Figure 2 shows the schematic diagram of the foam analyzer apparatus used in this research. Bulk foam test was conducted at ambient and 60 °C. First, a 50 ml of the solution sample was injected into the glass tube after that the pure N_2 (nitrogen) gas at 50 ml/min was injected as sparging gas to create the foam. The foamability of the solutions was tested by generating up to 100 ml of foam, and then, the time for the foam to reach the 100 ml foam volume was recorded. The bulk foam stability was measured by (half-life) the time needed for the foam to decay into half of its original volume after the sparging of the gas was stopped.

Results and discussion

Aqueous and thermal solution stability testing

A qualified surfactant formulation for foam EOR should be soluble and stable from injection to reservoir conditions (Cui 2014). It is important to test aqueous and thermal solution

Fig. 2 Schematic diagram of Foamscan apparatus (Jones et al. 2016)

stability because if a solution is not stable (single phase) and precipitates inside formation then it will block the pores and damage the formation. Results of the aqueous solution stability tests can be seen in Table 2. All the base surfactant solutions in the presence of brine were tested at temperatures 25 °C and 60 °C. Tested base surfactant solutions were found clear, and no phase separation and precipitation were observed. The base surfactant was then further used to blend with the LB for further testing. In the second phase, the foam booster (LB) was blended with the base surfactant at ratios 9:1, 7:3 and 6:4 as mentioned in Table 1. After blending the LB and base surfactants, aqueous and thermal stability were tested.

The solutions A 91, A 73, X 91, X 73 were found stable, and no phase separation or precipitation was observed at both temperatures 25 °C and 60 °C. The A 73 showed a little blurry solution at 25 °C temperature; however, when it was tested at 60 °C, it was found clear. The solution A 64, X 64, S 73 and S 64 were cloudy and has precipitation at 25 °C. When these solutions were further tested at 60 °C. Precipitations and cloudy solutions were still observed; however, the

solution S 73 at 60 °C was hazy, but the precipitation was still present in the solution. It was observed in this study that as the ratio of LB increased in the surfactant solutions, it had a negative influence on the stability of the surfactant solution. Not all the surfactant solutions were found stable as the ratio of LB increased in the surfactant solution. Complex interaction among the divalent ions and surfactant molecules could have the possibility of reduction in micelle formation that would lead to presence of large number of free monomers which in turn bind with divalent ions. This binding of divalent ions could be the possible reason for precipitation. The A 64, X 64, S 100, S 91, S73 and S 64 surfactant solutions was not further used for testing in this study.

Bulk foam test

Foamability

The ease of foam generation is known as foamability. It is a dynamic property of foam generating power of a liquid and the factors that help to attain immediate stabilization of the foam (Wilson 1996; Sakai and Kaneko 2004). The influence of LB on foamability is shown in Fig. 3a at 25 °C and Fig. 3b at 60 °C when blended with AOS and 'Surf X' surfactant, respectively. As shown in Fig. 3a, b, the foamability time of the individual surfactant solutions as compared to the mixed surfactant solutions was better.

As shown in Fig. 3a, when AOS was blended with LB at 9:1, the foamability time at 25 °C was increased by 39.08%. At 7:3, the time was increased by 27.58%. When 'Surf X' was blended with LB at 9:1, the time was 27.47% more than individual 'Surf X'. At 7:3, the foamability time was increased by 30.76% as compared to the time for base 'Surf X' surfactant.

Figure 3b represents the foamability of surfactant solutions at 60 °C. When AOS was blended with LB at 9:1, the foamability time was increased by 26.47%. At 7:3, the time was increased by 20.58%. When 'Surf X' was blended with LB at 9:1, the time was only 5.79% more. At 7:3, the

Table 2 Aqueous solution stability results of the surfactant solutions tested at 25 °C and 60 °C

Sample no.	Label	25 °C Remarks	60 °C Remarks
1	A 100	Clear	Clear
2	A 91	Clear	Clear
3	A 73	Blurry/hazy	Clear
4	A 64	Cloudy/precipitation	Cloudy/precipitation
5	X 100	Clear	Clear
6	X 91	Clear	Clear
7	X 73	Clear	Clear
8	X 64	Cloudy/precipitation	Cloudy/precipitation
9	S 100	Clear	Clear
10	S 91	Clear	Clear
11	S 73	Cloudy/precipitation	Blurry/precipitation
12	S 64	Cloudy/precipitation	Cloudy/precipitation

Fig. 3 Time needed to generate 100 ml foam for different surfactant solutions with and without foam booster (LB) at **a** 25 °C and **b** 60 °C

(a)

(b)
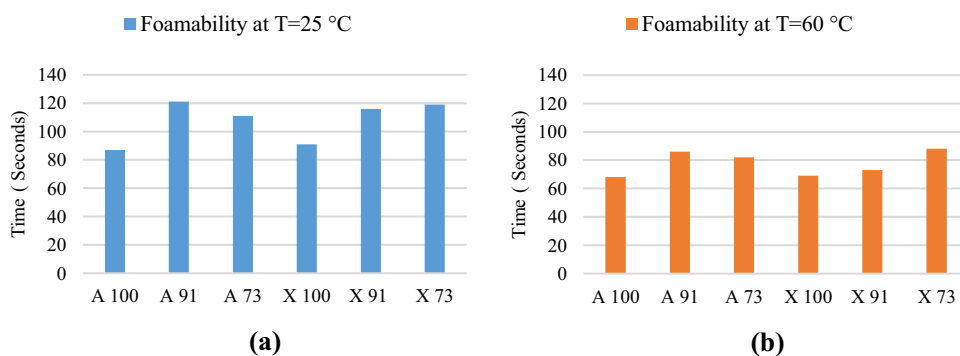
foamability time was 27.53% more as compared to the time for 'Surf X' without the blend of LB.

Temperature had a positive effect on the foamability of all the surfactant solutions tested in this study. The foamability time of surfactant solutions at elevated temperature was much better as compared to the foamability time at lower temperature. The improvement in foamability at 60 °C compared to 25 °C could be attributed to the increase in the internal kinetic energy of the gas due to increase in temperature and the decrease in liquid viscosity of the surfactant solution. At both temperatures 25 °C and 60 °C, the surfactant solutions A 100 and X 100 without the blend of LB had better foamability time. The foamability performance of the surfactant solutions tested in this study at 25 °C are ranked in the order of: A 100 > X 100 > A 73 > X 91 > X 73 > A 91, whereas at 60 °C temperature the order is as follows: A 100 > X 100 > X 91 > A 73 > A 91 > X 73.

In this work, LB was not able to have a positive impact on the foamability of surfactant solutions used. LB has more negative impact on foamability when blended with AOS as compared to the 'Surf X' surfactant. (Sakai and Kaneko 2004; Van Der Bent 2014) in their study also found the similar trend that the addition of amphoteric surfactant did not improve the foamability. Figure 4 shows A 100 foam generated inside a glass tube.

Foam stability

Foam stability can be defined as the time a foam film exists without rupturing (Sakai and Kaneko 2004). It is generally indicated by foam half-life (time needed for foam to decay half of its original foam) (Yekeen et al. 2017b) Fig. 5 shows the half-life of the bulk foam experiments, both with and without the blend of LB at 60 °C, with longer half-life indicating a more stable foam. AOS and LB blend of 9:1 generated 149.68% more stable foam as compared to individual AOS surfactant solutions. When AOS was blended with LB at ratio of 7:3, it increased half-life by 254.91%. When 'Surf X' was blended with LB at 9:1, it showed an improvement in stability by just 8.92%; however, when the blend ratio was increased and the 'Surf X' and LB was blended at 7:3, there was a decrease in stability of about 39.89%.

In comparison of individual surfactant solution, X 100 has higher foam stability as compared to A 100 surfactant solution generated foam. The half-life of the surfactant solutions was improved when LB was blended with the AOS and 'Surf X' surfactants. The influence on the stability was more profound with AOS surfactant as compared to the 'Surf X' surfactant. Among all the surfactant blended with the LB, 'Surf X' needed less amount of LB as compared to the AOS. Increasing the ratio of LB with 'Surf X' was not able to greatly improve foam stability at all the ratios tested. The A 73 surfactant solution generated the most stable foam among
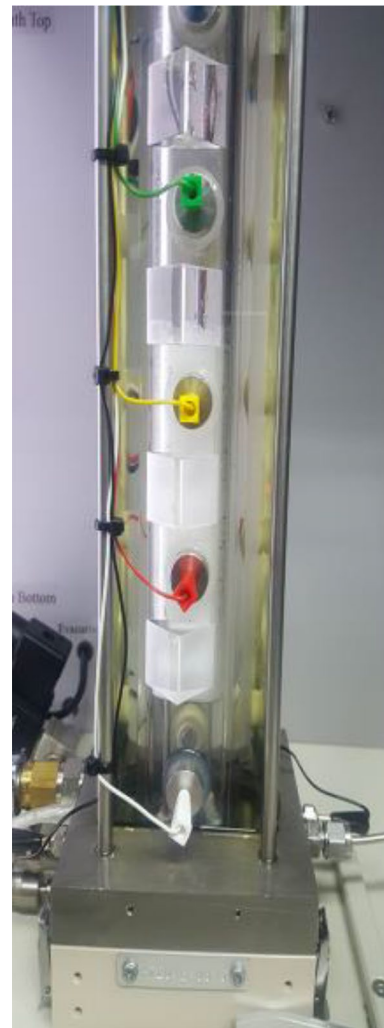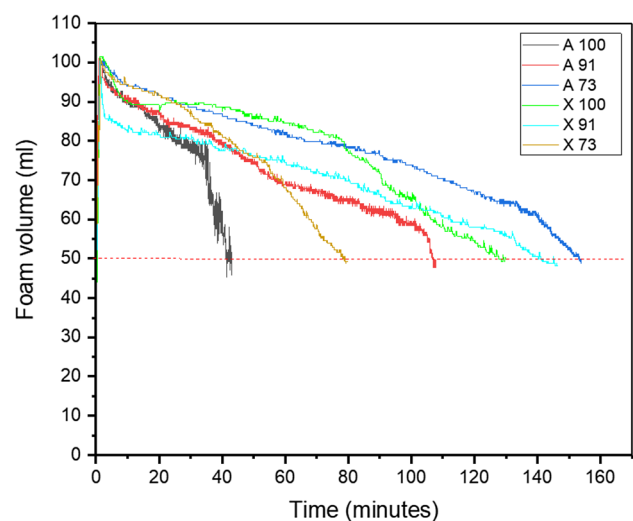

Fig. 4 A 100 foam inside glass tube

Fig. 5 Foam decay profile of different surfactant solutions with and without the foam booster (LB) at 60 °C

all the surfactant solution tested. Based on Fig. 5, the foam stability according to half-life is ranked as the following A 73 > X 91 > X 100 > A 91 > X 73 > A 100. The increase in foam stability with the blend of an amphoteric surfactant has also been reported by other researchers (Osei-Bonsu et al. 2015; Memon et al. 2016). As compared to individual component systems, the blend of different type of surfactants synergistically exhibit better foaming properties (Bian et al. 2012; Memon et al. 2016).

This result of the increase in the foam stability by LB can be due to the Marangoni effect, which is caused by electrostatic attraction between anionic surfactant and the cationic nitrogen (Domingo 1996; Sakai and Kaneko 2004). Gao et al. (2017) showed in their study using the simulation for foam stability that the presence of amphoteric surfactant relaxes the repulsion between the headgroups of anionic surfactants. This mechanism improved the foam stability and could also be responsible for the improved foam stability in the presence of LB as observed in this research. Moreover, it is anticipated that addition of LB to the solution could increase the liquid viscosity, consequently decreasing the liquid drainage from the foam plateau borders which causes high resistance to film thinning, thus influences the stability of foam (Osei-Bonsu et al. 2015).

Conclusion

In this work, when blended with different solutions, the influence of lauryl betaine on the aqueous solution stability, foamability and bulk foam stability in the presence of divalent ions and at an elevated temperature were studied. Parameters such as the aqueous solution stability (phase separation and precipitation), foamability and foam stability were systematically investigated. It was found that blending lauryl betaine with surfactant affects the solution stability; not all the solution was found stable as the ratio of LB increased in the surfactant solution in the presence of divalent ions. There was a negative impact on foamability when lauryl betaine was blended with the surfactant. A 100 and X 100 surfactant solutions had the best foamability time at both the tested temperatures. The foam stability of the solutions was improved; however, not all solutions were able to generate stable foam. 'Surf X' individually was able to generate more stable foam as compared to AOS and when blended with lauryl betaine. It also required less amount of lauryl betaine to generate more stable foam. The A 73 surfactant solution generated the most stable foam followed by X 91 surfactant solution. The presence of lauryl betaine (10%) in 'Surf X' increased the foam stability by approximately 9%, whereas the presence of lauryl betaine (30%) in AOS surfactant solution increased the foam stability by

approximately 255%. The surfactant solution used in this study that generated stable foam will be further tested in porous media.

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