Foaming Properties of Laurel Amide Betaine in High Temperature and High Salinity Oil Reservoirs

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Abstract. Laurel amide betaine (LAB) has good foaming properties under high temperature (90 ℃) and high salinity (220 000mg/L. In this paper, foaming properties of LAB were investigated comprehensively. The results showed that at low concentrations, LAB had good foaming properties and pH value had little effect on foaming properties. With an increase of NaCl or $CaCl_2$ concentration, drainage half-life increased linearly. At 90 ℃, with the increase of water salinity, critical micelle concentration (CMC) decreased. Thus, at the same surfactant concentration, the higher the salinity, the larger the CMC times, one reason for longer drainage half-life. A change in the Na_2SO_4, concentration has little effect on foam stability. The LAB had relatively low adsorption value and could alter wettability from oil-wet to water-wet.

Introduction

Gas flooding is an effective approach to enhanced oil recovery after water flooding because attic oil can be displaced by gas. During gas flooding, gas channeling is inevitable due to the low mobility of gas. Compared to gas, foam has larger viscosity and mobility, and has been applied as an effective method for inhibiting gas channeling in many field applications [1-4]. Common foaming agents in field application are anionic surfactants [5-8], such as dodecyl benzene sulfonate, alpha olefin sulfonate, sodium dodecyl benzene sulfonate, sodium lauryl sulfate, and sodium dodecyl sulfate. Betaine surfactants have recently attracted increasing attention for their advantages such as good tolerance to high temperature, high salinity and high hardness, and high interfacial activity at low concentration [9-10].

In our work, a clear and stable solution of LAB was achieved at various concentrations. The foaming properties of LAB without other surfactants at high salinity and high temperature were studied. Both foam volume and drainage half-life perform well. The main purpose of our work is to investigate the foaming properties and factors affecting LAB. In addition, factors affecting foam properties including adsorption and the wettability alteration ability of LAB were studied.

Experimental Sections

Material. LAB was procured from Nu Tong Chemical Company. The mimic brine used in this work was prepared with NaCl, $CaCl_2$, $NaHCO_3$, and $MgCl_2.6H_2O$ procured from Sinopharm, and the ion composition of the formation water is shown in our previous work [11].

Foaming properties. Aqueous solutions of LAB at various concentrations ranging from 0.5mg/mL to 3mg/mL were prepared using Tahe formation water. Foaming properties (both drainage half-life and foam volume) were tested by the Warning Blender method. At 90 ℃, 100mL solutions were stirred by Warning blender for 1 minute at 3000rpm. Then foam volume and drainage half-life were recorded.

LAB solutions with concentrations of 1mg/mL were prepared using Tahe formation water with pH values ranging from 3 to 9. To study the effect of different ions on foaming properties, LAB solutions were prepared using NaCl and $CaCl_2$ solutions. The foaming properties of these solutions were also tested by the Warning Blender method at 90 ℃.

Determination of Resistance Factor. Resistance factor is a key parameter in the foam plugging effect. Sand pack was prepared using carbonate particles from the Tahe oilfield. Simultaneous injection of water and nitrogen were conducted and the pressure difference during this process was recorded. Then foam with same gas/liquid ratio was injected. The resistance factor was calculated using the above pressure differences.

Surface Tension Measurement. The surface tension of LAB solutions of various concentrations were measured by the Du Nouy Ring method.

Adsorption Experiment Tension Measurement. Surfactant adsorption was measured in a static experiment. We used the similar method as Li [12].

Measurement of Contact Angle. Contact angle was measured by DSA100 (Kruss, Germany). The contact angle was measured by placing a crude oil droplet in direct contact with the core.

Results and Discussions

Foaming Properties of LAB at 90℃. LAB solutions with different concentrations were prepared by Tahe formation water and foaming properties were tested at 90 ℃. The results are shown in Table 1. When above 0.1%, LAB solutions behaved well in foaming properties. With further increase of concentration, there was little change in foaming properties.

Table 1. Foaming properties of LAB with different concentrations.

Concentration/mg/mL	Drainage half -life/s	Foam volume/mL
0.5	101	320
1	289	530
1.5	307	540
2	313	550
2.5	315	540
3	316	535

Effect of pH on Foaming Properties. The foaming properties of LAB at different pH values were tested and the range of pH varied from 3 to 9. The results are shown in Table 2. At all tested pH values, LAB had good foaming properties, and under weakly acidic conditions, LAB had better performance. This is likely because at a pH around the isoelectric point, electrostatic repulsion between the LAB molecules was minor, enabling the LAB to be arranged tightly at the air-water interface.

Table 2. Foaming properties at different pH.

pH	Foam volume/mL	Drainage half-life/s
3	540	273
4	520	305
5	520	307
6	525	285
7	530	287
8	530	276
9	545	268

Effect of ion Composition on Foaming Properties. The foaming properties at 90 ℃ were then tested, with the results shown in Figure 1. With an increase in NaCl or $CaCl_2$ concentration, drainage half-life increased linearly. However, the incremental growth of drainage half-life in NaCl solution and $CaCl_2$ solution were different. Incremental growth in the $CaCl_2$ solution was faster than in the NaCl solution. With the increase in the electrolyte, phase viscosity rose, increasing the drainage half-life. However, the LAB is a zwitterionic surfactant and with an increase of Ca^{2+}, Ca^{2+} adsorbs on the LAB, which increases the electrostatic repulsion and inhibits lamellar coalescence.

To demonstrate the effect of the ion on foaming properties, foaming properties in different Na_2SO_4 solutions were tested and the results shown in Table 3. With an increase in Na_2SO_4 concentration, drainage half-life did not behave as with NaCl or $CaCl_2$ solutions, and drainage half-life changed little. For viscosity changes with addition of Na_2SO_4, there must be some conditions which were adverse to foam stability. Though LHSB is a zwitterionic surfactant, under formation conditions, since it behaved like a cationic surfactant, the addition of SO_4^{2-} decreased electrostatic repulsion, and therefore drainage half-life did not increase.

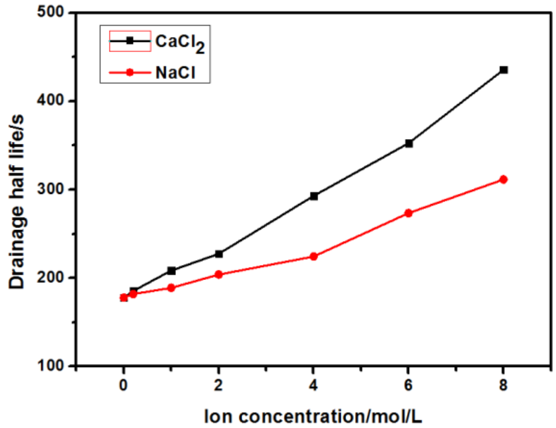


Figure 1. Comparison diagram of drainage half-life between NaCl and $CaCl_2$ solution

Table 3. Foaming properties in Na_2SO_4 solution

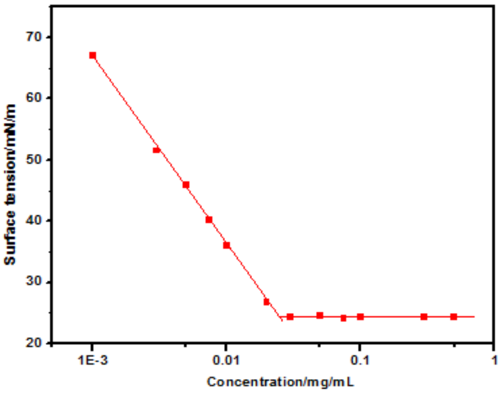
Concentration/ mol/L	Foam volume/mL	Drainage half-life/s
2	500	195
1.5	520	197
1	530	191
0.5	540	185
0.25	545	186
0.05	560	190
0	570	178

Since the main aim of foam injection is inhibiting gas channeling and profile modification, the pressure difference during foam injection is an important evaluation criterion. The resistance factor is the ratio of the pressure of between the foam injection and simultaneous injection of water and gas (SWG). Sand pack was prepared using carbonate particles. Flooding tests were conducted by SWG and foam using different gas liquid ratios (GLR). Equilibrium pressures are shown in Table 4. At all GLRs, the LHSB solution exhibited good plugging effect and with an increase in GLR, the resistance factor increased.

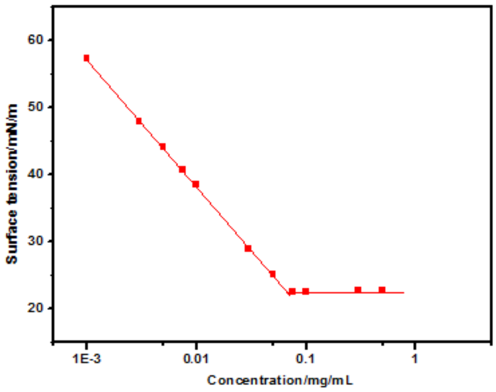
Table 4. Equilibrium pressure and resistance factor of different floodings

Flooding method	Equilibrium pressure/MPa	Resistance factor
SWG，GLR 1:2	0.009	-
SWG，GLR 1:1	0.011	-
SWG，GLR 2:1	0.012	-
Foam flooding SWG，GLR 1:2	0.59	65.56
Foam flooding SWG，GLR 1:1	0.79	71.82
Foam flooding SWG，GLR 2:1	1.18	98.33

Surface Tension. Results of surface tension in different waters were shown in Figure 2.



(a)



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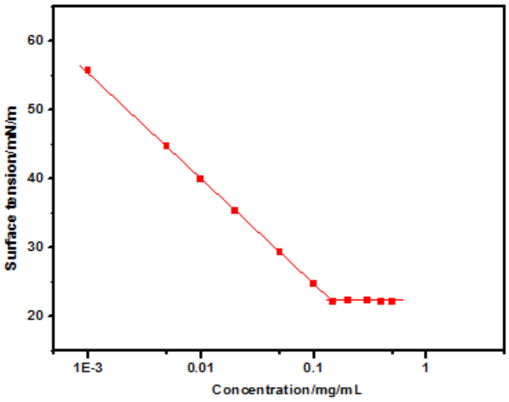

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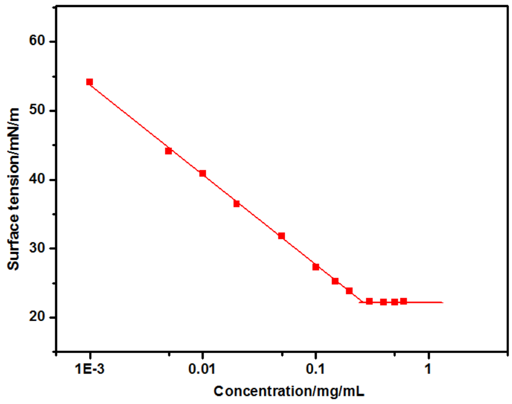

(d)

Figure 2. Surface tension variation in different water (a) Tahe formation water (b) 1/2 Tahe formation water (c) 1/4 Tahe formation water (d) distilled water

It could be found that with the increase water salinity, CMC value decreased and surface tension at CMC increased. Both the increase of surface tension and the decrease of CMC value was the result of electrolyte addition. It should be noted that in different waters, the decrease of CMC value meant that even at the same surfactant concentration, higher salinity could achieve higher CMC times concentration. That may be part of the reason that with the increase of salinity, foaming properties increased.

Determination of Adsorption. The results of adsorption are shown in Figure 3. With the increase of LAB concentration, adsorption of LAB on carbonate increased. The adsorption curve was L-type and matched the Langmuir isotherm [14]. The equilibrium adsorption was about 0.8mg/g, which was much lower than the adsorption of betaine on sandstone in our previous study [13]. The major reason for adsorption variance may be the different charges of the limestone and sandstone.

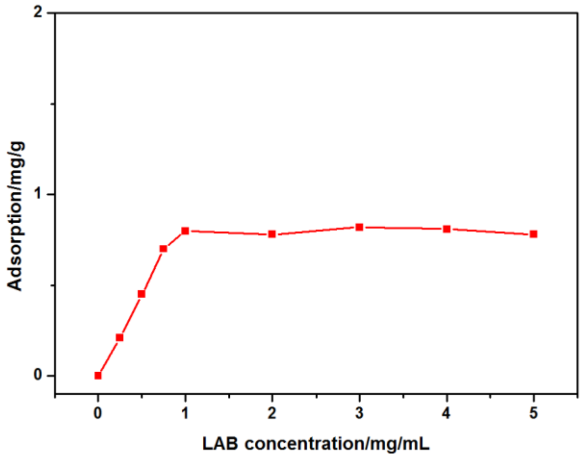

Figure 3. Adsorption of LAB on limestone

Wettability Alteration. Contact angle of a field core was measured before and after oil treatment. Then the core was soaked in LAB solution for 3 days, and the contact angle was measured again. The results are shown in Figure 4. After oil treatment, it became oil-wet, and after soaked in LAB solution, it became water-wet. So LAB had ability of wettability alteration to limestone. As to the reason, Austad [15-17] has done a lot of work on mechanism of wettability alteration, and to cationic surfactant, ion pair is responsible for wettability alteration. As previously mentioned, cationic property was the main reason for wettability alteration.

Figure 4. Contact angle in different stages Before oil treatment After oil treatment After LAB treatment

Summary

Under conditions of high temperature and high salinity, LAB has excellent foaming and plugging ability. With an increase in NaCl or $CaCl_2$ concentration, drainage half-life increased, while with an increase in Na_2SO_4, drainage half-life decreased. The divalent anionic ion had an adverse effect on foam stability. With an increase in water salinity, CMC decreased gradually, one of the reasons for better foam stability. In addition, LAB has low adsorption on limestone and can alter the wettability from oil-wet to water-wet, both of which are of significant importance in enhanced oil recovery by surfactant injection.

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