Experimental study on performance evaluation of fracturing fluid system with enhanced oil recovery

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Abstract. In order to screen out fracturing fluid system with enhanced oil recovery performance, performance experiments of three surfactants blended with low concentration guar gum fracturing fluid used in fracturing technology of Daqing Oilfield are conducted. The performance experiments include interfacial tension test, emulsifying performance test and wettability reversal experiment. Interfacial tension values of different surfactant concentrations are tested. Water separation rates of emulsion in nine liquid systems are tested. The wettability of 36 cores is tested. It is concluded WPS and LCG composite fracturing fluid system has the lowest interfacial tension and stable emulsifying property, also reverses the wettability of hydrophilic core and increases the wettability of hydrophilic core.

1. Introduction
Surfactant flooding technology is an important method to enhance oil recovery, mainly includes the mechanism to reduce the interfacial tension, to form the emulsified oil and to change the wettability of rock itself [1-3]. The surfactant solution can reduce the interfacial tension of the oil drop, make oil drop to be easy deformation and easy out from the channels, to enhance oil recovery. The interfacial tension of the oil and water can be reduced to the ultra-low level (10⁻³mN/m) by injecting the surfactant into the oil layer. The surfactant system has strong emulsifying power of crude oil in the oil and water two-phase flow shear conditions, can quickly remove the rock surface oil dispersion, to form oil in water (o/w) emulsion, so as to improve the mobility of oil-water ratio and increase the sweep coefficient. The wettability of the rock wall is an important parameter that affects the flow characteristics of the fluid. For surfactant flooding, surfactant molecules are adsorbed on the pore wall, the interfacial wettability changes from hydrophobicity into hydrophilicity, the capillary force becomes from flooding resistance into oil displacement power, thus to achieve the purpose of enhancing oil recovery.

Low concentration guar gum fracturing fluid (abbreviated as LCG) is low temperature fracturing fluid system, the new composite fracturing fluid is formed by a variety of chemical materials under certain conditions by chemical reaction with the boron as the main body, and it can break through the limit of the concentration of crosslinking cross-linked guar gum powder, forming a low concentration of fracturing fluid [4-6]. It does not need special and special additives. Under the same temperature condition, the concentration of gum thickener will be reduced by about 40% compared with conventional wells.

Obviously, when the fracturing fluid is combined with the surfactant, the properties and advantages of the new system with liquid fracturing fluid itself, and fracturing fluid into the formation also has the advantage of displacement. However, there are few reports on the performance evaluation of this type of fracturing fluid system at home and abroad. Therefore, the interfacial tension, emulsification and
wettability of the three selected surfactants and their combined solutions with low concentration gum fracturing fluid are evaluated. The composite fracturing fluid system with super low interfacial tension, stable emulsification performance and changing wettability is given.

2. Experimental conditions and Experimental procedure

2.1. Experimental conditions
The initial setting temperature of the experiment: Daqing reservoir formation temperature is 45°C, Oil in experiment: Simulation oil for oil and kerosene configuration in Daqing oil production plant, the oil viscosity is 3.0mPa·s (in 45°C), and the density is 0.72g/cm³. Three surfactants used in the experiment: petroleum sulfonate (abbreviated as WPS), 35% solid content, from Daqing Refining & Chemical Company; dodecyl benzene sulfonate (abbreviated as LAS), 50% solid content, from Daqing Refining & Chemical Company; Twelve alkyl hydroxypropyl phosphate ester betaine (abbreviated as BS), 45% solid content, from Shanghai NOVON company. The experiment water: W1, its salinity is 3585mg/L.

2.2. Experimental procedure
(1) According to the concentration of ions, the solution of salinity is arranged; (2) According to the solid phase ratio of three surfactants, the solutions of different surfactant concentration are configured; (3) Use spinning drop interfacial tension tester to test interfacial tension of different concentration surfactant solution [7]; (4) Mixing different surfactants and simulated oil to form oil and water mixtures, to obtain the separated water ratio curve at different times [8]; (5) Wetting reversal experiments use contact angle measuring instrument and natural core [9-10]; (6) The compound solution of the concentration of different surfactant and low concentration guar gum fracturing fluid are configured; (7) Repeat steps 3 to 5 to obtain the interfacial tension value, stability of emulsion in different complex system solutions and contact angle; (8) Compare and analyse experimental dates.

3. Results and Discussion

3.1. Interfacial tension value
With W1 formation water, the interfacial tensions of different concentration of surfactant and their compound system with low concentration guar gum fracturing fluid are measured at 45°C, and the concentration is set to 0.05wt%, 0.1wt%, 0.15wt%, 0.2wt%, 0.25wt%, 0.3wt%, 0.35wt%, 0.4wt% and 0.6wt%, respectively. The relationship between the concentration of different liquid systems and the interfacial tensions is shown in Figure 1.

![Fig. 1. The relation curve of concentration and interfacial tension.](image-url)
The dotted line in the Figure 1 represents the change of the interfacial tension of three surfactant solutions. It is showed that the concentration has an effect on the interfacial tension of the surfactant. With the increase of concentration, the interfacial tensions decrease firstly and then rise. The minimum interfacial tension values of various surfactants are 3.35mN/m of WPS, 0.155mN/m of LAS, and 0.18mN/m of BS, respectively. When the interfacial tension is at a lower range, the concentration range of the surfactant are 0.2%~0.3% of WPS, 0.25%~0.35% of LAS, and 0.2%~0.3% of BS, respectively. The interfacial tension values of WPS and BS are greatly influenced by the concentration, while the interfacial tension of LAS is less affected by concentration.

The solid line in the Figure 1 represents the interfacial tension curve of the solution mixed by the surfactant and LCG. The interfacial tension values of the fracturing fluid systems with anionic surfactants (WPS and LAS) reduced. Among them, the interfacial tension of WPS and LCG solution has the maximum reduction. However, the interfacial tension of the BS and LCG solution is higher than that of the pure BS solution. The main reason is LCG is alkaline liquid. Synergistic effect is produced by the combination of alkaline solution and surfactant solution. In different surfactant concentration conditions, the interfacial tension of WPS and LCG is maintained at $10^{-2}$mN/m magnitude, the interfacial tension of LAS and LCG is maintained at $10^{-1}$mN/m magnitude.

Therefore, to reduce the interfacial tension, the optimal solution system is WPS+LCG solution and LAS+LCG solution. The best application concentration of surfactants in these compound systems is 0.2wt% for LAS, 0.3wt for WPS.

3.2. Emulsifying property

With W1 formation water, the water separation rates of different concentration of surfactants and their compound system with low concentration guar gum fracturing fluid are measured at 45℃, the time are set to 5min, 10min, 30min, 1h, 2h, 3h, 6h, 24h and 48h, respectively. The concentration of surfactant is designed 0.3wt% for WPS, 0.2wt% for LAS and 0.25wt% for BS. The water content is 75% and the speed is 3000r/min. The relationship between the water separation rate of different liquid system and the time is shown in Figure 2.

Form Figure 2, it is showed that with the increase of time, the water separation rate of the solution increases. Compared with the water separation rate of a single surfactant solution (WPS and BS), the final stable water separation rates of WPS+LCG and BS+LCG reduce, the results show that the emulsion stability of these two complex systems is high. However, the final stable water separation rate of LAS and LAS+LCG are close to being equal. Sorted from strong to weak, the stability of the emulsion in these solutions is BS+LCG, BS, WPS+LCG, LAS+LCG, LAS and WPS.

Therefore, except for WPS, the emulsifying properties of other solutions are relatively strong.
3.3. Wettability evaluation

Wetting reversal experiments use contact angle measuring instrument and natural core. Five different random points are selected on the core for experimental test. The average value of the contact angles obtained by the five points is used as the evaluation parameter. The core after drying is placed in the DSA100 contact angle measurement to measure the original contact angle of the core. Soak the core in a surfactant or compound fracturing fluid for 2 days. After the core is dried, the modified core contact angle is measured. When the measured contact angle is greater than 90 degrees, the wettability of core is identified as oil wetness. When the measured contact angle is less than 90 degrees, the wettability of core is identified as water wetness. The wetting angle measurement results of single surfactant and composite fracturing fluid systems are shown in Table 1 and Table 2.

Table 1. Measurement results of single surfactant contact angle

| Type | Mean value of contact angle | D-value |
|------|-----------------------------|---------|
| WPS  | Original contact angle (oil wet) | 97.77 | 12.71 |
|      | Modified contact angle       | 85.06 |       |
|      | Original contact angle (water wet) | 83.35 |       |
|      | Modified contact angle       | 50.47 | 32.88 |
| LAS  | Original contact angle (oil wet) | 97.57 | 11.89 |
|      | Modified contact angle       | 85.68 |       |
|      | Original contact angle (water wet) | 85.09 |       |
|      | Modified contact angle       | 37.16 | 47.93 |
| BS   | Original contact angle (oil wet) | 97.34 | 5.16  |
|      | Modified contact angle       | 92.18 |       |
|      | Original contact angle (water wet) | 85.70 |       |
|      | Modified contact angle       | 53.11 | 32.59 |

Table 2. Measurement results of composite system surfactant contact angle

| Type   | Mean value of contact angle | D-value |
|--------|-----------------------------|---------|
| WPS+LCG | Original contact angle (oil wet) | 113.88 | 28.17 |
|        | Modified contact angle       | 85.71  |       |
|        | Original contact angle (water wet) | 66.91 |       |
|        | Modified contact angle       | 15.39  | 51.52 |
| LAS+LCG | Original contact angle (oil wet) | 106.08 | 27.23 |
|        | Modified contact angle       | 78.85  |       |
|        | Original contact angle (water wet) | 55.43 |       |
|        | Modified contact angle       | 12.91  | 42.52 |
| BS+LCG  | Original contact angle (oil wet) | 107.83 | 11.70 |
|        | Modified contact angle       | 96.13  |       |
|        | Original contact angle (water wet) | 64.60 |       |
|        | Modified contact angle       | 28.70  | 35.90 |

From Table 1, it is showed that the contact angle of the core that has been soaked with a single surfactant decreased. The addition of surfactants can reduce the wettability of oil phase and increase the wettability of water phase. The reduction value of the contact angle of the oil wet core is far less than the reduction value of the contact angle of the water wet core. For the oil wet core, the wettability of the core soaked with WPS and LAS is reversed, except for BS. For the water wet core,
the water wettability of the three surfactants is increased by the solution, and the increase of the water wettability is greater.

From Table 2, it is showed that the core after soaked by LCG fixed with three surfactants, the contact angle decreased. For the oil wet core, the decreased value of the contact angle is very large compared with pure surfactants, LCG added WPS and LAS (except for BS) reversed its core wettability. For the water wettability core, the decreased value of the contact angle is also large, which shows three kinds of composite system can improve the hydrophilicity of rock.

4. Results
Interfacial tension test, emulsion water separation rate test and rock wetting contact angle test are conducted, we have these results as follows:

a) The interfacial tension of the WPS solution is the largest and the interfacial tension of the WPS+LCG composite system is the lowest.

b) The stability of the emulsion in WPS solution is the worst, and the stability of the emulsion in other solutions is relatively good.

c) WPS, WPS+LCG, LAS, and LAS+LCG liquid systems can reverse the wettability of lipophilic core, and greatly increase the wettability of hydrophilic core.

d) WPS+LCG composite fracturing fluid system has the lowest interfacial tension and stable emulsifying property, also reverses the wettability of hydrophilic core and increases the wettability of hydrophilic core.

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