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Optimization and evaluation of binary composite foam system with low interfacial tension in low permeability fractured reservoir with high salinity

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ABSTRACT

The foam flooding technology can be used in low permeability fractured reservoir for tertiary oil recovery. In view of low permeability fractured reservoir with low temperature and high salinity, a binary composite low interfacial tension foam system is developed, and the composite foaming ability, interfacial tension, resistance to oil, salt and temperature of the foam system were evaluated in this paper, and then the plugging ability and oil displacement efficiency were studied. It is indicated that under the condition of 32 °C and 29 500 mg/L formation water salinity the optimized formulation of binary composite low interfacial tension foam system is selected for 0.12% W fluorocarbon foamer+0.08% QL betaine +0.1% BS betaine +1500 mg/L polymer; for the reservoir with big permeability difference existed between layers or high permeability reservoir, profile control measures are needed to be further taken before foam injection; 0.4 PV foam system and 0.1 PV profile control system were injected into the parallel core column with high permeability 1000mD and low permeability 10mD cores in the oil displacement experiment, and the recovery of low permeability core was enhanced by 18.87%. In practical application, the profile control system and its amount need to be optimized according to the actual situation.

1. Introduction

The air foam flooding oil system is constituted by foamer, foam stabilizing agent and air. It is more economical than injecting nitrogen foam and active water. And advantages of gas injection flooding and foam flooding are given full play. The applicability or high water cut, serious heterogeneity, large fractures or high permeability channels existed in low permeability reservoirs is showed up (Zhang and Liu, 2004). Foam composite flooding has become a kind of recovery method with comprehensive and multiple functions. It is an effective measure to enhance oil recovery of low permeability fractured reservoir, but with low stability and poor oil resistance in application. JY oilfield is located in the northwest of China. It is provided with average temperature 32 °C, salinity 29500 mg/L and permeability 10mD, belonging to the low permeability oilfield with low temperature and high salinity. The development degree of primary fracture is medium. The width and permeability of fractures are about 0.02 mm–20 mm and 300mD~1000mD respectively. Current process understanding is limited for this kind of reservoir.

A N_2-foam field trial was evaluated at the Painter reservoir in Wyoming by Kuehne D. L. et al., but foam injection was ineffective in controlling N_2 channeling (Kuehne et al., 1990). The surfactant concentration was optimized in the injection slug and the swelling effect was analyzed during CO2 injection by Saputra D. D. et al. (Saputra et al., 2013). It has been proved that the oxidation reaction of air in the formation to produce carbon oxides, such as carbon monoxide and carbon dioxide, to form a flue gas to displace the formation oil, while releasing heat to improve displacement efficiency by Li Yibo and Xu Bo (Yibo, 2014; Bo, 2016). Low Tension Gas flooding is a novel EOR process which can address challenging reservoir conditions such as high salinity, high temperature, and high permeability rock (Jong et al., 2016). An extensive study has been undertaken with different surfactants (foamingagents) and polymers to screen out the surfactant/polymer combinations providing the highestfoam stability for high permeability reservoir by Hernando, L.et al. (Hernando et al., 2016), but it was not discussedabout low permeability fractured reservoirwith high salinity. The displacement characteristics and mechanism of the binary composite foam system were studied from the microscopic view point by Li Lijun et al. and the recovery is enhanced mainly by the extrusion, selectively blocking large pores, shearing and carrying effect (Lijun Zhihonget al, 2012). High salt

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resistance was exhibited by ZY-1 composite oamer, but it was sensitive to temperature, and the desired foam composite index cannot be achieved (Jianli, 2011). The binary system obtained by dodecyl-hydroxypropyl-sulfo betaine (DSB) remixed with alkali and ZY-F foamer were studied only on the recovery of high permeability layer, and the scaling and fingering phenomenon along high permeability layer could be easily caused by alkali, so they were not applied availably in low permeability fractured reservoir (Yong, 2015; Qing, 2014). The binary composite foam system was obtained by the combination of sodium olefin sulfonate and polymer and low resistance index was only reached, and the plugging effect could not be achieved very well (Jia, 2015).

In this paper, the different formulations of foamer are optimized and evaluated for the characteristics of JY oilfield. A binary composite low interfacial tension foam system is developed for low permeability fractured reservoir with high salinity. Compared with the above researches, itis consist of W fluorocarbon foamer with salt resistance, QL betaine with strong oil resistance, polymer as stabilizing agent, and BS betaine producing low interfacial tension. A stable oil displacement system is formed in high salinity condition and adapts to the characteristics of low permeability fractured reservoir. The foaming ability, oil-water interfacial tension, resistance to salt and temperature, plugging ability and oil displacement effect of the foam system were evaluated. The oil-water interfacial tension and water-oil mobility ratio can be reduced by the composite foam system. The sweeping and oil displacement efficiency are improved. The binary composite low interfacial tension foam system shows good oil and temperature resistance which can be used in low permeability fractured reservoir for tertiary oil recovery.

2. Experimental materials and methods

The good foaming performance and foam stability to oil are respectively owned by fluorocarbon foamer W and QL betaine. Polyacrylamide (HPAM, 2500 × 10^4 molecular weight) isused as foam stabilizer, and a good foam stabilizing effect can be reached. BS betaine surfactant can be arranged alternately with the main agent of different electrical properties. The density of membrane molecules is increased, so the penetration of gas is reduced. And the interfacial tension of foam system is reduced at the same time, so the foam stability and oil displacement performance can be improved (Zhigang, 2016).

Air is used as experimental gas. Crude Oil in JY oilfield is dehydrated as experimental oil with different oil saturation. Different salinity of formation water is applied to evaluate the salt resistance of foam system. The resinous profile control agent with salt resistance is combined with the foam system to improve the recovery rate of the low permeability layer.

For simulating the fracture system of low permeability fractured reservoir, the experimental model is made of two parallel columns with high and low permeability cores. The high permeability cores are respectively 300mD, 500mD and 1000mD, and the low permeability cores are 10mD. 300mD, 500mD and 1000mD fracture systems are respectively simulated by high permeability cores in the parallel core columns.

The foam performance testing device is constituted by MC-DP710C gas mass flow controller, D08-1G flow indicator, HH-501S thermostatic water tank and type 2152 Ross-Miles foam meter etc.; the high temperature and high pressure foam flooding device is composed of high pressure and constant speed injection pump specially machined, foam generator and high pressure observation window (the working pressure: 35 MPa) etc.; the core flow experiment device is made up by HW-4A double thermostat, hand pump etc.; the type TX500K spinning drop interfacial tension meter is used to measure interfacial tension; Brookfield DV III ultra-rotary viscosity meter, JJ-1 type electric mixer and etc. are included.

3. Experiment 1: selection of foam system

The performance of the foamer is mainly evaluated from two aspects of the foaming ability and foam stability. The foaming volume (V_f) and half-life ($t_{1/2}$) are mainly used as the evaluation parameters. The foaming volume is installed independently from the half-life, and the foaming difficulty and quantity are reflected by V_f, while the foam stability is reflected by $t_{1/2}$. But the foaming performance in porous media cannot be sufficiently reflected by any one of these two parameters (Guoxi and Buyao, 2003). Under certain experimental apparatus conditions, the change of foam volume is only related to foam height. Because the ability of mobility adjustment of foam in the formation is comprehensively influenced by the foam amount (reflecting of the foaming height) and stability (reflecting of the half-life), the foam composite index F_c ($F_c = 0.75 \times h \times t_{1/2}$) is introduced to synthetically represent the foaming ability and foam stability (Defu, 2008). The Fig. 1 is a diagram of the relationship between foaming, foam-breaking time and foam heights obtained under experimental conditions.

The area of the shadow in the picture can reflect the foaming capacity of the system and make it a foam composite index F_c. Assuming that the equation of the curve is $h = f(t)$, there is

$$F_c = S = \int_{t_0}^{t_0+t_{1/2}} f(t)\, dt \tag{3-1}$$

In order to facilitate calculation, the approximate area of the trapezoidal ABCD as S can be obtained as follows:

$$F_c = S = 0.75 h_{max} t_{1/2} \tag{3-2}$$

The foaming height can be measured by the Ross-Miles foam meter, and the half-life can be recorded by using stopwatch.

3.1. Experimental procedures

(1) The 100 ml foaming system solution preheated to the experimental temperature in the separating funnel was released into the jacket cylinder, then the dehydrated crude oil was added into it;
(2) The thermostat was opened, and then the annular space was heated to the experimental temperature through the water circulation;
(3) The gas mass flow controller and flow indicator was opened, and then the air was inlet by 100 mL/min after the zero point stabilized;
(4) The foaming height h and time were recorded at the end of the air injection;
(5) The half-life of the foam $t_{1/2}$ was recorded;
(6) The foam composite index F_c was calculated according to the foam height h and the half-life $t_{1/2}$;
(7) The ratio of gas and liquid was changed, and the foaming height h and the foam half-life $t_{1/2}$ were recorded at different ratios, and then the foam composite indexes F_c were calculated.

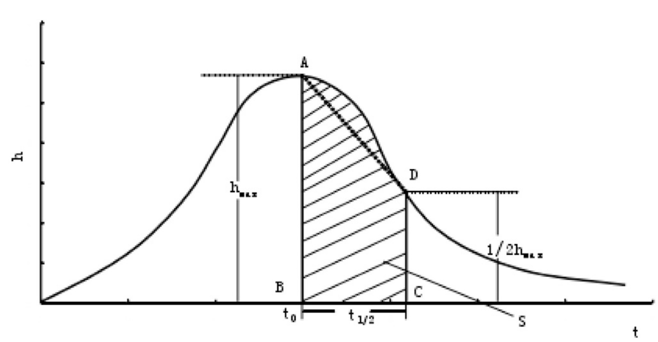

Fig. 1. The relationship between foaming, foam-breaking time and foam heights.