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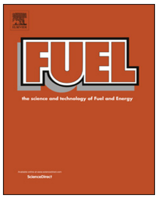

Full Length Article

The macroscopic and microscopic analysis on the performance of steam foams during thermal recovery in heavy oil reservoirs

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ABSTRACT

In heavy oil reservoirs, steam channeling and steam override seriously decrease oil production and the ultimate oil recovery during steam flooding. Aiming at the two problems, some experiments were carried out to analyze the EOR mechanisms through injecting foaming agents along with steam injection in heavy oil reservoirs. An orthogonal method was employed to analyze the multiple factors on foam's properties to optimize foaming agent for steam injection. Then a novel 2D-visualization experiment was carried out to quantitatively study the characteristics of steam channeling and the variation of sweep efficiency during steam or steam foams flooding. Based on the experimental results, many bubble's characteristics, such as migration, retention, regeneration and etc., were analyzed through the macroscopic and microscopic perspectives. The experimental results show that the Jamin effect increases the flow resistance of steam-phase in porous media to obviously enlarge the macro sweep efficiency and effectively increase micro oil displacement efficiency. On a macroscopic level, because of the unique structure, foams decrease steam override or steam channeling to improve sweep efficiency; on a microscopic level, due to the expansion effect of gas-phase, bubbles can desquamate the oil film on the pore wall and even the oil drop in the blind pore to decrease the residual oil saturation. In our experiments, the ultimate recovery of steam flooding can only reach 48.48%. However, the ultimate recovery of steam foams can reach 59.95%, which is 11.47% higher than steam flooding.

1. Introduction

Heavy oil is an important oil resource in the world, especially in China [1]. But because of its characteristic of high viscosity, the exploration of heavy oil is so difficult that thermal recovery technology is usually used. Nowadays, steam flooding has been regarded as a mature thermal recovery technology for heavy oil reservoirs [2]. The advantage of this technique over the other methods lies in its practicability and higher recovery rate [3]. The principal mechanisms responsible for enhancing oil recovery are identified by many researchers as thermal expansion of fluids and minerals, viscosity reduction of heavy oil and distillation effect of steam under reservoir conditions [4–6]. However, though steam flooding for heavy oil reservoirs is a favorable technology, some defects are found in the processes of oilfield applications [7]. There are two mainly significant problems. On the one hand, gravity segregation or steam override makes the injected steam gradually rise to the top of the reservoir and tend to form steam breakthrough to production wells [8–10]; On the other hand, the formation heterogeneity and the viscosity difference between steam and crude oil can cause steam fingering or steam channeling in high permeability formations [8,9]. The two problems can cause early steam breakthrough to production wells resulting in the poorer sweep efficiency or the lower oil recovery in heavy oil reservoirs [7].

To solve these problems and to get high oil recovery, thermal foams were applied to improve the development effect of steam injection [11,12]. The efficiency of steam injection can be effectively improved through the usage of additives, gas and surfactant, which generates foams to decrease the mobility of steam in higher permeability formation and to divert steam to lower permeability formation [13]. In laboratory studies, foams reduce steam mobility up to 40% in porous media [12]. Foams can effectively decrease fluid mobility in porous media, which has been demonstrated in several field tests [11,14,15]. Some researchers studied the selective blockage of fluids in thermal recovery projects and concluded that foams were best suited for this

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purpose [7,12]. It is well known that foams can increase the viscosity of gas-phase, enhance steam sweep volume, maintain reservoir pressure and increase steam heating volume. Meanwhile, foaming agent is a kind of surfactant, which can alter the wettability of formation rock and reduce the interface tension between oil and water, to improve the oil displacement efficiency [16,17]. But all the results did not give enough evidences on the microscopic characteristics of foams under high temperature conditions, and they even did not quantitatively describe the incremental degree of the sweep efficiency after thermal foams injection. Some important characteristics of foams, such as migration, retention, regeneration, coalescence, rupture and etc., were all not directly observed under high temperature conditions.

In China, about 70% of heavy oil reservoirs is buried from 600 m to 1400 m, whose corresponding saturation temperature of steam is over 250 °C at which the foam system has poorer stability [1,5]. Therefore, the surfactant must be stable at high temperature; foams can be generated after the injection of gas and surfactant under reservoir conditions; and foams' blocking ability and stability should be retained for a long period under reservoir conditions [18]. Aiming these unsolved problems, an orthogonal method was employed to analyze the influencing factors on foams' stability and foaming ability under high temperature. Meanwhile, a static and dynamic evaluation method for foaming agents was applied to choose the optimum foaming agent. Then a novel 2D-visualization experiment was used to observe the processes of oil displacement by thermal foams enhancing steam flooding. On the macroscopic and microscopic level, the EOR mechanisms of thermal foams were summarized according to the experimental results.

2. Experimental apparatus and procedures

2.1. Experimental materials

2.1.1. Foaming agents

Five foaming agents, such as ZWF-1, GMH-1, HFA-3, FP-2 and DRF-3, were used to measure foam properties. ZWF-1 is a kind of alkyl glycerol ether sulfonate. Its color is milky white and it shows weak acidity. GMH-1 is secondary alkyl sulfonate whose color is also milky white. It belongs to a kind of anionic surface agent whose pH value is 7 ± 0.5. HFA-3 is an improved Alpha olefin sulfonate that is a kind of anionic surface agent. Its color is light yellow and it shows weak alkaline. FP-2 is a kind of non-ionic or anionic surface agent that belongs to sulfonate. Its color is brown and it shows weak acidity. DRF-3 is sodium alkylbenzene sulfonate. Its color is brown black and the pH value is 7 ± 0.5.

2.1.2. Reservoir fluids

In our experiments, the crude oil is characterized by density 0.958–0.974 g/cm^3. Its viscosity is 449–926 mPa·s at reservoir temperature, which belongs to conventional heavy oil. Formation water belongs to $NaHCO_3$ type. The total salinity of formation water varies from 1380 to 4229 mg/L. The main cationic is K^+ and Na^+ whose content is 436–1404 mg/L. The main anion is $C1^-$ whose content is 112–401 mg/L. Non-condensate gas used for generating foams was industrial nitrogen with a purity of 99%.

2.2. Static experiments

A reaction vessel, CWYF-1, was used to evaluate the foaming volume and the half-life of foams under high temperature and high pressure conditions, as shown in Fig. 1. The main part of CWYF-1 includes: heating oven, vessel body, stirring device and magnetic transmission system, safety valve and etc. An electric heating tube is installed inside the vessel body. Some devices, such as pressure gauges, safety valves and outlet valves, are connected with the upper head of CWYF-1. The inlet valve is installed on the bottom of CWYF-1. A stirring electric machine is installed on the bottom of vessel body to make magnetic rotor rotate in vessel body. The control system of CWYF-1 includes: temperature controller, speed governor, power switch and etc. The highest working pressure is 20 MPa at 160 °C but only16 MPa at 250 °C. The volume of vessel body is 600 mL. The visible range of visualization window is 15 mm × 200 mm. The range of stirring speed is from 0 to 4500 rpm.

The experimental procedures are given as: (1) High pressure N_2 was injected into vessel body to check whether leakage or not; (2) The foaming agent solution of 100 mL was taken into the vessel body; (3) The back pressure of the outlet was controlled 0.5 MPa higher than the saturation pressure that was corresponding to an experimental temperature. Then the whole system was controlled at the experimental temperature for at least 4 h; (4) The stirring speed was gradually adjusted to 3000 r/min. The largest foaming volume ($V_{\text{f-max}}$) can be recorded through the visualization window of the vessel body after stirring for 5 min; Then, the half-life ($T_{\text{f-0.5}}$) can be also recorded when the foaming volume changes to the half; (5) A new parameter, foam stability index (S_f), is introduced to represent the foaming ability and the foams' stability, which can be calculated according to the area of shadow part in Fig. 2. If the shape of the foaming volume (V_f) vs. time (only from 0 to $T_{\text{f-0.5}}$) is divided equally into n parts, then the foam stability index, S_f, can be expressed as Eq. (1) [19].

$$S_{\text{f}} = \frac{T_{\text{f}-0.5}}{2n}\left(\frac{3}{2}V_{\max} + \sum_{i=1}^{n-1} V_{f-i}\right) \tag{1}$$

where S_f is the foam stability index, mL·min; $V_{\text{f-max}}$ is the largest foaming volume, mL; $T_{\text{f-0.5}}$ is the half-life of foams, min; $V_{\text{f-i}}$ is the foaming volume corresponding to the i parts, mL.

The orthogonal method was employed to study the influence of different factors on foams' properties. Two important parameters, such as the range (R) and the sum of square of deviations (DEVSQ), were used to determine the key factors that influenced on foam stability index (S_f) and finally to choose the optimum foaming agent. The factors involved: the type of formation water (distilled water, $CaCl_2$ type and $NaHCO_3$ type), the experimental temperature (100 °C, 200 °C and 300 °C), the foaming agent concentration (0.4 wt%, 0.5 wt% and 0.6 wt %), the time of thermal degradation (1 h, 120 h and 240 h at experimental temperature).

2.3. Dynamic experiments

As shown in Fig. 3, the experimental apparatus is mainly consisted of five parts: sand-pack model (single or double sand-packs), injection system, data acquisition system, production system and auxiliary system. For the sand-pack model, the highest working pressure and temperature are 32 MPa and 350 °C respectively. The sand-pack is 60 cm in length and 3.8 cm in inner diameter. The injection system is mainly consisted of a constant-flux pump, a steam generator, a nitrogen cylinder, an intermediate container and a gas mass flow controller. It can inject steam, foaming agent and gas into the experimental system together. The data acquisition system is consisted of a computer, a data conversion device, pressure sensors, temperature sensors and etc. It can record the data of temperature and pressure during experiments. The main function of production system is to precisely measure the volume of oil and water at the outlet. The auxiliary system mainly includes a constant temperature oven, a cooling tank, an electronic balance and etc. For the constant temperature oven, the highest working temperature is 350 °C. The precision of the electronic balance is 0.01 g.

Experimental procedures are given as: (1) The sand-packs were filled with glass beads. Then the pressure test was conducted to ensure no leakage; (2) Formation water was injected into the experimental system at 2 mL/min to measure the porosity and the absolute permeability; (3) The temperature of the whole system was controlled at an experimental temperature for 4 h; (4) Hot water (2 mL/min) and