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A laboratory study of enhancing heavy oil recovery with steam flooding by adding nitrogen foams

Zhanxi Pang [a,*], Huiqing Liu [a], Ling Zhu [b]

[a] College of Petroleum Engineering, China University of Petroleum, Beijing 102249, China
[b] School of Business Administration, China University of Petroleum, Beijing 102249, China

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ABSTRACT

Two significant problems, steam override and steam channeling, decrease the sweep efficiency of steam to result in a lower oil recovery in heavy oil reservoirs. Thermal foam flooding, which is in fact steam flooding by adding non-condensate gas and foaming agent, presents a satisfactory effect in laboratory and field pilot. In this article, a new evaluation method was introduced to choose the optimum foaming agent for thermal foam flooding. The method considered the influence of temperature variation on the properties of foaming agent during steam flooding. Then the chosen surfactant and nitrogen were injected into the reservoir model in our experiments. The results showed that nitrogen foams effectively increased displacement efficiency of steam flooding from 43.30% to 81.24% in the single sand-pack experiment. Thermal foams can effectively improve injection profile to restrain steam injection from gravity override and steam channeling in reservoirs. Foaming agent is an important component in thermal foam flooding; on the one hand, it decreases oil–water interface tension to improve oil displacement efficiency, and on the other hand, it increases the stability of foams to improve sweep efficiency. Therefore, steam flooding by adding nitrogen foams is an effective EOR method to develop heavy oil reservoirs.

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1. Introduction

Application of steam injection technology to heavy oil reservoirs is the most commercially successful EOR method (Patzek and Koinis, 1990; Yang and Han, 1991; Friedmann et al., 1994; Jabbour et al., 1996; Patzek, 1996; Fatemi and Jamaloei, 2011). The advantage of this technique over the other methods lies in its practicability and higher recovery rate. 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 (Demiral and Okandan, 1987; Muijs et al., 1988; Eson and Cooke, 1989; Hiraski, 1989; Jabbour et al., 1996). Two significant problems exist with the application of steam injection in heavy oil reservoirs (Fan et al., 2002). One is known as gravity segregation or steam override resulting from lower density of steam than water or oil. Steam injection gradually rises to the top of the reservoir and tends to form a steam channel to production wells. The other is known as steam channeling, caused by the formation of heterogeneity. The majority of steam easily flows to higher permeability formation resulting from its lower flow resistance. The two problems can cause early steam breakthrough to production wells and decrease the sweep efficiency of steam in reservoirs.

The efficiency of steam injection can be effectively improved through the usage of additives, nitrogen and surfactant, which generates foams to decrease the mobility of steam in higher permeability formation and to divert steam to lower permeability formation (Dilgren and Owens, 1982; Cheng et al., 2004; Jamaloei et al., 2011; Lu et al., 2013). One mechanism for decreasing steam mobility is to have steam present as a portion of the gas phase in a bubble (Sharma and Shan, 1983; Kovscek and Bertin, 2003; Simjoo et al., 2012). Nitrogen is a kind of non-condensate gas, which can maintain reservoir pressure and increase steam heating area. Surfactant is an active material, which can improve displacement efficiency by reducing the interfacial tension between oil and water or by modifying reservoir wettability. Foam is a kind of special fluid, which is defined as a dispersion of a gas in a liquid. A liquid thin film, called lamella, separates gas bubbles from each other or solid surface. Gases dispersed in liquids are normally unstable. However, if a surfactant is present, the stability of foams is improved. In addition, the surfactant must meet the following requirements to be effective in applications of thermal recovery (Dilgren and Owens, 1982): (1) the surfactant must be stable at high temperature due to steam injection; (2) after nitrogen and surfactant are injected into reservoirs, foams can generate under reservoir conditions, such as high salinity, elevated temperature and certain oil saturation; and (3) the resistance

* Corresponding author at: Faculty of Petroleum Engineering, China University of Petroleum, Fuxue Road No. 18, Changping District, Beijing 102249, China.
Tel.: +86 18201281464.
E-mail address: pxiad9827@163.com (Z. Pang).

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ability of foams should persist for an extended period of time under reservoir conditions.

In laboratory studies, foams reduced steam mobility by up to 40% (Zitha et al., 2006). The effect has also been demonstrated in several field tests (Liu et al., 2007; Li et al., 2011). Some researchers studied the selective blockage of fluids in thermal recovery projects and concluded that foam was best suited for this purpose (Green et al., 1991; Siddiqui et al., 2003; Kam et al., 2007). Friedmann and Jensen (1986) carried out a laboratory study to develop a steam-foam surfactant for field application. The test variables studied involved foam liquid volume fraction, temperature, pressure, brine concentration, nitrogen concentration, surfactant concentration and foam flow rate. Zhou et al. (2013) indicated that thermal stability is a critical factor in the choice of a foaming agent for thermal EOR processes. They evaluated surfactants for thermal stability and their effectiveness in steam diversion.

Two successful steam-diverting field tests were conducted at the Midway-Sunset Field in the San Joaquin Valley, California (Brigham et al., 1989). Shell has conducted two steam-foam pilots in the Kern River field (Dilgren et al., 1982). Foam was generated by continuous injection of 50%-quality steam containing 0.5 wt% surfactant and 4.0 wt% NaCl in the aqueous phase and 0.6 mol% nitrogen in the vapor phase. Surfactants that are effective in reducing steam mobility at relatively low temperatures (100–150 °C) are not necessarily effective at temperatures over 200 °C. For very high steam temperature the long-chain alkylaryl sulphonates are the best choice, because of excellent foam mobility reduction with good thermal stability, even at temperature as high as 275 °C.

The objectives of this study were to identify which surfactants were suitable for thermal recovery of steam injection and to summarize the EOR mechanisms of steam flooding by adding nitrogen foams. Five surfactants were selected to evaluate their thermal stability and resistance factor at high temperature. In addition, a series of flooding experiments were carried out to investigate displacement efficiency in sand-pack or 3D reservoir model during steam flooding and thermal foam flooding.

2. Experimental approach and equipment

2.1. Evaluation experiments of foaming agents

2.1.1. Static studies

Foaming ability and foam stability are, respectively, expressed by the following two important parameters: the foaming volume and the half-life (Kovscek and Bertin, 2003). The foaming volume (V_{max}) is defined as the maximum foam's volume for a certain volume (100 ml) of foaming agent solution at a fixed shearing velocity (1400 r/min) for 5 min at a certain temperature. The half-life ($t_{1/2}$) is defined as the time taken by the foaming volume to decrease to half its size at a certain temperature. Aiming at five foaming agents with a concentration of 0.5 wt%, we respectively measured their foaming volume and half-life at 50, 75, 100, 125, 150, and 225 °C in laboratory. The experimental apparatus included HJ-5 automatic mixer, 1000 ml beaker, glass rod, stopwatch, and visual reaction oven. The visual reaction oven was used to measure the foaming volume and the half-life of different foaming agents.

The experimental procedures were presented as follows. (1) 100 ml foaming agent solution (0.5 wt%) was injected into the visual reaction oven. (2) The temperature controller of the oven was controlled at an experimental temperature for 2 h at least. (3) The rotating speed of the oven was set to 1400 r/min to continuously stir the foaming agent solution for 5 min. (4) The foaming volume (V_{max}) was recorded. When the foam's volume became half of V_{max}, the time taken was called half-time ($t_{1/2}$) of foams. (5) The reaction oven was controlled at another temperature to measure a new foaming volume and half-time of this surfactant.

A curve figure was finished to show the foaming volume (V_{max}) and the half-time ($t_{1/2}$) of different surfactants at multiple temperatures in order to visually display experimental results. A new parameter, foam comprehensive index, was defined as an integral value about foam volume vs. time from the initial time (0) to the half-time ($t_{1/2}$) at a certain temperature, which was expressed as S. Therefore, a curve about foam comprehensive index, S, vs. temperature, T, can be drawn according to the experimental results. Finally, we can calculate a value, called average foam comprehensive index, $\bar{S}$, to evaluate foaming agents.

$$S = \int_0^{t1/2} V dt \tag{1}$$

$$\bar{S} = \frac{1}{T_n - T_1} \int_{T_1}^{T_n} S dT \tag{2}$$

where S is the foam comprehensive index, ml min; $t_{1/2}$ is the foam half-time, min; V is the foam volume, ml; V_{max} is the maximum foaming volume, ml; $\bar{S}$ is the average foam comprehensive index, ml min; T_1 is the lowest experimental temperature, °C; and T_n is the highest experimental temperature, °C.

2.1.2. Dynamic studies

In porous media, foams can effectively block higher permeability formation to divert the flow direction of steam and improve the sweep efficiency in reservoirs (Dilgren et al., 1982; Friedmann and Jensen, 1986; Lu et al., 2013). Foam resistance factor (R) is often employed to characterize blocking ability of foams in field or laboratory. But for foams under conditions of steam injection, the blocking ability of those foams can hardly be expressed by the conventional foam resistance factor due to a process of temperature variation during steam and foam migration. In this article, a temperature weighted average of resistance factor ($\bar{R}$) was employed to objectively evaluate foam's blocking ability at high temperature. The experimental apparatus included constant temperature oven, steam generator, injection pumps, nitrogen cylinder, gas mass flowmeter, oil tank and water tank, back-pressure valve, hand pump, sand-pack, etc. The schematic diagram of the foam resistance experiment is shown in Fig. 1.

The experimental procedures are listed as follows. (1) The sand-pack filled with certain mesh of glass beads was equipped in the experimental system, as shown in Fig. 1. (2) The whole experimental apparatus was under the pressure of 10 MPa for 30 min to ensure the system good seal. (3) Distilled water was injected into the sand-pack to measure porosity and permeability at a flow rate of 2 ml/min. (4) The temperature of the oven was controlled at a certain experimental temperature (50, 70, 100, 150, 200, 250 and 300 °C). (5) First, hot water (2 ml/min) and nitrogen (100 ml/min) were simultaneously injected into the sand-pack to measure one pressure difference, named basic pressure difference, which was expressed as Δp_{wg}. Then, surfactant solution (2 ml/min) and nitrogen (100 ml/min), that is, foams, were simultaneously injected into the sand-pack to measure the other pressure difference, named resistance pressure difference, which was expressed as Δp_{fm}. Finally, the foam resistance factor (R) can be calculated through the ratio between the resistance pressure difference, Δp_{wg}, and the basic pressure difference, Δp_{fm}. (6) Then the constant temperature oven was controlled at another temperature to measure another resistance factor of this surfactant.

$$\Delta p_{fm} = p_{fm} - p_{out} \tag{3}$$

$$\Delta p_{wg} = p_{wg} - p_{out} \tag{4}$$

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