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A visual investigation of enhanced heavy oil recovery by foam flooding after hot water injection

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ABSTRACT

Hot water flooding is an important method for the development of heavy oil. But due to water channeling and low enthalpy, oil recovery by hot water flooding is very limited. In this paper, a two-dimensional visual experiment is conducted to intuitively study foam flowing characteristics and blocking mechanisms in porous media, as well as the microscopic mechanisms of enhancing heavy oil recovery by foam after hot water flooding. The experiment visually reproduces foam generation in porous media and the processes of hot water flooding and foam flooding. The results show that foam flows along the channels with lower flow resistance in oil layer and can effectively improve the sweep efficiency. Compared with pure hot water flooding, the ultimate sweep efficiency increases from 40.5% to 70.7% after foam injection. Moreover, foam can effectively displace the residual oil caused by hot water flooding. The ultimate oil recovery of thermal foam flooding is 67.54%, 31.30% higher than that of hot water flooding. This paper can provide reference for the study for foam and thermal foam flooding in heavy oil recovery.

1. Introduction

Thermal recovery methods such as cyclic steam stimulation (CSS), steam flooding, in-situ combustion are the major thermal recovery methods for the development of heavy oil (Closmann and Seba, 1983; Heel et al., 2008; Wu et al., 2011; Zhao et al., 2013). But with the increase of CSS cycles, oil production of a single well gradually decreases, and steam-oil ratio (SOR) increase dramatically in the later stage, resulting in the low economic benefit (Buger and Sahuquet, 1972; Tewari et al., 2011). As a result of viscosity fingering and steam override in heavy oil reservoirs, steam breakthrough usually appears earlier in steam flooding projects, leading to low sweep efficiency in both vertical and areal directions, and causing low thermal efficiency. In order to make thermal recovery project more profitable, it needs to take measures to make full use of the residual heat energy after steam injection process (Liu, 1998). The further development of the mature oil reservoirs has been an interactive and a broad subject (Abu El Ela et al., 2013).

Hot water flooding is a typical alternate thermal recovery method for steam injection (Fournier, 1965; Wang et al., 2011a, 2011b; Alajmi et al., 2009; Vinsome 1974). Hot water flooding is actually an immiscible displacement process of crude oil by hot water and cold water (Dong et al., 2011). The initial purpose of injecting hot water is to increase injection ability of water wells instead of enhancing oil recovery. Hot water in reservoir on one hand can transfer heat to oil layer and increase reservoir temperature. On the other hand, it can implement reservoir energy and displace crude oil to wellbore. Compared with conventional water flooding, the EOR mechanisms of hot water flooding for heavy oil include decreasing crude oil viscosity to reduce mobility ratio, improving relative permeability and preventing the formation of oil strata with high viscosity, etc. (Abass and Fahmi, 2013; Lu et al., 2013; Lv et al., 2003). There are two significant problems with the application of hot water flooding in heavy oil reservoirs. One is that hot water cannot carry enough heat into reservoir because of its low enthalpy. The other is water channeling caused by reservoir heterogeneity and the density difference between hot water and crude oil. Hot water tends to flow to higher-permeable formation with lower flow resistance. Water channeling is easily formed between the injection and production wells as a consequence of viscosity fingering. The two disadvantages will cause earlier water breakthrough in production wells and have a negative effect on the thermal recovery for heavy oil.

One of the feasible methods of enhancing oil recovery after hot water flooding in heavy oil reservoir is to add surfactant that can

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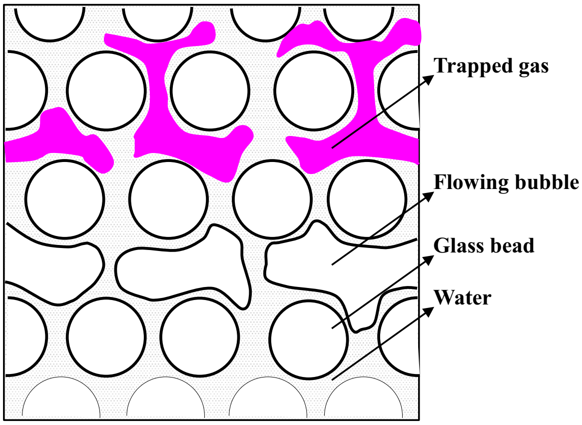


Fig. 1. Schematic diagram of foam propagation in homogenous model.

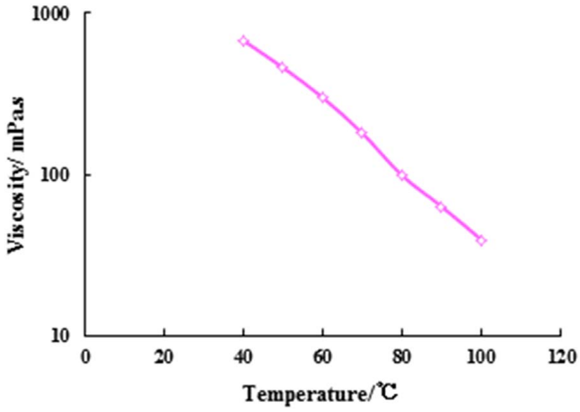
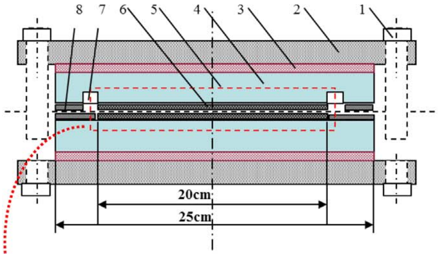


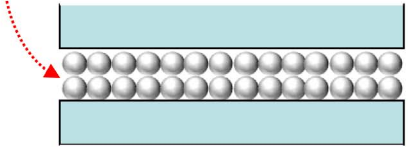
Fig. 3. Viscosity-temperature curve of the oil.

create foams in porous media (Lv et al., 2007; Lu et al., 2003; Muijs et al., 1988; Isaacs et al., 1994; Bagheri and Clark, 2015; Friedmann et al., 1991). Foam in porous media is a dispersive system that gas bubble disperses in liquid film, which is called lamellae. Lamellae snap-off is one of the main mechanisms of foam generation (Roof, 1970; Kovscek et al., 2007). Some long bubbles can also have a function of blocking. The distribution of foam in porous media is shown in Fig. 1 (Gauglitz et al., 2002). In general, foam is created by the co-injection of gas and surfactant solution. Gas bubbles dispersed in liquids cannot exist stable without surfactants. Foam preferentially enters high-permeable zone of formation to block big pores and diverts steam or hot water into low-permeable layer by its high apparent viscosity, thus expanding sweep efficiency of hot fluids injection process (Eson, 1983; Casteel and Djabbarah, 1988; Patzek, 1996). Surfactant maintains the stability of foam and makes a contribution to the reduction of oil/water interfacial tension (IFT) and the variation of reservoir wettability, hence improving oil displacement efficiency (Jamaloei et al., 2011; Liu et al., 2011; Kumar and Mandal, 2016). As a common non-condensate gas used in petroleum industry, nitrogen can implement reservoir pressure and maintain heat left by steam or hot water. In addition, nitrogen can be dissolved in crude oil to form miscible phase under high pressure, which is helpful to decrease heavy oil viscosity and improve oil mobility. What's more, the capillary pressure which usually acts as the main factor that traps the crude oil in pores will be zero when miscible phase is created. Therefore, the oil will be pushed out of the formation and recovery increases. One of the successful hot water foam EOR projects is conducted in Block A of Xinjiang Oilfield in China (Wu et al., 2015). Compared with pure water flooding, hot water foam flooding massively lowered down the water cut and enhanced oil displacement efficiency from 29.8% to 53%. In addition, Block Jin90 of Liaohe Oilfield in China conducted hot water foam flooding pilots in 19-141 well group (Yuan et al., 2004). Results showed that from September 1996 to September 1999, the cumulative oil production was 3.54×10^4 t and the cumulative oil increment was 2.14×10^4 t. From January 2004 to December 2004, also in Jin 45-19-141 well group, hot water foam flooding was conducted again and brought a profit of 3.13 million dollars and the rate of output and input was 2.65 (Wang, 2006).

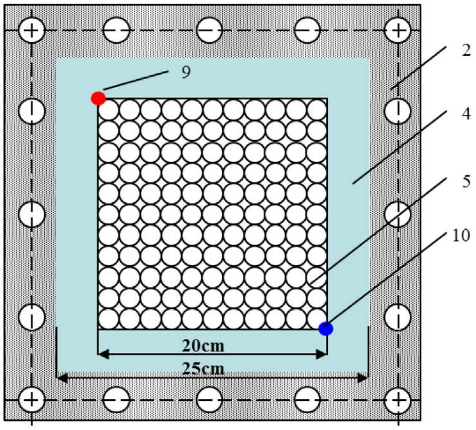
To explore the EOR mechanisms of foam flooding after hot water flooding for heavy oil, a series of experiments are performed. Inspired by the studies of several researchers on visualizing the sweep efficiency improvement by chemical flooding (Pei et al., 2011, 2013; Wang et al., 2011a, 2011b; Guillen et al., 2012), in this paper, hot water flooding process is firstly carried out to display the macroscopic distribution of remaining oil in a visual model filled with glass beads. Then, foam is injected into this model. In this process, foam generation and migration in porous media are intuitively reproduced, which vividly reflects foam seepage characteristics and blocking mechanism. The more important is to make a comparison of sweep efficiency and oil recovery prior and posterior foam injection. Finally, the EOR mechanisms of foam flooding after hot water flooding for heavy oil are summarized. This work is of significance for the selection of foam systems and the implementation for foam projects.



(a) Side elevation diagram



(b) Porous media area



(c) Top view diagram

Fig. 2. Structure diagram of the visualization model. 1 – nut; 2 – model holder; 3 – silicone pad; 4 – quartz glass; 5 – porous media; 6 – glass beads; 7 – draining trench; 8 – tape; 9 – injection pot; 10 – production pot. (a) Side elevation diagram. (b) Porous media area. (c) Top view diagram.

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