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Use of air to improve the efficiency of foamy flow and reservoir pressurization in heavy oil recovery

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ABSTRACT

Primary recovery of heavy-oil is remarkably low due to high viscosity and low energy by solution gas exsolution to drive the oil. Gas injection to improve foamy flow and also to dilute the oil in such reservoirs has been proposed as a secondary recovery method. However, because of the high costs of injected gases, efforts are needed to optimize the process by selection of proper gas type (or gas combinations) and suitable injection scheme. To achieve this goal, an experimental procedure was followed with rigorous analyses of the output. A 1.5 m long and 5 cm diameter sand-pack was first saturated with brine, which was replaced with dead oil. Then, gas solvents were injected to dead-oil containing core-holder until nearly reaching 500 psi followed by a two-day soaking period. Pressures all along the sand-pack were recorded with eight pressure transducers. Different combinations of various gas solvents (methane, CO_2, and air) aiming to select the most competitive and economic formula were tested with a certain set of pressure depletion rates.

The physics of the foamy oil flow for different solvent mixtures and depletion conditions were analyzed using pressure profiles acquired, recorded oil/gas data with time, and gas chromatography and SARA analyses of the produced gas and oil. Three huff-n-puff cycles were applied. Compared with other light hydrocarbon solvents and carbon dioxide, air has a significant advantage in terms of accessibility and lowered cost. Hence, attention was given to air mainly used to pressurize the system and increase oil viscosity due to oxidation process with an expectation of better foam quality when injected with other gases such as CO_2 and methane. Methane (CH_4) yielded the quickest response in terms of gas drive but, in the long run, CO_2 was observed to be more effective technically. Air was observed to be effective if mixed with CO_2 or methane from an economics point of view. To sum up the results, air Huff-n-Puff (HnP) followed by 2-cycles of CH_4 HnP yielded 36.21% recovery, while air HnP followed by 2-cycles of CO_2 HnP delivered 30.36% oil. When the gases are co-injected, air 50%-CO_2 50% and air 50%-CH_4 50% recovered 29.85% and 23.74% of total oil-in-place, respectively.

1. Introduction

Heavy-oil can be produced by its natural drive if the dissolved gas within creates a discontinuous phase making oil foamy. This can be achieved by injecting low carbon number hydrocarbon gases or CO_2. As a follow-up method for Cold Heavy Oil Production with Sands (CHOPS), cyclic solvent injection (CSI) can be applied in this manner. Although quite a number of field applications of the CSI method exist to our knowledge, reported cases are limited (Chang et al., 2015). However, remarkable number of field scale modeling and optimization studies were documented recently (Rangriz-Shokri and Babadagli, 2014; 2016a; b; c; Ivory et al., 2010; Jamaloei et al., 2012; Du et al., 2014; Chang and Ivory, 2013).

The gas solvents can pressurize depleted reservoirs after CHOPS and wormholes can work positively with solvents by increasing contact area between solvents and heavy oil in the matrix for effective diffusion. Under high pressure, solvents become dissolved into heavy oil and this heavy oil containing gas solvents starts to release gas gradually with given pressure drawdown. Because of high oil viscosity compared with conventional solution-gas drive, it takes a much longer time for dissolved gas-bubble to be completely separated from heavy oil to free-gas phase. This oil state is called “foamy oil”. Foaminess gives efficient driving force for highly-viscous heavy oil to be produced. However, since the effective use of solvents is necessary due to the high solvent costs (especially propane and carbon dioxide), studies have focused on the effect of solvent type on the generation of good quality foamy oil (Sheng et al., 1997, 1999) and the impact of solvent type on the foaminess performance (Diedro et al., 2015).

Sheng et al. (1997) studied foamy oil stability and concluded that the higher the oil viscosity and the higher amount of dissolved gas, the

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more stable foamy oil will be. When using faster pressure decline rates where fluid speed is most likely higher, they discovered that more smaller-sized bubbles were generated and scattered for a long time, which contributes to foamy oil stability. Alshmakhy and Maini (2012) defined foam stability as the reference point that shows the speed of foam decays when left in a static state, which is related to surface activity. This surface activity is influenced by viscosity, surfactant type, and concentration.

Looking into the process of gas-bubble formation to decay, Albartamani et al. (1999) separated this process into four steps: supersaturation, bubble nucleation, bubble growth, and bubble coalescence/breakup. They illustrated that higher supersaturation led to more gas-bubbles, and, as bubble nucleation rate becomes slow with oil viscosity (Walton, 1969), the degree of supersaturation of viscous oil also becomes higher. Nevertheless, it should be noted that even if most of the gas solvents show consistency with these four steps when undergoing unconventional solution-gas drive, the degree of each step should correspond to the solvent type as every gas solvent manifests different chemical behavior with heavy oil (e.g. mass/heat transfer, surface tension, etc.).

Previous studies mostly focused on the performance of foamy oil or the factors that affect foam quality. Yet, studies on specific solvents individually and their chemical and physical behavior with heavy oil are limited. This study reports an experimental study of foamy oil created by various gas solvents. Attention is given to the foamy oil characteristics and behavior, and, consequently, oil recovery by different solvents. The focus is on air used as an EOR agent due to its low cost. This idea stems from the fundamental knowledge that low-temperature oxidation increases oil viscosity (Mayorquin and Babadagli, 2016a-b) and, under unconventional solution-gas drive, the more viscous oil there is, the slower dissolved-gas is released, resulting in higher oil recovery. Alshmakhy and Maini (2012) could align the idea of using air through their observations that the materials that work to retard the coalescence of bubbles would delay generation of continuous bubbles, which should be helpful, achieve a higher oil recovery. Sheng et al. (1997) also proved that higher oil viscosity plays a role in enabling higher resistance to the flow of gas bubbles in the liquid oil phase; hence, the foamy oil system becomes more stable. This paper covers a comprehensive experimental analysis of gas injection for heavy-oil recovery. Operational conditions for the optimal use of different solvents in various combinations of methane, CO_2, and air, and for air to achieve a more economically feasible application.

2. Experimental work

Sands sorted into 250–500 µm with sieves were poured into a 1.5 m length and 5 cm diameter core-holder filled with water. During this process, the core-holder was vertically positioned and hammered until the sands densely packed the holder. Porosity was measured by the volume difference of water in and out. Absolute permeability was measured by injecting water into the system applying Darcy's law. Next, brine was flushed to replace water in the sand-pack. Note that brine was injected at a very slow rate and every six ports were open one-by-one to check if brine fully filled the system and removed existing free-gas. Subsequently, 1.2 PV of dead oil was injected until no more water escaped. At the end of this process, the initial oil and water saturations were estimated.

Designated gas (solvent, air or mixture) was directly injected into the dead oil-filled sand-pack until the pressure reached 500 psi (injection stage). Several pilot experiments were run to determine the optimal soaking time, i.e., no incremental production is obtained even if the soaking time is elongated for given depletion rate. After soaking for 2–3 days (i.e., soaking stage), production was started with given depletion rates until all of the pressure ports reached ~70 psi (i.e., production stage). Depletion rates used were −0.51 psi/min from ~500 to 190 psi (1st depletion stage), and −0.23 psi/min from 190 to 70 psi (2nd depletion stage). The range of depletion rates were determined based on field experience. These three stages (i.e., injection, soaking, and production) were repeated whenever restarting a new cycle.

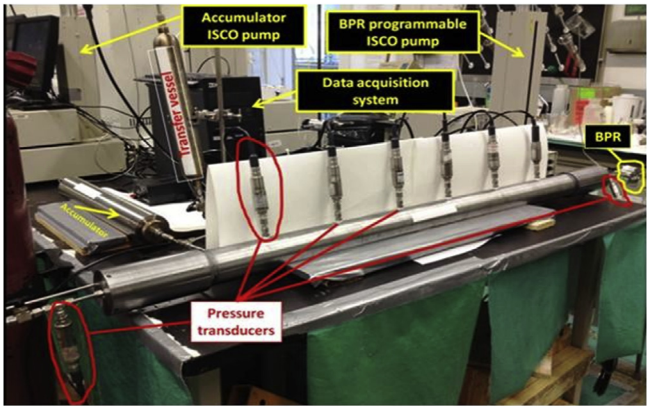

Fig. 1. Experimental set-up (Rangriz-Shokri and Babadagli, 2016a).

For the cases beginning with air huff-n-puff (air experiments showed the recovery of slightly lower than 10% original oil in place), the next secondary recovery stage started. The experimental setup is displayed in Fig. 1. All of the pressure data were recorded with eight pressure transducers, of which the locations are shown in Fig. 2. Obtained from a field in Eastern Alberta, the specific gravity and viscosity of the oil used were 0.95 and 27,400 cp, respectively, measured at 25 °C.

3. Results and analysis

Four different experiments were conducted. Note that air was used to increase oil viscosity initially so that secondary recovery, such as CH_4 or CO_2 huff-n-puff, could take advantage of this higher oil viscosity to produce better foaming performance. Sand-pack properties are illustrated in Table 1. The four experiments are as follows:

1. Experiment 1: Air Huff-n-Puff, followed by CH4 Huff-n-Puff (Exp. 1);
2. Air Huff-n-Puff, followed by CO2 Huff-n-Puff (Exp. 2);
3. Air 50%-CO2 50% Huff-n-Puff (Exp. 3);
4. Air 50%- CH4 50% Huff-n-Puff (Exp. 4).

3.1. Pressure differential

Considering pressure differential, ΔP = P2-P7 (Fig. 2), can be a useful indication of foaming capacity of oil (Soh et al., 2016, 2018), the first analyses of the experiments were done using this data. Air huff-n-puff experiments (Figs. 3 and 4) showed smaller and less frequent fluctuations in ΔP compared with the CH_4 experiments (Figs. 5 and 6) and CO_2 (Figs. 7 and 8) huff-n-puff, and showed lower oil recovery. The experimental results for the four different injection schemes listed below are summarized in Table 2.

The peak pressure points in these figures is related to the dissolution of the gas phase in the oil (foaminess). To explain the reasons of having two obvious peaks in the case of air (Figs. 3 and 4) needs further research, but at first sight, they can be attributed to the different dissolution times needed for nitrogen and oxygen. Another possible explanation is that oxygen also reacts with oil and change it properties. This might cause the dissolution and exsolution resulting in a pressure drop (between ~11th and ~13 the hours in Figs. 3 and 4) and a pressure increase period (dissolution) after a stagnant period (between ~13th and ~15 the hours in Figs. 3 and 4). This was not observed in “air free” environment like the second cycle of CH_4 injection in Fig. 6 (air –and oxygen-was removed during previous air and CH_4 cycles from the system). Also, note that the higher the peak pressure, the more gas