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Full Length Article

Optimization of methane use in cyclic solvent injection for heavy-oil recovery after primary production through experimental and numerical studies

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ABSTRACT

Although cold heavy oil production with sands (CHOPS) is an economically attractive method, ultimate recovery does not exceed 15%. Cyclic solvent injection (CSI) has been under consideration as a follow-up EOR application in the industry. This method targets extracting large amounts of remaining oil in the matrix by solvent diffusion, taking advantage of its high contact area with wormholes. Methane and propane are two potential solvents to be used in this practice. Methane is preferred due to its availability and stronger foaming characteristics, while propane has lower foaming but better mixing capability.

A far-reaching -core to field scale- study was conducted in this paper to test out the potential of pure methane and its mixture with propane as well as CO_2 as prospective CSI solvents. After the petro-physical properties of the sand-pack (1.5 m-length and 5 cm-diameter) were measured, live oil (saturated with methane and methane-propane mixture at different ratios) production was carried out with certain pressure decline rates: −0.51 psi/min from 500 to 190 psi and −0.23 psi/min from 190 to 70 psi. Pressure data with time was monitored through eight equally spaced transducers. The solution GOR from the live oil saturated with methane vs. pressure was matched using the Peng-Robinson EOS (Peng and Robinson, 1976) method. The data points starting injection period (representing equilibrium condition) were fitted to develop K values using the Crookston equation. These matched data were carried to a field scale model to analyze the CSI performance for methane. In field scale modeling, 15-well data from a CHOPS field in Alberta, Canada were history matched and 6-cycle CSI performances were followed as post-CHOPS with different well patterns (central, peripheral, all-wells).

As a result of these experiments, methane showed about 14% oil recovery but with additional CO_2 huff 'n' puff, around 15% recovery was added, totaling 29% recovery. Methane-propane mixture resulted in a lower oil recovery of about 5% due to decreased foamy effect. Valid core-scale simulation was completed by tuning K-values and considering non-equilibrium or equilibrium impact depending on solvent type, showing mostly less than 5% error. In field scale modeling, central and peripheral well patterns yielded oil recoveries consistent with the experiments while all-well huff 'n' puff- type pattern showed a slightly higher value.

Based on the outcome of the methane and methane-propane mixture experiments, it was of more importance to further study the way to enhance the foaminess in methane-live oil recovery. Different pressure depletion rates, namely −0.23, −0.51, and −1.53 psi/min, were applied and more oil was produced with increasing depletion rates. These experimental results were simulated at the core scale and the change of reaction coefficients was considered with varying decline rates. In field-scale modelling, sensitivity analyses were done with a variety of scenarios by changing injection/soaking period and pressure decline rates. The ratio of injection to soaking period was observed to be more critical than the injection period itself in terms of production efficiency. Also, the influence of pressure depletion rate as a new constraint in the simulation work was studied.

1. Introduction

Cyclic solvent injection (CSI) has been proposed as a feasible method for post-CHOPS EOR in thin reservoirs. The solvents fill the wormholes and contact the oils left in the matrix of the reservoir. Considerable efforts have been made related to CSI testing the applicability of different solvents experimentally and numerically [3,6,4,15]. In a recent attempt, Ivory et al. [10] numerically showed that 28%

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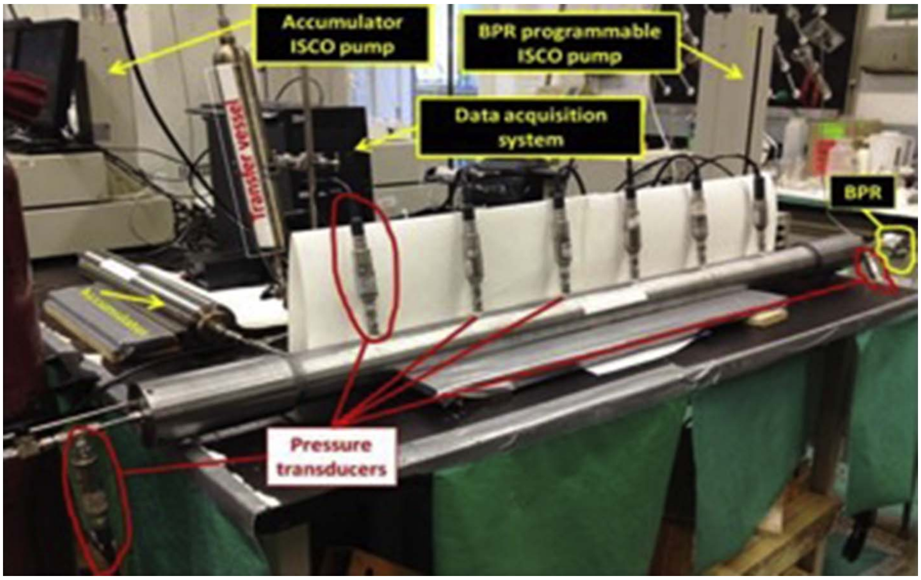

Fig. 1. Experimental set-up [15].

C_3H_8-72% CO_2 mixture as a CSI material result in 50% recovery in 6 cycles. They observed that because of higher solubility of C_3H_8, a large portion of C_3H_8 gas came out much before CO_2 did.

Bjorndalen et al. [2] also studied the foaminess of heavy oil saturated with different solvents (CH_4, C_3H_8, CO_2) and concluded that the more nucleation sites of gas formed, the higher the oil recovered. Dong et al. (2012) reported that using propane as solvent and methane to chase gas increased the total oil recovery to 34.3% after 6 cycles, whereas six cycles of methane resulted in only 4.27% recovery. Focusing on non-equilibrium behavior of solvents, Wang et al. [18] carried out PVT experiments with methane and propane. They observed in the methane case that when the higher pressure decline rate was applied, the longer the foaminess maintained, leading to higher oil recovery, where the experiment with propane showed the opposite. In addition, Rangriz-Shokri and Babadagli [15] presented several sets of CO_2 foamy flow-depletion experiments with numerical simulation using non-equilibrium behavior of pure CO_2 in CSI after CHOPS. Bera and Babadagli [1] implemented relative permeability studies by making three different types of foamy oils saturated with CO_2, methane, and propane. Their experiments showed oil relative permeability with CO_2 was the highest oil recovery, followed by methane and propane. From their results, starting from 400 psi, CO_2 accomplished about 55% recovery of original oil in place (OOIP), while methane and propane showed 15% and 17% recoveries, respectively.

CSI after CHOPS needs to be further investigated to understand the foamy oil recovery under depletion, solubility of different solvents in oil, and the ultimate effect of these on the recovery. Upscaling to the field scale is also a critical issue and lack of experimental data is one of the drawbacks in performing reliable field-scale modeling. This paper presents a comprehensive core- to field-scale study that tests the suitability of using methane and methane-propane mixture as potential CSI solvents for post-CHOPS EOR applications.

2. Experimental study

2.1. Set-up/procedures

A horizontally positioned sand-pack with 1.5 m-length and 5 cm-diameter was filled up with 250–500 μm size of sands. The sand-pack was initially positioned in a vertical direction by pouring/hammering sands into the core holder to pack it compactly. CO_2 was flushed through the sand-pack to remove any air trapped in the pores. Whilst saturating the sand-pack with brine, its porosity was estimated by knowing the volume of injected water. Permeability was measured by injecting the brine at different rates and was calculated by applying Darcy's law. Next, 1.2 PV of dead oil was injected to reach the irreducible water saturation and to maintain initial oil saturation. The dead oil (specific gravity of 0.995 and viscosity of 17,500 cp) was obtained from a CHOPS reservoir in Eastern Alberta.

To remove any occurrence of initial free-gas saturation, brine was injected at a very slow injection rate and the ports of six pressure transducers were opened one-by-one to release any gas. Meanwhile, live oil was prepared separately in two transfer vessels. About 700 ml of dead oil was injected to each of two transfer vessels and then were connected to corresponding gas tank, which was set at 500 psi. Note that in the methane-propane mixture case, to control the volume percentage of each gas, certain volumes of methane and propane were moved to ISCO pump first and then this mixture-form gas was injected to transfer vessel. Live oil, after about 2 days of saturation, was transferred into the sand-pack replacing the dead oil, which had been injected previously to obtain initial water saturation. The reason why live oil was made separately and transferred to the sand-pack rather than following huff-n-puff manner is to assume even foaminess quality across the sand-pack. Live oil production was implemented with two sets of pressure-decline rates: 500–190 psi with −0.51 psi/min and 190–70 psi with −0.23 psi/min, which was achieved using a back-pressure regulator (BPR) at the outlet. Eight pressure transducers (six on the core holder and two at the inlet and outlet ports) recorded the

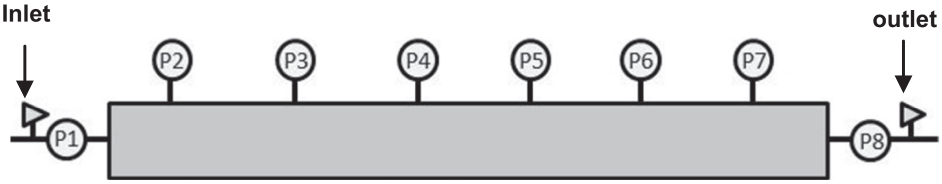

Fig. 2. Numbered pressure ports.