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CO_2-cyclic solvent injection (CO_2-CSI) and gas/waterflooding in the thin post-CHOPS reservoirs

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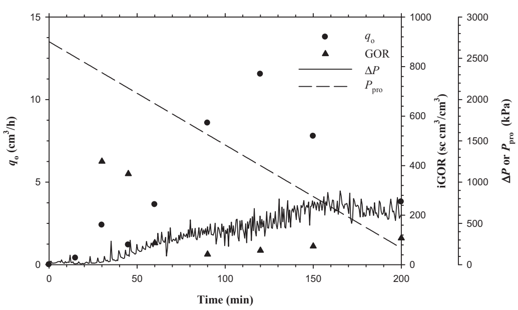
GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, a new combined CO_2-cyclic solvent injection (CO_2-CSI) and gasflooding (GF) process is proposed as an effective enhanced oil recovery (EOR) process in the post cold heavy oil production with sand (CHOPS) reservoirs. The synergy of the CO_2-CSI and GF is explored and compared with that of the CO_2-CSI and waterflooding (WF). A total of ten sandpacked laboratory tests were conducted to study and compare the production performances of the WF, CO_2-CSI, combined CO_2-CSI and GF/WF after the primary production. In the combined CO_2-CSI and GF/WF processes, CO_2/water is injected post, at the same time with, and prior to the CO_2-CSI in the CSI + GF/WF, simultaneous (CSI + GF/WF), and GF/WF + CSI, respectively. Also the effect of CO_2 injection rate is studied by injecting CO_2 at three different flow rates in the CSI + GF. It is found that CO_2-CSI + GF or CO_2-CSI + WF performs better than the CO_2-CSI or WF alone due to the extended foamy-oil flow. The combined CO_2-CSI and WF outperforms the combined CO_2-CSI and GF in terms of the heavy oil recovery factor (RF), heavy oil production rate, and cumulative gas-oil ratio (GOR). CO_2 channeling is hindered by the subsequently injected water. In the combined CO_2-CSI and GF, however, strong free-gas flow adversely affects the foamy-oil production in the later cycles of the CSI and in the subsequent GF. The best fluid injection timing in terms of the heavy oil RF is to inject CO_2/water immediately after each cycle of the CSI production. A moderate CO_2 injection rate gives the highest heavy oil RF of the CSI + GF. In conclusion, the combined CO_2-CSI and GF/WF process is capable of recovering the remaining oil in the post-CHOPS reservoir.

1. Introduction

The Canadian heavy oil reserves are estimated to be 55 billion barrels, almost 2/3 of which are located in Saskatchewan. Of the provincial proven heavy oil reserves, 97% have less than 10-m main pay zones (MPZs) and 55% have less than 5-m MPZs [1]. Cold heavy oil

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production with sand (CHOPS) is widely used in the Western Canadian heavy oil reservoirs in the last two decades as the field-scale primary production process [2]. A typical CHOPS primary production process has a heavy oil recovery factor (RF) of 5–15% of the original oil-in-place (OOIP) due to the foamy-oil flow and sand production, which is higher than a conventional primary production [3]. The foamy oil is formed when the nucleated small gas bubbles are dispersed and trapped in the viscous heavy oil. In the foamy-oil flow, the gas mobility is substantially controlled [4]. Also, the sand production generates some extremely high-permeability channels or wormholes to greatly increase the foamy heavy oil production rate [5]. Nevertheless, there is still 85–95% of the OOIP left in many post-CHOPS reservoirs [6].

As an economical secondary improved oil recovery (IOR) method, over 200 heavy oil waterfloods (WFs) have been applied in the Western Canada in the past 60 years [7]. Nevertheless, only 2–8% incremental heavy oil is recovered during the WFs in the post-CHOPS reservoirs because of the strong water channeling [8]. Similarly, gasflooding (GF) or continuous gas injection (CGI) also suffers from severe viscous fingering and an early gas breakthrough (BT) due to an extremely adverse gas-to-oil mobility ratio [9]. The incremental heavy oil production usually cannot offset the high costs of gas acquisition, transportation, storage, compression and injection, which make the GF alone uneconomical for most post-CHOPS reservoirs [10].

Thermal-based enhanced oil recovery (EOR) methods, such as cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD), have been commercially applied in a number of thick heavy oil reservoirs [11,12]. However, the extensive heat losses to the overburden and underburden and/or bottom-water zone make the thermal-based methods unsuitable for many thin post-CHOPS reservoirs [13]. Among the solvent-based methods, cyclic solvent injection (CSI) has been studied in the laboratories and tested in the thin post-CHOPS reservoirs recently because of its high energy efficiency and low greenhouse gas (GHG) emissions [14]. In the CSI, solvent is injected into a well to dilute the heavy oil. The well is shut in to soak for a period of time after solvent is injected and dissolved into the heavy oil. Then the same well is open and the solvent-diluted heavy oil with a much reduced viscosity is produced. The CSI is repeated in many cycles until the heavy oil production rate becomes too low. The CSI uses the solvent to reduce the heavy oil viscosity and restore the foamy-oil flow by repressurizing the heavy oil reservoir. The major technical shortcoming is that the heavy oil viscosity is regained after the solvent is released from the heavy oil during the CSI pressure-depletion production period. In addition, the foamy heavy oil in the reservoir is pushed away from the production well by the subsequently injected solvent in the next solvent injection period. An unfavourable injected gas-to-heavy oil mobility ratio also causes an early gas BT [15].

In the past, some modified CSI processes have been investigated to remedy the afore-mentioned major technical shortcomings of the traditional CSI. For example, the enhanced cyclic solvent process (ECSP) was proposed to alleviate the heavy oil viscosity regainment, in which a volatile solvent (e.g., methane) was injected prior to the injection of a soluble solvent (e.g., ethane or propane) [16]. Thus there was the solution-gas drive due to the volatile solvent dissolution and there was the heavy oil viscosity reduction due to the soluble solvent dissolution. The experimental results showed that the ECSP gave higher heavy oil production rate and RF with a lower gas-oil ratio (GOR) than the traditional CSI. On the other hand, the gasflooding-assisted cyclic solvent injection (GA-CSI) was tested by using gasflooding to push the remaining foamy oil towards the producer post the CSI production period, which also reduces the so-called back-and-forth movement of the foamy oil [17]. It should be noted that the solvent injector and the heavy oil producer were two different wells during the GA-CSI. It was found from nine sandpacked tests that an incremental 10–20% heavy oil was recovered in the GA-CSI by using propane as an extracting solvent during the CSI and as a displacing solvent during the GF. In addition, foamy oil-assisted methane huff-n-puff (FOAM H-n-P) was examined to control the gas mobility and strengthen the foamy-oil flow by injecting a foaming agent [18]. The heavy oil RF in the FOAM H-n-P was increased by 43.3% in comparison with the methane huff-n-puff alone.

In this paper, a new hybrid EOR process, namely, the combined CO_2-CSI and GF, was proposed to recover the heavy oil in the thin post-CHOPS reservoirs and maximize the synergy of the two processes. It is worthwhile to emphasize that the GF can not only maintain the reservoir pressure to prevent the quick solvent release but also displace the remaining foamy oil at the end of the CSI production. A series of ten sandpacked tests were conducted to identify the optimum combined CO_2-CSI and GF and compare it with the combined CO_2-CSI and WF. During each test, the heavy oil RF, instantaneous GOR, instantaneous water–oil ratio (WOR), injection and production pressures were measured. The experimental results were analyzed to evaluate and compare three different production schemes: CSI + GF/WF; simultaneous (CSI + GF/WF); and GF/WF + CSI. Three CSI + GF tests with three different CO_2 injection rates were performed to examine the effect of CO_2 injection rate on the enhanced heavy oil recovery process.

2. Experimental section

2.1. Materials

In this study, the original heavy oil and brine samples were collected from the Colony formation in the Bonnyville area, Alberta, Canada. The dead heavy oil density and viscosity were measured to be $\rho_o = 0.992$ g/cm^3 and $\mu_o = 33{,}876$ cP at the atmospheric pressure of $P_a = 1$ atm and reservoir temperature of $T_{res} = 21$ °C, respectively. The brine density and viscosity were measured to be $\rho_w = 1.030$ g/cm^3 and $\mu_w = 1.2$ cP at t $P_a = 1$ atm and $T_{res} = 21$ °C, respectively. Methane (Praxair, Canada) with the purity of 99.97 mol% was dissolved into the dead heavy oil to reconstitute the live heavy oil at the initial reservoir pressure of $P_i = 3.0$ MPa and $T_{res} = 21$ °C. The corresponding GOR was equal to 9.6 sc cm^3/cm^3. Carbon dioxide (Praxair, Canada) with the purity of 99.998 mol% was injected as the extracting and displacing gaseous solvent in all solvent-based EOR processes. The detail compositional analysis result of the heavy oil, physicochemical properties of the brine, and PVT data of the heavy oil-CH_4/CO_2 system can be found elsewhere [15].

2.2. Combined CO_2-CSI and GF/WF

The experimental set-up for conducting the primary production, WF, CO_2-CSI, combined CO_2-CSI and GF/WF is schematically shown in Fig. 1. This experimental set-up consisted of a sandpacked physical model, a fluid injection system, and a fluid production system. The combined CO_2-CSI and GF/WF was carried out in a two-well configuration. The primary production with the live heavy oil and the subsequent CSI were conducted by using the injection/production well at the centre on the left-hand side of the physical model, whereas CO_2/water was injected from the injection well at the centre on the right-hand side of the physical model during the GF/WF. One CO_2 or brine cylinder was used to inject CO_2 or brine during the combined CO_2-CSI and GF/WF. The detailed experimental set-up and procedure for preparing the sandpacked physical model were described in the previous study [15]. Table 1 summarizes the major physical properties of the 2-D sandpacked physical model used in Tests #1–10.

The specific production schemes of the primary production and subsequent IOR/EOR processes in Tests #1–10 are summarized in Table 1. The same production scheme of the primary production was used in each test, which started at an initial reservoir pressure of $P_i = 3.0$ MPa. A constant pressure drawdown rate of $dP/dt = 5.0$ kPa/min was used to model a pressure-depletion process in the actual CHOPS reservoir. The primary production process was terminated when the production pressure reached $P_f = 0.2$ MPa. In Test #1, about 1.0 PV brine was injected at $q_w = 0.5$ cm^3/min for 600 min post the

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