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Comparison analyses between the linear and non-linear pressure-decline methods in cyclic solvent injection (CSI) process for heavy oil recovery

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ABSTRACT

Cyclic solvent injection (CSI), also known as huff-n-puff process, has been demonstrated as the most effective and promising solvent-based method in some heavy oil reservoirs in which thermal-based methods are not suitable due to economic constraints and environmental concerns. Such process involves many operating parameters that can affect the recovery performance in different degrees. As the production pressure decline rate is one crucial factor, this study aims to further investigate its role on recovery process of CSI and compare production performances when the pressure decline rate is executed under linear and non-linear decline methods.

A total of six series of CSI tests were performed in oil-saturated sandpack models with the diameter of 15.24 cm and the length of 30.48 cm. Three tests were conducted, with decline rate of 50 kPa/4 min, 100 kPa/4 min and 500 kPa/4 min, under the non-linear decline method, while another three tests were with decline rate of 12.5 kPa/min, 5 kPa/min and 1 kPa/min under the linear decline method. The experimental results show that the main difference between the linear decline method and non-linear decline method is the latter cannot provide a continuous driving force for diluted oil as well as the former. More oil can be produced in the test under the linear decline method than that with the same decline rate but non-linear decline method. For a single cycle of tests with decline linearly, oil is produced in most production time even though with wide difference. However, for a single cycle of tests with decline non-linearly, 80% oil is approximately produced in the production pressure of 800 kPa–650 kPa with accompanying of high gas production. Generally, there is almost oil production before pressure decline to atmosphere pressure in linear decline tests, while this pressure at least increases to 450 kPa in non-linear decline tests. Addition, residual oil saturation profiles reveal that 90.84% original oil in place (OOIP) of near wellbore zone is recovered in a non-linear decline test, which is 5%–8% higher than those of linear decline tests.

1. Introduction

Thermal-based heavy oil recovery methods, such as steam-assisted gravity drainage (SAGD), cyclic steam stimulation (CSS) and steam flooding etc., have been widely applied more than three decades. However, there are several technical problems associated with these thermal-based methods, such as large energy and water consumption, extensive heat loss and expensive water treatment, as well as considerable greenhouse gas emission. For some heavy oil reservoirs with thin pay zones, bottom waters and low rock thermal conductivities, thermal-based methods are not feasible due to economic constraint and environmental concerns [1]. In particular, thermal-based methods would have significant heat loss if applied in post cold heavy oil production with sand (CHOPS) reservoirs possessing wormhole networks [2]. Alternatively, solvent-based heavy oil recovery methods are considered. Vapor extraction (VAPEX) and cyclic solvent injection (CSI) process, also known as huff-n-puff process, are two typical solvent-based methods proposed for enhancing recovery of heavy oil reservoirs with those constraints aforementioned. VAPEX process is a solvent analogue of SAGD by dissolving a gaseous solvent into heavy oil [3], while CSI process is a solvent analogue of CSS as well [4]. VAPEX has a vital shortcoming that a very low production rate is due to very slow mass transfer rate and only drove by gravity force [5]. Compared with VAPEX, CSI has been proved as the most promising solvent-based heavy oil recovery method because of its higher production rate resulting from more driving mechanisms [6–9].

These driving mechanisms in CSI process are known as foamy oil flow, viscosity reduction, solution gas drive, gravity force drive and swelling effect, as well as diffusion and dispersion effect [10–16]. Many experimental works have been done to investigate effects of injection pressure, solvent type, soaking time, wormhole and pressure decline rate on these driving mechanisms. Lim et al. [17], Shi et al. [18], and

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Yadali Jamaloei et al. [19] performed CSI tests by using ethane, methane, carbon-dioxide, propane respectively to investigate the efficiency and effectiveness of the solvent. It was found that ethane was effective for deasphalting and producing bitumen. Carbon-dioxide was found to be much easier to dissolve into heavy oil than methane. Propane was the most effective solvent to enhance heavy oil recovery in laboratory tests. Qazvini F. and Torabi [20] investigated the effects of the injection pressure and soaking time by their fourteen huff-n-puff tests. They found a longer soaking time did not noticeably increase the recovery factor if the injection pressure was low. Ivory et al. conducted CSI experimental study to evaluate the performance of injecting a 28 vol% C_3H_8–72 vol% CO_2 mixture solvent in a stepped cone laboratory model (3 m long) [21]. The inside diameter of the bottom cylinder of the stepped cone was 1 cm and that of the top cylinder was 9.7 cm. Their results emphasized the importance of the wormhole and the foamy oil flow in CSI process. Jia et al. further found the foamy oil flow contribute a lot in CSI production and proposed a gasflooding-assisted method to blow foamy oil out [22]. It was found that this method increased the production rate 4.37 times of that in conventional CSI tests. The author's previous study also suggested the significance of the foamy oil flow on CSI production [23]. It means it's critical to activate and maintain the foamy oil flow for enhancing heavy oil recovery in CSI process.

The term "foamy oil" describes dispersed gas-liquid two-phase flow that occurs in heavy oil reservoir during primary production [24]. Foamy oil flow is believed to be an important contributing mechanism of solution gas drives in many heavy oil reservoirs [25–27]. Through studied over the last three decades by many researchers, it has been suggested that the pressure decline rate is the most important affecting the production performance of heavy oil recovery process which involves foamy oil flow and solution-gas drive [28,29]. Bora et al. carried out a series of flow visualization experiments using a high-pressure etched glass micro-model to gain insight into the pore level processes involved in foamy oil flow [30]. It was found that the pressure decline rate is the most important parameter that influences the supersaturation required for appearance for the first bubble. Maini conducted a pressure depletion test by using a heavy oil-methane system and found that a critical pressure depletion rate was required to maintain the foamy oil flow, which provided better understanding of the primary pressure depletion process for heavy oil recovery [31]. In addition, their experimental results show that a higher recovery factor was attributed to a larger decline rate [32]. Zhou et al. conducted a series of depletion test in heavy oil-solvent systems by using small decline rates (1.70 kPa/min–3.97 kPa/min) for foamy oil flow study [33–35]. The results indicated that the critical pressure decline rate varies with the reservoir condition and solvent composition. Kamp et al. experimentally investigated foamy oil flow on the nucleation and growth of bubbles and gas clusters, and their possible break-up and coalescence [36]. In their depletion tests, the results show that at higher pressure decline rate, higher recovery factors are obtained. This is consistent with results reported in Maini's studies. The study also discussed dependence of the critical gas saturation on the dynamics of the gas nucleation process, and on the local pressure gradients. Alshmakhy et al. conducted depletion tests to investigate effects of gravity, foaminess and pressure drawdown on recovery factor in heavy oil-methane systems [37]. Linear decline was applied in their tests controlled by the rate of nitrogen flow out of the gas dome of the back pressure controller (BPR). The results obtained all fit the same trend of increasing recovery factor with increasing decline rate. Kumar et al. also conducted depletion tests in a sandpack model to study the effects of the pressure decline rate [38]. It was found that gas mobility decreased with increasing of the pressure decline rate. The studies of Maini et al. and Kumar et al. both indicated that a higher recovery factor can be achieved by a lower gas mobility, which can be initiated through a faster pressure decline rate. Then Bayon et al. confirmed this conclusion by performing two depletion tests with different pressure decline rates of 80 kPa/day and 800 kPa/day, respectively [39]. The recovery factor was improved from 25% to 35%.

These extensive studies by depletion tests show the importance of the pressure decline rate on foamy oil flow in heavy oil recovery process. The results also demonstrate the effects of the pressure decline rate on the nucleation, growth, break-up and coalescence of gas bubbles and clusters, as well as the gas mobility and gas-oil ratio (GOR). Although the pressure decline rate in depletion tests have been adequately, it has not been studied yet in CSI process which also involves foamy oil flow. The rules of the pressure decline rate for the CSI process could be quite different from the rules for the depletion test since the propane in the CSI process is much more soluble than the methane/nitrogen in their depletion tests. Also, during the injection period of the CSI process, gas saturation has been established, while there is no initial gas saturation during the depletion tests. These differences indicate that the conclusion drawn from the pressure depletion tests for a methane/heavy oil system may not be applicable for the CSI process. Then the authors examined the effects of the pressure decline rate on the foamy oil flow of the CSI process in their previous study [40]. It was found the pressure decline rate still plays a primary role in CSI process by affecting foamy oil flow and solvent chamber growth. In terms the recovery factor, different driving mechanisms in different production stages lead to different optimum pressure decline rate. However, the pressure decline in this study, also in all depletion tests aforementioned, is linear or very close to linear decline. Non-linear decline method has never been studies in the pressure decline rate researches. Experimental results show that pressure profiles through non-linear decline are totally different from those through linear decline. This difference is believed to have a significant impact on oil and gas behaviors in CSI process. Therefore, it is necessary to apply non-linear decline method in CSI process for comparing its differences with linear decline method on flow behavior of oil and gas and have a better and more comprehensive understanding on the effects of the pressure decline rates on the recovery performance of the CSI process.

In this study, three CSI tests were conducted with the decline rate of 500 kPa/5 min, 100 kPa/4 min and 50 kPa/4 min through the non-linear decline method, while another three tests were operated by the linear decline method with the decline rate of 12.5 kPa/min, 8 kPa/min and 5 kPa/min, respectively. Comparison between the recovery factor, production rate, minimum production pressure, oil and gas behavior and residual oil saturation was conducted. The experimental results show that the main difference between the linear decline method and non-linear decline method is the latter cannot provide a continuous driving force for diluted oil as well as the former. More oil can be produced in the test under the linear decline method than that with the same decline rate but non-linear decline method. For a single cycle of tests with decline linearly, oil is produced in most production time even though with wide difference. However, for a single cycle of tests with decline non-linearly, 80% oil is approximately produced in the production pressure of 800 kPa–650 kPa with accompanying of high gas production. Generally, there is almost oil production before pressure decline to atmosphere pressure in linear decline tests, while this pressure at least increases to 450 kPa in non-linear decline tests. Addition, residual oil saturation profiles reveal that 90.84% original oil in place (OOIP) of near wellbore zone is recovered in a non-linear decline test, which is 5%–8% higher than those of linear decline tests.

2. Method and materials

2.1. Materials

The used heavy oil is typical sample from the western Canada basin with molecular weight of 389 g/mol. The viscosity of the heavy oil sample is 2700 mPa·s at room temperature (21 °C). Propane and nitrogen were supplied by Praxair, Inc., both with purities of 99.99%. Propane was used as the injected solvent and nitrogen was used as the