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Characterization of gas-oil flow in Cyclic Solvent Injection (CSI) for heavy oil recovery

Sam Yeol Hong, Fanhua Zeng*, Zhongwei Du

Faculty of Engineering and Applied Science, University of Regina, SK, Canada S4S 0A2

A R T I C L E I N F O

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A B S T R A C T

Cyclic Solvent Injection (CSI) has emerged as an effective follow-up process to the primary cold production, namely, Cold Heavy Oil Production with Sand (CHOPS). In this recovery process, the solvent is designed to maintain a strong nature of gas at in-situ conditions. As a result, the porous medium is spatially divided into two zones with differing fluid properties, which are gas zone, also called solvent chamber, and heavy oil zone. The CSI process is governed by the gas-oil flow as the solvent chamber is predominated by free gas-oil flow and the heavy oil zone by dispersed gas-oil flow (i.e. foamy oil flow).

The gas-oil flow in CSI considerably differs from that in heavy oil solution gas drive, and therefore, needs to be investigated separately. The differences mainly arise from the origin of free gas. In CSI, the free gas originates at the solvent chamber, whereas in heavy oil solution gas drive, it evolves from solution gas. The free gas, in accordance with where it originates, yields occurrence time and quantity that have different dependency on the pseudobubblepoint pressure of oil. Consequently, the gas-oil flow in CSI results in the characteristics far more susceptible to the quantity of free gas and the nonequilibrium nature of foamy oil than heavy oil solution gas drive.

This study is aimed at characterizing the gas-oil flow in CSI under the effects of pressure depletion rate as well as the solvent chamber. To fulfill this objective, the gas-liquid relative permeability curves were inferred with the use of numerical simulations and modified fractional flow models. The numerical simulations were carried out to history-match seven lab-scale CSI tests performed at different pressure depletion rates. The modified fractional flow models were applied to describe the foamy oil flow. The distinct characteristics of the gas-oil flow were examined based on sensitivity analysis and comparison to the previous findings on heavy oil solution gas drive.

The results suggest that, at low pressure depletion rates, the gas-oil flow in CSI yield the characteristics that have also been observed in heavy oil solution gas drive. At sufficiently high pressure depletion rates, however, the free gas that exists even when the dispersed gas bubbles are immobile results in the different behavior of critical gas saturation and gas phase mobility. The solvent chamber misleads the gas-liquid relative permeability curves if the critical gas saturation is too high to properly describe the simultaneous flow of free gas and foamy oil. The solvent injectivity is also affected by the pressure depletion rate due to the foamy oil that has remained as unproduced in the solvent chamber during a previous production period.

1. Introduction

Cyclic Solvent Injection (CSI) has emerged as an effective follow-up process to the primary cold production, namely, Cold Heavy Oil Production with Sand (CHOPS). The CSI process is deemed the most suitable for the post-CHOPS reservoirs characterized as thin and unconsolidated formations with a strong wormhole network (Dong et al., 2006). Under CHOPS, the unconsolidated formations induce sand productions and in turn high permeability channels in communication with each other. These channels develop the wormhole network extending outward the wellbore. CHOPS has been operated in the field over the last decades. The recovery factor, however, has been reported to be only 5–10% of the original oil in place (Chang and Ivory, 2013). That is, the economic life of CHOPS is facing an imminent end of its economic life leaving 90–95% of the reserves untapped afterward. A full understanding of CSI process is immediately required to exploit the vast amount of the heavy oil deposits left underground. Such potential of CSI has led to the field tests on heavy oil reservoirs in Saskatchewan, piloted

* Corresponding author.
E-mail addresses: hongsamy@uregina.ca (S.Y. Hong), fanhua.zeng@uregina.ca (F. Zeng), du225@uregina.ca (Z. Du).

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by Nexen at Plover Lake (Saskatchewan Petroleum Research Incentive, 2006), and Husky at Mervin (Saskatchewan Petroleum Research Incentive, 2011).

CSI is a huff-n-puff process operated cyclically by a single well with the use of solvent as the injectant. A CSI cycle consists of three sequential stages: injection, soaking, and production, in the order of precedence. In general, the solvent is composed of light hydrocarbons (e.g. methane, propane, etc.) and carbon dioxide in a pure or mixed form. It is designed in a manner that the gaseous compound at atmosphere is put slightly below its dew point at the end of the injection stages. In this phase equilibria, the solvent is equipped with a tendency to liquefy, and yet the nature of gas is preserved to the utmost. It attains a high solubility while its inventory in the oil phase is minimized apart from the dissolved quantity. As a result, the solvent dilutes heavy oil without being excessively liquefied. At the same time, the dissolved quantity is effectively retrieved with the aid of high gas phase mobility.

The mechanisms of CSI involve those of solvent-based processes as well as heavy oil solution gas drive. The mechanisms of heavy oil solution gas drive take place due to the in-situ pressure depletion in the absence of an external driving source during the production stages. The solvent dissolved in heavy oil therefore not only adds light components in the oil phase but also restores solution gas oil ratio (GOR). The resulting recovery mechanisms are summarized into oil viscosity reduction including in-situ upgrading of heavy oil, surface tension reduction, oil swelling, and foamy oil flow (Das et al., 1998; Luo et al., 2007; Maini et al., 2010).

The foamy oil flow appears as the dispersed gas-oil flow in which the gas in the form of microbubbles migrates in company with the oil rather than flowing independently as a continuous phase. Its generation was delineated by Maini et al. (2010) based on the evolution process of gas bubbles, divided into: bubble nucleation, bubble growth, bubble trapping-mobilization, and bubble coalescence/breakup. The gas bubbles that have undergone such evolution process eventually develop free gas flow in a continuous gas phase at a local pressure below the pseudobubblepoint pressure of oil (Kraus et al., 1993).

The nonequilibrium nature of foamy oil varies as a function of pressure depletion rate. Bora et al. (2000) visualized the foamy oil flow in a pore scale with the use of transparent glass micromodel at different pressure depletion rates (380–3100 kPa/h). At slow depletion rates, the gas-oil flow behaved analogously to the conventional solution gas theories - the gas bubbles grew without migrating until a continuous gas phase was formed. At fast depletion rates, however, the gas bubbles evolved into dispersed gas-oil flow before a continuous gas phase was formed. Maini et al. (2010) explained this phenomenon as a result of high viscous forces comparable to capillary forces. In other words, the fast depletion rates induce large pressure gradients and thereby increase the capillary number, defined as the ratio of viscous force to capillary force (Eq. (1)), high enough to mobilize the isolated gas bubbles.

$$N_{ca} = \frac{k}{\sigma_{og}}\frac{\partial p}{\partial x} \tag{1}$$

where N_{ca}: capillary number; k: absolute permeability; σ_{og}: surface tension between oil and gas; $\partial p/\partial x$: pressure gradient.

Maini et al. (2010) utilized a sandpack model to investigate the heavy oil solution gas drive under the effect of the pressure depletion rate (7–170 kPa/min). It was observed that the recovery factor increased with the depletion rate. Such effect of the pressure depletion rate prompted the application of cyclic pressure depletion in continuous solvent injection processes (Jia et al., 2013; Jiang et al., 2014). It was suggested that the foamy oil flow was generated, promoting the heavy oil recovery.

In CSI, the injection of the solvent that maintains a gas state at in-situ conditions spatially divides the porous medium into two zones of differing fluids properties, which are gas zone, also called solvent chamber, and heavy oil zone. The solvent chamber mainly contains the solvent in the form of free gas and under the huff-n-puff operation locates at inner region towards the well. The heavy oil zone represents the bulk oil bordering the outer face of the gas zone.

The recovery process of CSI is governed by the gas-oil flow as the solvent chamber is predominated by free gas-oil flow and the heavy oil zone by dispersed gas-oil flow (i.e. foamy oil flow). The gas-oil flow appears as the combined flow of free gas and foamy oil which have originated at the solvent chamber and the heavy oil zone, respectively. The flow paths are formed across the solvent chamber in accordance with the potential gradients traversing the gas zone in both injection and production stages. In the injection stages, the free gas injected travels across the solvent chamber along with the foamy oil that has remained as unproduced during a previous production period. In the production stages, the free gas is discharged from the solvent chamber along with the foamy oil that has generated from the solvent-enriched heavy oil.

The gas-oil flow in CSI results in the characteristics that depend on the properties of the solvent chamber in addition to the pressure depletion rate which, as previously discussed, alters the nonequilibrium nature of foamy oil. In fluids flow aspects, the solvent chamber serves as free gas storage in the porous medium and the porous paths that the moving fluids encounter. Its volume and geometry (i.e. dimensions and location compared to the wellbore) therefore govern the quantity of the free gas and the configuration of the flow paths, respectively. The quantity of the free gas determines the relative quantity of the fluid to another. The configuration of the flow paths establishes the extent and degree of the flow resistance.

The gas-oil flow in heavy oil systems has been widely studied based on heavy oil solution gas drive (Kumar and Pooladi-Darvish, 2002; Ostos and Maini, 2004; Maini et al., 2010). However, the combined flow of free gas and foamy oil in CSI considerably differs from that in heavy oil solution gas drive and therefore needs to be investigated separately. The differences mainly arise from the origin of free gas. The free gas, in accordance with where it originates, yields occurrence time and quantity that have different dependency on the pseudobubblepoint pressure of oil.

Specifically, in CSI, the free gas originates at the solvent chamber containing the gas mainly supplied from an external source. The combined flow of free gas and foamy oil therefore occurs from the beginning at the in-situ pressure higher than the pseudobubblepoint pressure of oil. As a result, the free gas always amounts in addition to the continuous gas phase that develops from the dispersed gas bubbles. While the free gas is present, the foamy oil undergoes when the dispersed gas bubbles nucleate, grow, and sustain strong nonequilibrium nature against thermodynamic phase behavior.

In heavy oil solution gas drive, on the other hand, the free gas evolves from solution gas. The combined flow of free gas and foamy oil therefore takes place relatively late at the in-situ pressure lower than the pseudobubblepoint pressure of oil. As a result, the free gas amounts virtually equivalent to the continuous gas phase that develops from the dispersed gas bubbles. While the free gas is present, the foamy oil only undergoes when the dispersed gas bubbles have diminishing nonequilibrium nature in favor of thermodynamic phase behavior.

Consequently, the gas-oil flow in CSI considerably differs from that in heavy oil solution gas drive in the significant aspects of occurrence time, quantity of the free gas, and behavior of the foamy oil. It always results in the combined flow of free gas and foamy oil far more susceptible to the quantity of the free gas and the nonequilibrium nature of the dispersed gas bubbles than heavy oil solution gas drive.

This study is aimed at investigating the characteristics of the gas-oil flow in CSI. In particular, the gas-liquid relative permeability curves need to be thoroughly understood under the effect of the pressure depletion rate as well as the solvent chamber. Until now, there has been no study specifically examining the two-phase fractional flow curves in