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Analysis of steam–solvent–bitumen phase behavior and solvent mass transfer for improving the performance of the ES-SAGD process

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ABSTRACT

Steam-Assisted Gravity Drainage (SAGD) has been the preferred thermal method for bitumen recovery from reservoirs in western Canada. To save energy and to be more environmentally friendly, Expanding-Solvent SAGD (ES-SAGD) is herein proposed by adding solvent into the injection vapor. The addition of solvent gives rise to different phase behavior (solvent–steam–bitumen) characteristics than that of the steam-only injection (steam–bitumen) process. Early steam condensation, solvent accumulation in the vapor phase, and convective oil flow near the steam boundary are critical mechanisms of the ES-SAGD process. In this paper, the phase behavior of the steam–solvent–bitumen system and solvent mass transfer in oil are studied through a numerical simulation method. Results show that the dominant mechanism of solvent dissolution in oil is by gas–oil equilibrium, rather than condensate mixing. The dissolved solvent is further convectively delivered into the mobile oil zone by gravity drainage. Under high solvent injection concentration, oil production rate is improved by the significant amount of solvent dissolution in oil. The high injection pressure enhances oil production rate through enlarging the mobile oil zone. In addition, this study proposes a steam–solvent injection strategy to improve the ES-SAGD process.

1. Introduction

The main property of bitumen is its extremely high viscosity under reservoir conditions. To lower bitumen's viscosity sufficiently so that it becomes mobile, two methods are applicable: increasing the temperature of the bitumen by steam injection, or diluting the bitumen by light hydrocarbon component (solvent) dissolution (Gates and Chakrabarty, 2008). To take advantage of temperature and gravity drainage, SAGD was proposed as an in-situ bitumen recovery method by Butler and his colleagues in the 1970s (Butler et al., 1981; Butler and Stephens, 1981). With recent advances, SAGD has become commercially viable and has been an extensively deployed method as a bitumen recovery operation in Alberta, Canada.

Typically, SAGD consists of a pair of horizontal wells drilled into a bituminous formation. The spacing between a well-pair is primarily governed by the reservoir conditions of net pay thickness, bitumen viscosity, permeability, and heterogeneity (Al-Bahlani and Babadagli, 2009). In a SAGD operation, the production well is usually located about 2 m above the base of the reservoir, with the injection well drilled parallel to and about 5 m above the producer (Butler et al., 1981; Butler, 1994; Edmunds, 1999; Komery et al., 1999). Steam is introduced into the reservoir through the injection well and a steam chamber is formed within reservoir at the saturated steam temperature. Steam flows and condenses when it comes in contact with cold oil sands at the boundary of the steam chamber. The latent heat of the steam transfers to the surrounding formations and thereby warms up the bitumen. Under the action of gravity, the heated oil and condensate flow to the production well (Butler, 1987; Gates and Leskiw, 2010). As the oil is produced, the evacuated pore space is occupied by injected steam, which results in steam chamber growth (Butler, 1997).

The main cost of the SAGD process is the extensive amount of steam consumption as indicated by the Cumulative Steam–Oil Ratio (cSOR), where the amount of steam is expressed in Cold Water Equivalents (CWE). The cSOR indicates the amount of consumed steam per unit of produced bitumen. It has been demonstrated that heavy oil or bitumen can be produced at rates from 100 to 400 m^3/day, with the cSOR varying from 2 to 10 m^3/m^3 (Butler, 1998). Costs are more adverse for a highly fractured reservoir with a typically high cSOR and low oil recovery factor (Zendehboudi et al., 2014).

Vapor Extraction (VAPEX), which utilizes a similar well configuration as SAGD, is a process for heavy oil recovery with injection of a mixture of hot water and a low boiling point vaporized solvent

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into the reservoir. In VAPEX, a solvent vapor chamber is formed and the diluted bitumen flows towards the lower producer by gravity drainage along the boundary of the chamber. The dissolved solvent acts as a carrier of heat when it is boiled off back to the chamber as the drained oil interacts with hot water at the bottom of the reservoir (Butler and Mokrys, 1991, 1993, 1989). Although this process exhibits high energy efficiency, the major drawback of VAPEX is the typically low production rate (Deng et al., 2010).

ES-SAGD was proposed by Nasr et al. (2003) to combine the advantages from both SAGD and VAPEX. In the ES-SAGD process, the injection into the reservoir of a hydrocarbon additive, at low concentration in stream, has the potential benefits of both heat introduction and solvent dissolution for reducing the in-situ bitumen viscosity. Solvent is vaporized under the condition of saturated steam and is delivered into the reservoir through the injection well. Near the boundary of the steam chamber, solvent dissolves into oil to enhance oil mobility. The effect of solvent dilution on oil viscosity is apparent in Shu's correlation (Shu, 1984). For example, at 100 °C, the viscosity of bitumen is around 200 cp. When the C6 mole fraction is higher than 0.48, the viscosity of the solvent–bitumen mixture can drop to as low as 10 cp, at the same temperature (Shu, 1984). As a result, oil recovery is effectively improved, as indicated by experimental evidence based on an Athabasca oil sands reservoir, which showed a 20% increase in oil production rate when compared to the SAGD process (Mohammadzadeh et al., 2012).

The addition of solvent into the vapor turns the ES-SAGD operation into a more complex process. Previous studies have reported little on the gas–oil equilibrium in the steam–solvent–bitumen system. In particular, there is little information available regarding the phenomenon of solvent dissolution into the bitumen under the action of the equilibrium state in the thermal-solvent gravity drainage process. Previous studies show that hydrocarbon additives with similar saturation properties as steam should be chosen. At the boundary of the steam chamber, solvent condenses with steam simultaneously (Li and Mamora, 2011; Jha et al., 2013). However, Dong investigated the phase behavior of the steam–solvent system and proposed an algorithm to estimate the equilibrium temperature and solvent fraction in the vapor phase at the boundary of the steam chamber (Dong, 2012). It was found that, in a large range of solvent fractions in vapor, steam condenses first from the vapor, and that the condensation of solvent can occur only when the solvent concentration in the vapor phase is extremely high. As further described by Dong (2012), at pressures lower than 2000 kPa, the first condensation from the mixture, which occurs at 210.9 °C, is steam, in a mixture which contains a 0.03 mol fraction of C6 and a 0.97 mol fraction of steam. It was also found that the solvent fraction in the vapor phase increases as steam condenses by means of heat transfer to the cold oil sands. The lowest temperature of vapor is reached at the boundary of the steam chamber. For heavier solvents, at the steam chamber boundary, there would be a lower solvent concentration and a higher temperature, compared to lighter solvents (Dong, 2012). Thus, further study is needed to achieve an improved understanding of steam–solvent–bitumen phase behavior near the boundary of the steam chamber.

Furthermore, detailed studies of the mechanism of solvent distribution in the mobile oil zone is scarce. Previous studies established that the diffusion of solvent into bitumen is the mechanism for solvent–bitumen mixing beyond the steam chamber (Gates, 2007; Leyva-Gomez and Babadagli, 2013). However, solvent diffusion into bitumen, which is a very slow process, cannot deliver much solvent into the oil sands under the fast growing steam chamber (Mohammadzadeh et al., 2010). Pore-level studies of the mass transfer mechanism reveal that the mobile oil region thickness of ES-SAGD is greater than that of VAPEX, in which molecular diffusion is the dominant solvent mass transfer mechanism. In ES-SAGD, the solvent–bitumen mixing is supported by direct gravity drainage (Mohammadzadeh et al., 2010). Simulation studies also show that there is little effect on oil production by varying the solvent diffusion coefficient (Ivory et al., 2008). However, the understanding of how the solvent is distributed in the mobile oil zone needs further study.

Examples from industrial operations show the varying success of ES-SAGD. Nexen tested ES-SAGD on Pair 3 of the Long Lake pilot in 2006 (Orr, 2009). From the results, for the co-injection of Jet B (C7 to C12), Keyera condensate (C5 and C6), and C6, each solvent can improve oil production rate to a similar degree: from 17% to 24%. However, the co-injection of butane was found to reduce bitumen production (Orr, 2009). A project managed by Suncor with naphtha co-injection in SAGD in the Firebag area found that naphtha addition has no effect on bitumen production (Nasr and Ayodele, 2006).To achieve a better understanding of ES-SAGD, reservoir simulation was employed to examine the profiles of different reservoir properties, including temperature, gas phase composition, oil phase composition, oil and water saturations, oil viscosity, and oil flow rate in regions near the boundary of the steam chamber. Figures are presented to show important phenomena occurring in those regions and their consequences on oil flow. The solvent distribution and solvent mass transfer in the mobile oil zone were also investigated through reservoir simulation. Furthermore, the effects of operating parameters such as solvent injection concentration and steam injection pressure are studied to investigate improvements in the ES-SAGD process.

2. Reservoir model

In this study, a right half 2-D regular Cartesian grid simulation model was generated to investigate the ES-SAGD process using CMG STARS (2011).

2.1. Oil sands model

The key reservoir properties are summarized in Table 1. This model is of a single well pair and is homogeneous with respect to permeability, porosity, and initial oil saturation. The modeled reservoir has a depth of 300 m, a thickness of 20 m, and a half width of 30 m. The initial water saturation and oil saturation are 0.2 and 0.8, respectively, and the model has a porosity of 35%, a horizontal permeability of 4 darcies, and a vertical permeability of 2.4 darcies. In the thermal-solvent recovery process, the wettability alteration of a heavy oil reservoir is important and needs to be included (Rao, 1999). Experimental results show that reservoir rock becomes more water-wet with temperature increase from 100 to 500 °F (Sola et al., 2007). Owing to the observation that water-wetness is preferred for high oil recovery (Hascakir et al., 2009), the water-wetness change was examined by (1) alternating end-points of water, oil, and steam saturations, and (2) using various temperature-dependent relative permeability curves in the reservoir simulation (Hascakir and Kovscek, 2010). In addition, experiments demonstrate that wettability can also be changed from oil-wet to preferred water-wet by solvent dissolution in bitumen (Mohammed and Babadagli, 2014). Due to the mostly water-wet reservoir conditions induced by steam and solvent injection, a water-wet rock–fluid system was used in the simulation (Zhao et al., 2013). The initial reservoir temperature is 10 °C and pressure is determined by a hydrostatic method, with a reference pressure of 1210 kPa specified at the top of the reservoir. The bitumen properties are modeled by tuning the Peng–Robinson equation of state (1978) through CMG Winprop (2011), based on the experimental results from Khan et al. (1984), using a similar