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Mechanistic simulation study of expanding-solvent steam-assisted gravity drainage under reservoir heterogeneity

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ABSTRACT

Expanding-solvent steam-assisted gravity drainage (ES-SAGD) is a potential method to reduce steam-oil ratio (SOR) of SAGD, which is a critical concern especially for highly-heterogeneous reservoirs. The main objective of this research is to investigate the flow characteristics of heterogeneous reservoirs in which solvent is more likely to lower SOR of SAGD.

SAGD and ES-SAGD with normal hexane are simulated for fifty geostatistical realizations consisting of clean sand and shale, qualitatively representative of the middle member of the McMurray formation. Thermodynamic models are calibrated with experimental phase behavior data for reliable comparison between SAGD and ES-SAGD, including the water solubility in oil at elevated temperatures.

Results show that the SOR reduction by steam-solvent coinjection is positively correlated with the increase in SAGD's SOR due to heterogeneity. Enhancement of bitumen flow by dilution is more important for lowering SOR for those reservoirs in which the permeability variation makes slow-flow regions during SAGD.

Simulation results show that a larger amount of bitumen tends to be diluted by solvent in those reservoirs for which SAGD exhibits slow production of bitumen. Then, the observed results are analyzed by use of SAGD analytical equations that clarify several influential factors for bitumen flow beyond the edge of a steam chamber. It is shown that dilution of bitumen by solvent in steam-solvent coinjection becomes more significant where flow barriers limit the local bitumen flow under SAGD even at high temperatures. In such slow-flow regions, the bitumen flow rate can be substantially increased by accumulation of solvent in ES-SAGD, which reduces the oleic-phase viscosity and increases the oleic-phase saturation and, therefore, relative permeability. Solvent accumulation within a steam chamber can also reduce thermal losses because of lower operating-chamber temperatures.

1. Introduction

Steam-assisted gravity drainage (SAGD) is currently the most widely-used technique for in-situ bitumen recovery, and uses the sensitivity of bitumen viscosity to temperature (Keshavarz et al., 2014, 2015). In SAGD, a steam chamber is formed as the injected steam propagates within the reservoir. The chamber edge represents the boundary of a steam chamber, where the vapor phase condenses. Bitumen situated beyond the chamber edge is mobilized by the heat released by steam upon condensation.

The cumulative steam-oil ratio defined as the ratio of cumulative steam injected [expressed as a cold-water equivalent (CWE)] to cumulative bitumen produced is a commonly-used metric to evaluate the performance of SAGD. SOR directly correlates with thermal losses to the over- and underburden (Das, 1998; Ito and Ichikawa, 1999; Edmunds and Chhina, 2001; Butler and Yee, 2002; Gupta and Gittins, 2005; Edmunds and Peterson, 2007; Miura and Wang, 2012), and inversely correlates with the bitumen drainage rate.

In efficient SAGD projects, where the targeted formations are relatively homogeneous, the cumulative SOR is typically between 2.0 and 5.0 (Butler, 2001). SOR for SAGD is expected to be greater in highly heterogeneous reservoirs because reservoir heterogeneities result in more tortuous fluid flow. An important example of a highly heterogeneous bitumen reservoir is the middle McMurray member, which holds about 70% of the bitumen reserves within the McMurray formation (Musial et al., 2012). Prior studies on SAGD in the presence of

Abbreviations: BHP, bottom-hole pressure; BIP, binary interaction parameter; CWE, cold water equivalent; ES, expanding solvent; SAGD, steam assisted gravity drainage; hom, homogeneous case; het, heterogeneous case; SIS, sequential indicator simulation; SOR, steam-oil-ratio

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permeability barriers indicate that the extent to which the SOR increases due to heterogeneity is sensitive to the size of the barriers (i.e., thickness and lateral extents) and their proximity to the SAGD well-pair (Yang and Butler, 1992; Chen et al., 2008; Yazdi and Jensen, 2014; Wang and Leung, 2015).

Lowering the SOR to meet a given cumulative bitumen production is a priority from economic and environmental standpoints. The need for lower SORs and the challenges associated with their obtainment using steam-only injection has led to the search for alternatives to SAGD. Expanding solvent-SAGD (ES-SAGD) is a widely-investigated alternative, where a small quantity of a condensable solvent is coinjected with steam. Growing interest in ES-SAGD can be attributed to two factors. Firstly, it retains many of the advantages of SAGD. Secondly, it could potentially enhance the bitumen drainage rate by the dilution of bitumen by solvent, while lowering thermal losses to the overburden through the reduction of operating-chamber temperatures (Dong, 2012; Jha et al., 2013; Keshavarz et al., 2014, 2015; Khaledi et al., 2015; Venkatramani and Okuno, 2017a; b). The combination of these two facets could lower the SOR accompanying a given cumulative bitumen production.

Mobilization of bitumen in ES-SAGD is a result of the interplay between the phase behavior of water/solvent/bitumen mixtures and fluid flow. The dilution of bitumen by solvent is driven by concentration gradients, and expedited by mechanical dispersion under high temperatures near the edge of a steam chamber. Heating of the reservoir beyond the chamber edge occurs by the mechanisms of conduction and convection; the temperature gradient available for heat transfer depends substantially on temperature along the chamber edge. The chamber edge, where the vapor phase condenses, represents the transition from oleic-vapor-aqueous (inside the chamber) to oleic-aqueous coexistence (outside the chamber). Phase equilibrium measurements and thermodynamic calculations indicate that the vapor-condensation temperature is lower than the steam-condensation temperature for a mixture of solvent, water, and bitumen at a given pressure; e.g., see Amani et al. (2013a), Brunner (1990), and Brunner et al. (2006) for fundamental data for water/oil mixtures, and Sheng et al. (2017) for such thermodynamic calculations for different solvents. These inferences have been presented by prior studies on ES-SAGD for single-component n-alkane solvents in homogeneous reservoir models (Jha et al., 2013; Keshavarz et al., 2014, 2015; Khaledi et al., 2015).

A vast majority of prior studies on ES-SAGD have been restricted to homogeneous reservoir models. Consequently, they do not address the important question of the effect of reservoir heterogeneity on the relative performance of ES-SAGD to SAGD. To our knowledge, the investigations by Li et al. (2011) and Venkatramani and Okuno (2017b) are the only detailed, systematic studies on the relative performance of ES-SAGD to SAGD under heterogeneity published in the literature.

With the aid of numerical simulations conducted for one hundred geostatistical realizations for SAGD and n-C_6 SAGD, Venkatramani and Okuno (2017b) demonstrated that (i) the SOR for ES-SAGD is less sensitive to heterogeneity compared to that for SAGD; and (ii) the reduction in SOR by steam-solvent coinjection is enhanced under heterogeneity. These simulation results were attributed to the enhanced mixing between solvent and bitumen under heterogeneity, and the interplay between solvent-bitumen mixing and temperature distribution within the reservoir.

While both Li et al. (2011) and Venkatramani and Okuno (2017b) presented useful insights on the relative performance of ES-SAGD to SAGD under heterogeneity, neither study elucidated how heterogeneous reservoirs may be identified in terms of their suitability for the application of ES-SAGD. This is an important engineering question in view of the greater cost of solvent relative to the price of bitumen. The main objective of this research is to numerically investigate the flow characteristics of heterogeneous reservoirs for which solvent coinjection is more likely to lower SOR of SAGD, and the basis underlying the effectiveness of solvent in such cases.

Section 2 presents the basic conditions for reservoir simulations conducted for fifty geostatistical realizations of a heterogeneous reservoir. Section 3 presents the main results for SAGD and n-C_6 SAGD simulations and an analysis of them with the aid of analytical equations for oleic-phase flow along the edge of a steam chamber. Section 4 summarizes the main conclusions of this research. n-C_6 is used as the solvent for ES-SAGD in this research because it has been reported to be an effective solvent for Athabasca bitumen reservoirs.

2. Simulation model

2.1. Reservoir model

Two-dimensional numerical flow simulations using STARS of Computer Modelling Group (CMG, 2011–16) are performed for a homogeneous reservoir comprising entirely of clean sand, and also for fifty geostatistical realizations of a heterogeneous reservoir consisting of clean sand (net facies) and mudstone (i.e., shale or non-net facies).

Heterogeneous realizations are generated by use of unconditional sequential indicator simulation (SIS) (Remy, 2005). The permeability barriers in this study are inclined relative to the top and basal planes of model in order to render it qualitatively representative of the middle McMurray member (Musial et al., 2012, 2013; Thomas et al., 1987). Table 1 summarizes the values assigned to the parameters pertaining to geostatistical simulations. The porosity, horizontal/vertical permeabilities, and bitumen saturation of the clean sand facies have been set to 36%, 6100 mD/3500 mD, and 85%, respectively. The corresponding values for mudstone facies are 5%, 1 mD/0.1 mD, and 15%. The consistency has been confirmed between the input values used for geostatistical simulation and properties of the simulated geological models.

The initial reservoir temperature and pressure are assumed to be 286.15 K and 15 bars, respectively. Bitumen considered in this research is “live”, comprising of a mixture of 10.22 mol% methane (C_1) and 89.78 mol% dead Athabasca bitumen. The corresponding gas-to-oil-ratio (GOR) is 5.0 m^3/m^3.

The reservoir model used is of dimensions 141 m × 500 m × 20 m in the x, y, and z directions, respectively; the y-direction represents the length along the well-pair. The model is discretized into 141 × 1 × 40 grid blocks in the x, y, and z directions, respectively. That is, each grid block is 1 m × 0.5 m in the x-z plane. This is smaller than the grid blocks of dimensions 1 m × 1 m in the x-z plane used for 2-D SAGD simulations for heterogeneous reservoirs by Deutsch (2010) and Wang and Leung (2015). The lateral, top and bottom boundaries of the reservoir model are impermeable to fluid flow.

Both the injection and production wells are situated in the 71st grid column from the left boundary of the reservoir model. The injection and production wells are respectively located in the 28th and 36th grid layers from the top of the model.

The temperature of the injected stream is equivalent to the saturation temperature of water at the operating pressure of 35 bars. The

Table 1
Input parameters for sequential indicator simulation for simple heterogeneous reservoir models comprising of clean sand and shale. The spherical model is used for the indicator variogram for the shale facies. A more detailed discussion underlying the choice of values for the parameters used for the geostatistical simulations can be found in Venkatramani and Okuno (2017b).

Property	Value
Global proportion of clean sand	0.75
Global proportion of shale	0.25
Nugget effect for indicator variogram model	0
Azimuth for variogram model	78°
Horizontal range parameter, m	12.0
Vertical range parameter, m	1.0