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Novel insights on initial water mobility: Its effects on steam-assisted gravity drainage performance

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ABSTRACT

Steam-assisted gravity drainage (SAGD) is a primary commercial in-situ thermal recovery method for oil sands/bitumen in Alberta, Canada. Evidence of initial water mobility during the SAGD processes has been observed by previous studies, yet little research has been done on its effects on SAGD performance. In this study, initial water movement ahead of the steam chamber is investigated and its effects on the steam chamber development, as well as well production performance are quantified. Initial water mobility is firstly classified into two categories (low and high) based on the shapes of their steam chambers. Results show that initial water mobility can change the shape of steam chamber, pressure distribution in the reservoir and the steam condensate flow pattern along steam chamber edge. Cumulative oil production in nine years for the low initial water mobility scenario is 18.1% higher than that of the immobile initial water scenario due to the convective heat transfer induced by initial water flow ahead of the steam chamber. On the other hand, cumulative oil production in nine years of the high initial water scenario is 34.6% lower than that of immobile scenario. For the adjacent well pairs located in the same pad, compared to immobile initial water case, low initial water mobility case with the same injection pressure has the highest NPV, while high initial water mobility has a negative impact on SAGD performance. An injection pressure difference of only 200 kPa for the high initial water mobility case can reduce NPV by 40%.

1. Introduction

Steam-Assisted Gravity Drainage (SAGD) has become the preferred in-situ recovery process for producing oil sands reservoirs. In this process, an upper horizontal well is used to inject steam into the bitumen reservoirs to decrease the bitumen viscosity, while a lower underlying parallel horizontal well produces the mobilized oil [1]. At present, SAGD has been adopted in half of in-situ bitumen extraction projects for oil sands reservoirs [2]. There are many factors that can affect the economic success of a SAGD project, such as reservoir heterogeneity, vertical and horizontal permeability [3], gas cap [4,5], top water zones [5–8], bottom water zones [8], intraformational water zones [9] and shale barriers [10,11].

Besides the aforementioned parameters, previous studies have concluded that initial water mobility is a crucial parameter in oil sand reservoirs and one of screening criteria for SAGD process [9,12,13]. During measuring heavy-oil/water relative permeabilities using freshly drilled core plugs, Maini and Batycky [14] first found that initial water saturation in some fresh cores was higher than the irreducible water saturation measured from heavy oil drainage experiments. In other words, initial water could flow in the core flooding tests. Chan et al. [15] further measured the initial water mobility in sandpacks in the presence of immobile heavy oil using water-wet membrane. They concluded that initial water saturations were not necessarily equal to irreducible water saturations and initial interstitial water could be mobile in bitumen reservoirs. Oskouei et al. [16] investigated the effect of initial water saturation on the SAGD process using a 2D high-pressure physical model. Their results showed that, compared to the immobile-initial-water case, the oil recovery of the highly-mobile-initial-water case was decreased by 6.6% and its cumulative steam-oil-ratio was nearly two times higher. Alvarez et al. [17] examined the effect of initial water saturation on SAGD performance using numerical simulation approach. Their results illustrated that with the increase of initial water saturation, the oil production rate decreased gradually, while the SAGD startup period was shortened. Zhou et al. [18] proposed a novel effective method (namely, using wax as the stationary oil phase) to deter-

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mine the mobility of initial water in the bitumen reservoirs. Their experimental results showed that the initial water could be mobile even if the water saturation decreased to 6% in the simulated bitumen–water system.

In addition to the above experimental and numerical simulation studies, analytical models were also derived to examine the contribution of convection induced by initial water flow beyond the steam chamber. Sharma and Gates [19] first proposed an analytical theory to investigate the role of convection at the steam chamber edge with initial water mobility by introducing the fluid mobility ratio. They concluded that the contribution of convection resulted from the condensate flow to heat transfer was larger than that of conduction at the steam chamber edge. Li and Chen [20] improved Sharma's analytical model [19] by correcting the condensate velocity formula. The results from the improved model provided a better consistency with the field data. Their analysis also indicated that the condensate flow (normal to the steam chamber edge) induced by initial water mobility could enhance convective heat transfer, but the convection decreased quickly within a short distance ahead of the steam chamber edge. Irani and Ghannadi [21] developed a new analytical model by considering initial water mobility and the pressure difference between high steam pressure in the steam chamber and low initial reservoir pressure. Their study revealed that the condensate velocity normal to the steam chamber interface was the main controller of convection and convection played a dominate role of heat transfer around the chamber edge in reservoirs with high water permeability at initial saturations. Ji et al. [22] derived an analytical model to examine the thermal expansion flow of the initial water into the cold oil sands zones. Their results showed that convection induced by the thermal expansion flow of the connate water has a dominant role in the heat transfer ahead of the steam chamber edge.

Evidence on initial water mobility has also been found in the field study. In the Dover SAGD Pilot, Aherne and Maini [23] examined the cold water injectivity and they detected that the initial water mobility in oil sands was more significant than what was previously estimated. Moreover, their history matching study also indicated that initial water was mobile ahead of the steam chamber. Higher initial water mobility than originally anticipated was also observed in the Firebag SAGD project of Suncor [24,25]. As it is easier and faster to heat bitumen reservoirs with mobile initial water via convective heat transfer than traditional circulation startup, bullheading (injecting steam without producing return fluids) has been proposed and successfully applied in Suncor's Firebag SAGD project [26]. Furthermore, in Tucker Lake oilfields, Husky Energy Inc. also found that the initial water was mobile and thus used bullheading on their SAGD startups [27].

Previous studies have mainly demonstrated that the initial water in oil sands possesses a degree of mobility in both experimental studies and field studies. Although Oskouei et al. [16] and Alvarez et al. [17] analyzed SAGD performance with different initial water saturations, they only used a closed boundary model and didn't consider the initial water flowing boundary (used in this study). In addition, all the analytical models [19–22] focused on analyzing the effect of initial water mobility on the drainage along the sides of the steam chamber (that is, only lateral-growth stage where the steam chamber has already touched the top of the formation) with Butler's assumption of quasisteady-state flow, so how the initial water movement can affect the steam chamber shape in the early-production stage (the steam chamber expands both upwards and sideways and has not yet touched the top formation) of a SAGD process cannot be obtained. In this study, the elaborated numerical simulation is conducted to analyze the effects of initial water mobility on steam chamber shape, oil flow rate, pressure profiles, oil saturation profiles, temperature profiles and water movement in the regions close to the steam chamber boundary. Subsequently, the effects of different initial water mobility on the adjacent steam chambers in the same pad are also studied using reservoir numerical simulation. The cumulative oil production, steam chamber growth, formation water movement and economic benefits of different initial water mobility scenarios are analyzed and the improving strategies for SAGD process between the adjacent well pairs to obtain a high economic efficiency are proposed.

2. Reservoir simulation model

In this study, a detailed reservoir geological model is firstly built for a typical Athabasca oil sand reservoir and applied to investigate the effects of initial water mobility on SAGD performance using CMG STARS [28]. The production well is positioned 1.5 m above the bottom of the formation, while the injection well is in parallel with the production well and placed 5 m above. The length of both producer and injector is 1000 m and reservoir thickness is 30 m. In the model, *X*, *Y* and *Z* directions represent the cross-well direction, the down-well direction and the vertical direction, respectively. In other words, the horizontal wells are perpendicular to *X*–*Z* plane. The dimensions of grid blocks are $1\ \mathrm{m} \times 50\ \mathrm{m} \times 1\ \mathrm{m}$ in the *X*–*Y*–*Z* directions. Thermal properties, rock/fluid properties and other reservoir simulation input properties are summarized in Table 1. The reservoir fluid is composed of solution gas, water and bitumen. Relative permeability curves are shown in Fig. 1 and obtained from Underground Test Facility [4,29,30]. CMG Winprop [31] is used to match the dead oil viscosity and bubble point pressure [32]. Initial reservoir temperature is 12 °C and initial reservoir pressure distribution is generated using a hydrostatic method with the model top pressure of 1500 kPa.

For the well constraints during the SAGD process, the injection wells are operated under a constant injection pressure of 2100 kPa with the steam quality of 90%. While, all production wells are constrained by a steam-trap of 10 °C to avoid producing the live steam and a maximum liquid production rate of 600 m^3/day.

Prior to SAGD operation, a period of steam circulation (that is, SAGD startup period) is simulated to establish the flow communication between the injector and producer by using temporary heaters (HEATR). The heaters are used until the temperature of the midpoint between injector and producer gets 80 °C [32,33]. In addition, temporary production well is placed at the same location as the injector to maintain the initial reservoir pressure and removed at the end of the startup period [32,33].

Net present value (NPV) is utilized as the objective function while investigating the effects of initial water mobility on the economic benefit of SAGD process. Based on the reports from National Energy Board [34], NPV including the factors of operation revenue, initial investment and well drilling cost, steam injection cost, operation costs and produced water treatment cost can be calculated by:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{(p_o Q_o)_t - (C_{si} Q_{si} + C_{wp} Q_{wp} + C_{op} Q_o)_t}{(1+i)^t} - C_{INV+WD} \qquad (1)$$

where n is the number of evaluation years; i is discount rate, 10%; $(p_o Q_o)_t$ is the total revenue due to oil production of the tth year, \$; $(C_{si}Q_{si} - C_{wp}Q_{wp} - C_{op}Q_o)_t$ is the total costs due to the oil and water production and water injection of the tth year, \$; p_o bitumen price, \$251.6/m^3; Q_o is the cumulative bitumen production, m^3; C_{si} is steam injection cost, \$16.54/m^3 cold water equivalent (CWE); Q_{si} is the cumulative steam injection, m^3 (CWE); C_{wp} is produced water treatment cost, \$2/m^3; Q_{wp} is the cumulative water production, m^3; C_{op} is operation costs, \$6.29/m^3 bitumen [35]; C_{INV+WD} is the initial investment and well drilling cost, \$2,500,000 per single horizontal well.