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Full Length Article

Investigation of initial water mobility on steam-assisted gravity drainage performance using a two-dimensional physical model

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ABSTRACT

Steam-assisted gravity drainage (SAGD) has become a primary commercial in-situ recovery method for oil sands in Alberta, Canada. Industrial field studies have found that the initial water mobility in oil sands has an impact on the SAGD process. However, no experimental research has been conducted to investigate such effects on SAGD performance. In this study, a novel two-dimensional (2-D) physical model with a water-flow boundary is designed for the first time to simulate the flow of initial water in oil sands during the SAGD process. The model investigates the impact of initial water mobility on the steam chamber shape and captures the growth of the steam chamber at different times. The experimental results show that low initial water mobility can promote vertical and lateral growth of the steam chamber, compared to immobile initial water, while high initial water mobility results in accelerated vertical expansion of the steam chamber in the SAGD process. The oil recovery in the scenario of low initial water mobility is 6.6% higher than that of immobile initial water scenario, and is 12.6% higher than that of high initial water mobility scenario. Subsequently, the numerical simulation study for the experiments is conducted in order to acquire insight into the effects of initial water mobility on SAGD performance. Results show that initial water mobility has a great influence on water movement profiles and water distribution along the steam chamber boundary in the SAGD process.

1. Introduction

Initial reserves of Alberta oil sands in Canada are reported to be 1845 billion barrels [1], where 80% of the recoverable bitumen contained in oil sands is likely to be produced by in-situ thermal methods, such as Steam-Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS). 58% of in-situ bitumen production was achieved by SAGD in 2014 [1]. SAGD was first proposed as an in-situ thermal recovery process for oil sands in 1981 [2,3]. Since then, many experimental and numerical simulation studies have been conducted to investigate factors affecting the economic performance of SAGD, such as reservoir heterogeneity [4], oil viscosity heterogeneity [5], geometrical configurations of the injection well [6,7], shale barriers [8,9] and the existence of thief zones [10–14] which include top water zones, intraformational water zones, bottom water zones and gas cap.

As well as the above factors, industrial field case studies also presented evidence of initial water mobility. Aherne and Maini [15] first investigated initial water mobility in a cold water injection process. They found that initial water should have mobility in order to obtain a good history-match result of cold water injectivity in the Dover SAGD Project. In the Firebag SAGD project, Suncor Energy Inc. experienced higher initial water mobility than initially expected [16]. Nexen Inc. found vertical pressure conduction through the mobile water phase in its Leismer oil sands property [17]. By taking advantage of mobile initial water in the oil sands, Anderson and Kennedy [18] examined a new startup strategy named bullheading (injecting steam without producing return fluids). As initial water was mobile, bullheading could increase heat transfer by convection, as compared to the conventional circulation startup in which only conductive heat transfer occurs. Due to its great benefits of higher thermal efficiency, less steam consumption, decreased facility requirements and operational simplicity, bullheading has been successfully employed in Suncor's Firebag SAGD project [18]. In addition, Husky Energy Inc. also tried the bullheading startup in the Tucker Lake oilfield by using the mobile initial water in the reservoir [19].

Several analytical model studies of the SAGD process were conducted to investigate the effect of initial water flow on heat transfer ahead of steam chamber boundary. A simple analytical model considering initial water mobility was first developed by Sharma and Gates [20] to examine the contribution of convection ahead of the steam

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chamber boundary. Their analysis revealed that the convective heat transfer resulting from the condensate flow was higher than the conductive heat transfer ahead of the steam chamber boundary. By considering the pressure difference between the steam chamber (high steam pressure) and the initial reservoir (low reservoir pressure), Irani and Ghannadi [21] proposed a new analytical model to analyze the effect of initial water mobility on heat transfer behavior in SAGD. Their analysis showed that for high initial water mobility reservoirs convection had a dominant contribution to heat transfer near the steam chamber boundary. By revising the condensate velocity formula in Sharma's model, Li and Chen [22] obtained an improved model which can better correlate to the condensate velocity field data. Their results showed that convective heat transfer could be boosted by the condensate flow, which is induced by initial water flow, but it was greatly reduced within a short distance beyond the steam chamber boundary. Using a new derived analytical model, Ji et al. [23] studied the impact of initial water flow resulting from the thermal expansion of initial water on SAGD performance. They claimed that convective heat transfer caused by thermal expansion flow of initial water played a dominant role in heat transfer ahead of the steam chamber boundary, compared to conductive heat transfer.

Experimental and numerical studies have also focused on initial water flow in the SAGD process. Chan et al. [24] experimentally examined initial water mobility in oil sands by using sandpacks, where the immobility of bitumen was modeled. Their results demonstrated that initial water in the range of 20–30% [25,26] could flow with an effective permeability of 0.01 Darcy. To measure initial water mobility in bitumen reservoirs more effectively and easily, Zhou et al. [27] developed a novel method to determine initial water mobility by using wax to simulate immobile bitumen in oil sands. They found that initial water could still have mobility at a saturation of 5% in the wax-water system. Oskouei et al. [28] studied the impact of initial water saturation on the economic performance of SAGD by using a two-dimensional physical model with no water-flow boundary. Their results illustrated that high initial water saturation could accelerate vertical growth of the steam chamber and lead to a decrease of 6.6% in oil recovery, compared to immobile initial water. Alvarez et al. [29] estimated SAGD performance of various initial water saturations by using a numerical simulation method. They concluded that high initial water saturation could speed up SAGD startup but could also reduce oil production rate and cumulative oil recovery.

In summary, the analytical studies [20–23] have only investigated the impact of initial water movement after the steam chamber has reached overburden formation with a simplified assumption of quasi-steady state flow [30], while a no-flow boundary is used in the experimental studies of scaled two-dimensional (2-D) physical models [6,7,9,28,31–34] and the numerical studies [29,35,36]. It remains unclear how the initial water flow would affect the performance of a SAGD process. Lab experiments need to be conducted to fully understand the impact of initial water movement on the steam chamber growth and well productivities. In this work, a new experimental setup is designed with a water-flow boundary to visualize the expanding steam chamber for the immobile, low and high initial water mobility scenarios as production proceeds. The effect of initial water mobility on the growth of the steam chamber and the well productions has been clearly demonstrated for the first time.

In this study, a new 2-D physical model with a water-flow boundary is designed to investigate the effect of initial water mobility on SAGD performance. The experimental setup mimics a well pair with a constant flowing boundary during the SAGD process. The water-flow boundary is realized by using a water-wet membrane, which only allows water to flow through. Very fine water-wet sands are tightly packed and saturated with water to maintain a capillary continuity of the water on both sides of the membrane. The impact of initial water mobility on steam chamber development in SAGD process is investigated by capturing growth of the steam chamber at different times in the 2-D model. Oil production rate and oil recovery in the 2-D model tests with different initial water saturations are measured and analyzed. Subsequently, a numerical model of the experiments is built and history-matched, and growth of the steam chamber is simulated. Initial water movement in oil sands is analyzed and discussed to understand the effects of initial water mobility on SAGD performance.

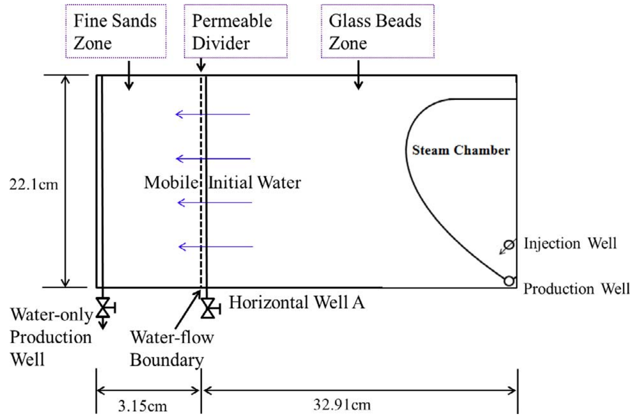

Fig. 1. Schematic diagram of the two-dimensional physical model with a water-flow boundary (top view).

2. Experimental

2.1. Two-dimensional physical model with a water-flow boundary

Fig. 1 shows the schematic diagram of a 2-D physical model with a water-flow boundary, which represents a cross-section of a semi-SAGD pattern. It is 36.07 cm in width, 22.10 cm in height and 2.54 cm in depth, following the dimensionless scaling factor to make the model dimensionally similar to the field case [2,9,28,30,31]. The chamber of the model is separated into two parts by a permeable divider, which is a stainless steel frame. As shown in Fig. 1, the left half is packed with fine sands and saturated with water, while the right half of the model is packed with glass beads and saturated with oil and water. A horizontal well (water-only production well) in the fine sands zone is used to remove the water flowing from the glass beads zone to the fine sands zone during the SAGD process. The horizontal well (horizontal well A) in the glass beads zone is used as the water or oil fill-up port. The production well is placed in the lower right corner, while the steam injection well is designed 5.0 cm above the production well using the SAGD-scaling method [2,9,28]. All the wells are made of stainless steel tubes with a diameter of 0.95 cm. They are perforated in four different directions around their circumference with holes 0.25 cm in diameter. All the wells are also covered with stainless steel screens to present glass beads or sands from moving through the holes.

Fig. 2a and b show the front and back views respectively of the permeable divider. As shown in Fig. 2a, a layer of water-wet (Durapore VVLP Millipore) membrane is attached to the front of the permeable divider to prevent the fine sands from migrating into the glass beads zone. Two rows of holes, with a diameter of 0.99 cm, are drilled on the permeable divider to allow water flow from the glass beads zone to the fine sands zone, as presented in Fig. 2b. The novelty of the newly designed 2-D model is that the capillary pressure generated from the water-wet membrane and the fine sands zone (with a very strong water wettability) can prevent oil from flowing into the fine sands zone and allows only water flow from the glass beads zone into the fine sands zone. Thus, a 2-D physical model with a water-flow boundary is realized. The 2-D model has a Plexiglas cover with 5.08 cm thickness. The transparent cover allows for visualization and photography of steam chamber development during the SAGD process.