Experimental Comparative Investigation of Hot Solvent/Steam-Assisted Gravity Drainage in Oil Sand Reservoirs

Yu Bai, Jianbo Liu, Shangqi Liu, Zhaohui Xia, Yuxin Chen,* Guangyue Liang, and Yang Shen

ABSTRACT: Hot solvent-assisted gravity drainage (HS-AGD) is an effective way to exploit oil sands and heavy oil both economically and environmentally. The visualized microscopic seepage experiments and two-dimensional (2-D) macroscopic simulation experiments of HS-AGD are carried out, and the results are compared with that of steam-assisted gravity drainage (SAGD) in detail for the first time in order to compare their development effects of the oil sand reservoir. MacKay River oil sand bitumen is taken as an oil sample in the experiments, with n-hexane as the solvent. Micro seepage characteristics of the hot solvent and steam and the remaining oil distribution of the solvent and steam drive are investigated through microseepage experiments. The expanding process of the solvent/steam chamber and production performance of HS-SAGD and SAGD are investigated through macrosimulation experiments. The study found that the sweep efficiency of hot solvent is higher than that of steam at the same temperature due to the small interfacial tension between the condensed solvent and heated bitumen. Due to the severe gravity segregation, the steam accumulated at the top of the model during the 2-D physical simulation experiment, which results in the huge heat loss at the top of the model. The temperature of the steam chamber is significantly lower than that of the solvent chamber. The components of oil produced in SAGD have little difference compared with that of the original bitumen. In HS-AGD, both mass transfer and the sensible heat transfer reduce the viscosity of oil sand bitumen. The in situ asphaltene precipitation induced by heated-solvent extraction also upgrades the bitumen. The results of component analysis show that in HS-AGD, the content of heavy components in the oil sand bitumen is obviously reduced. This paper aims to reveal the oil drainage mechanism of HS-AGD and SAGD from the macroscopic and microscopic view and to provide theoretical guidance for the field application of this technology.

1. INTRODUCTION

Steam-assisted gravity drainage (SAGD) is the most commonly applied heavy oil thermal recovery technique. The advantages of SAGD over other conventional oil recovery processes are higher oil rates and faster reservoir depletion, but it still has some limitations. The energy consumption for SAGD is high, due to the large requirement of steam. The investment on the SAGD plant and the operation cost are relatively high as well. At the same time, the produced heavy oil still has a high content of asphaltene and metallic elements, resulting in higher refining and transport costs. Expanding solvent SAGD (ES-SAGD) was proposed. In the ES-SAGD process, the solvent is injected with steam in a vapor phase to reduce the steam requirement. The condensed solvent around the interface of the steam chamber dilutes the oil and, in conjunction with heat, reduces its viscosity. However, ES-SAGD needs both solvent and steam disposal facility. With the increase of steam requirement, the CapEx of ES-SAGD exceeds that of SAGD.

Mokrys and Butler published their first VAPEX paper on the solvent analogue of SAGD in 1991. VAPEX or vapor extraction is the process of injecting a solvent into a heavy oil reservoir (through an upper horizontal well) to reduce the viscosity of the heavy oil via mass transfer. The solvent-enhanced live oil then drains via gravity drainage and is produced through a lower horizontal production well. The energy requirement of VAPEX is 3% of SAGD for the same project. The capital costs for VAPEX are approximately 30% that of SAGD. There is no need for the steam generator,
through pressure decay methods,22,23 dynamic pendant drop volume analysis,24−27 NMR and X-ray CAT scanning,28,29 and thermal expansion method.30 Rezaei et al.31 studied the mechanism of warm VAPEX. Ancheyta et al.32 found that the rate of interface advancement, which increased the condensation of the solvent on the bitumen surface increased through heat transfer on warm VAPEX and found that the most suitable solvent is a critical task for an efficient warm VAPEX process. Oil−solvent mixture quality and rate of mixture formation solvent are two main selection criteria for solvent-aided recovery processes. James et al.19 believes that the mass transfer is an important mechanism in warm VAPEX. The solvent is transferred mainly, via diusion coe cients can be determined through pressure decay methods,22,23 dynamic pendant drop volume analysis,24−27 NMR and X-ray CAT scanning,28,29 and thermal expansion method.30 Rezaei et al.31 studied the effect of heat transfer on warm VAPEX and found that the condensation of the solvent on the bitumen surface increased the rate of interface advancement, which increased the production of the upgraded oil. Ancheyta et al.32 found that asphaltene precipitation greatly reduces the viscosity of heavy oil. The condensed solvent interacts with bitumen, which leads to the in situ upgrading of bitumen via asphaltene precipitation. The operating temperature of warm VAPEX is commonly between 40 and 60 °C. In this paper, the solvent vapor is heated to a higher temperature, and the technology is called hot solvent-assisted gravity drainage (HS-AGD), the mechanisms of which are the same as warm VAPEX. The schematic diagram is shown in Figure 1. Up to now, microscopic and macroscopic displacement experiments of HS-AGD have not been investigated systematically. There have been no detailed report on the seepage characteristic of hot solvent in the reservoir and the production performance of oil sands recovered by hot solvent injection. Moreover, there have been no comprehensive comparison between the production performances of HS-AGD and SAGD.

In this paper, MacKay River oil sand bitumen is taken as an oil sample, with n-hexane as the solvent. The visualized microscopic seepage experiments and two-dimensional (2-D) macroscopic simulation experiments of HS-AGD are carried out, and the results are compared with that of SAGD in detail for the first time. The seepage characteristics of the hot solvent and steam in oil sand reservoirs, the expanding process of the solvent and steam chamber, and the production performance of HS-AGD and SAGD are investigated. What is more, the four component analyses are applied to the produced oil. Through the abovementioned research, the mechanisms of hot solvent and steam-assisted gravity drainage can be more clearly demonstrated.

2. EXPERIMENTS

2.1. Experimental Materials. All experiments are conducted using MacKay River oil sand bitumen, the density and viscosity of which are 1.032 kg/m3 and 24,578 mPa·s (0.101 MPa, 50 °C). The viscosity−temperature curve of bitumen is shown in Figure 2. The result of SARA (saturates, aromatics, resins, and asphaltene) analysis of MacKay River bitumen is given in Table 1. Analytically pure n-hexane and deionized water are used in the experiments.

2.2. Experimental Setup. The experimental setup for microscopic seepage experiments is shown in Figure 3. The apparatus is composed of the injection system, micromodel holder, digital microscope camera system, collection system, and heating and insulation system. Etched glass micromodels are used in the experiments, whose permeability is $2700 \times 10^{-3}$ μm², etching range is 40 by 40 mm, edge size is 100 by 85 mm, diameter of the visible range is 68 mm, and distance between the injection end and production end is 91 mm. The rotary
evaporator of the collection system is utilized to heat the oil collection cylinder by water bath. The evaporated solvent is collected by the method of draining water, so as to acquire the oil production and then calculate the recovery factor.

The experimental setup for 2-D physical simulation experiments is shown in Figure 4. The device consists of five parts, including injection system, 2-D physical models, data acquisition system, collection system, and heating and insulation system. The data acquisition system incorporates a temperature sensor, computer, and digital camera. The temperature sensor records the real-time temperature of the 2-D physical model, which is then transmitted to the computer. The digital camera is used to take a real-time picture of the expanding process of the solvent and steam chamber during the experiment. The collection system excludes the solvent separation device in SAGD experiments.

The dimension of the 2-D physical model for HS-AGD is approximately 25 by 25 by 1.3 cm. The model is composed of a stainless steel shell with a glass cover coated with heat insulation resin. The model offers a visible front, and the pressure assistance is 3 MPa. As shown in Figure 5, the injection and production well are located at the edge of the 2-D model. The production well is 2 cm away from the bottom of the model and the injection well is 5 cm above the production well, which is utilized to simulate the production mode of HS-AGD. The size of the 2-D physical model for SAGD is 50 by 40 by 1 cm, as shown in Figure 6. The injection well and production well are located on the axis of the model, the spacing between them is 5 cm, and the production well remains at the bottom of the model, which is used to simulate the production mode of SAGD.

2.3. Experimental Procedure. The experimental procedure for microscopic seepage experiments is shown in Figure 7A. The procedure for 2-D macroscopic simulation experiments is shown in Figure 7B.

2.3.1. Procedure for Microscopic Seepage Experiments. The etched glass micromodel was first placed in its holder, the confining pressure was added, and the model temperature was set to 20 °C. The model was then vacuumed and then saturated with formation water from the injection end of the model. The etched glass micromodel was heated to 80 °C, and MacKay River bitumen was heated to 120 °C. The model was later saturated with the heated bitumen from the injection end at a rate of 0.05 mL/min until the oil flows out continuously.

Table 1. Component Analysis of MacKay River Oil Sand Bitumen Using the SARA Method

| component     | weight % |
|---------------|----------|
| saturates     | 18.05    |
| aromatics     | 39.36    |
| resins        | 32.52    |
| asphaltene    | 10.07    |

Figure 2. Viscosity–temperature curve of MacKay oil sand bitumen.

Figure 3. Schematic diagram of microscopic seepage experiments.
from the production end. The amount of oil saturated into the model was recorded, and the initial oil saturation was calculated. The model temperature was reset to 20 °C, and the injection temperature of hot solvent vapor and steam was set at 110 °C. Hot solvent vapor/steam was injected at the rate of 0.1 mL/min until the oil content at the production end is less than 2%. The real-time images were captured, and the formation and distribution pattern of the remaining oil were investigated through the subsequent process of video and images. The sweep efficiency was then calculated. At the same time, the oil production was determined and the displacement efficiency was worked out to obtain the recovery ratio.  

2.3.2. Procedure for 2-D Macroscopic Simulation Experiments. The 2-D physical model was packed with sand, covered with the glass lid coated with heat insulation resin, and sealed from outside to form a closed structure. The model was dried with compressed air for several hours and vacuumed with pump. Leak detection was carried out using the leak detecting solution. The model was saturated with formation water, and the permeability was measured and it was ensured that it was constant at 2700 × 10⁻³ μm², which is the permeability of the MacKay River oil sand reservoir. The sand packed model was heated to 80 °C, and the oil sand bitumen was heated to 120 °C. The heated bitumen was injected into the two-dimensional physical model at 0.5 mL/min until the oil spilled out of the...
production well continuously. The amount of oil saturated into the model was recorded, and the initial oil saturation was calculated. The temperature of the model was reset to 60 °C, and the heating belts were preheated at the same time. When the temperature reached the steady state, the HS-AGD and SAGD experiments was started. The operating temperature of HS-AGD is 150 °C, and the injection rate is 1 mL/min (liquid solvent equivalent). The operating temperature of SAGD experiments was 300 °C with the injection rate of 10 mL/min (water equivalent). The growth of the steam and solvent chamber was captured by a high-definition camera. The temperature data of the model were automatically recorded by the temperature data collector, and the production data in the production end were documented.

The heavy oil produced from HS-AGD and SAGD was sampled, and the components were analyzed. During HS-SAGD experiments, oil samples were taken from the ramping up stage, steady and peak stage, and declining stage. During SAGD experiments, oil samples were taken from the steady and peak stage. The components of oil samples were analyzed using the SARA method, the °API gravity of which was also determined.

3. RESULTS AND DISCUSSION

3.1. Microseepage Characteristics of Hot Solvent and Steam. The microseepage characteristic of 110 °C steam is illustrated in Figure 8. The steam reduces the viscosity of bitumen sufficiently by heat transfer to mobilize the in situ oil. The low density of steam accounts for the great resistance provided by oil sand bitumen, resulting in the steam diffusion that starts after the injection and formation of two advantage channels (0.5PV). After the injection of 1PV (pore volume) steam, the connection between the injection end and the production end is established. After that, the high mobility ratio between steam and oil sand bitumen leads to the steam and condensed water mainly producing from the advantage channels, resulting in the difficulty to increase the sweep efficiency. When 3PV is injected, there is almost no oil produced in the production end, and the ultimate sweep efficiency of 110 °C steam is 73%.
The microseepage characteristics of 110 °C n-hexane vapor is illustrated in Figure 9. The high mobility ratio of solvent vapor and MacKay River bitumen accounts for the obvious fingering phenomenon that appears in the model, and the solvent diffuses rapidly along the advantage channels to the production end. When the injection volume reaches 0.5PV, the advantage channel communicates with the production end. With the subsequent injection of hot solvent, the sweep range of solvent expands rapidly, which is distinct from the seepage characteristics of steam. The distinct displacement mechanisms explain the difference. The steam condenses on the cold bitumen surface, reducing the viscosity of the bitumen through heat transfer. The hot solvent vapor condenses on the bitumen interface and diffuses rapidly into the bitumen due to the small interfacial tension between the condensed solvent and bitumen, reducing the bitumen viscosity through both heat transfer and mass transfer, which enhances the mobility of bitumen more sufficiently and enlarges the sweep range. After the injection of 2PV, there is no more oil produced in the production end and the ultimate sweep efficiency of 110 °C hot solvent vapor attains 90%.

3.2. Remaining Oil Distribution of the Steam and Solvent Drive. As shown in Figure 8, when the injection volume reaches 3PV, there are still some areas where the steam has not swept, resulting in the high remaining oil saturation. Due to the high temperature of steam, there is little remaining oil in the pores that the steam flows through; most of the remaining oil is located in the area that has not been swept. As

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a consequence of low density of steam, it mainly flows through large pore throats and bypasses the smaller ones. The remaining oil is trapped in the smaller-size pore throats distributed in clusters. The displacement efficiency of the recovery of 110 °C steam is shown in Table 2.

As illustrated in Figure 9, after the injection amount of hot solvent reaches 2PV, there is little remaining oil in the model. In addition to the remaining oil located in the unswept area, the remaining oil saturation in the swept area is much lower. The remaining oil sparsely disperses, including the asphaltene precipitated from bitumen due to the solvent extraction. The displacement efficiency of the recovery of 110 °C hot solvent vapor is shown in Table 2, which are much higher than those of steam at the same temperature.

3.3. Expanding Process of the Solvent and Steam Chamber. The temperature field patterns of the 2-D physical model at different times throughout the physical simulation experiments of HS-AGD are shown in Figure 10, and the images of the model are shown in Figure 11. With the hot solvent vapor injected into the upper horizontal well where the bitumen is heated and extracted by the solvent, the asphaltene precipitates from the oil sand bitumen, which reduces its viscosity and allows the upgraded bitumen to drain under gravity to a bottom production well. As shown in Figure 11, with the gradual recovery of oil sand bitumen, the pores are gradually occupied by hot solvent vapor to form the solvent chamber, which constantly expands during the production. Owing to the gravity differentiation, the solvent chamber first develops in the longitudinal direction during what is called the chamber rising phase. The solvent chamber reaches the top of the model after 2 h, and the longitudinal growth of which was limited by the model edge. Then, the chamber starts to spread laterally outward, known as the chamber spreading phase. The lateral spreading is relatively slow due to the huge heat loss at the top of the model. After 5 h of the experiments, when the solvent chamber reaches the extent of the model, the solvent chamber begins to expand downward, known as the chamber falling phase. After 6 h of the experiment, there is almost no more oil production and the temperature of most parts of the model exceeds 60 °C.

Figure 11. Images of the 2-D physical model during HS-AGD.

Figure 12. Temperature field patterns of the 2-D physical model during SAGD.
The temperature field patterns of the 2-D physical model at different times throughout the physical simulation experiments of SAGD are shown in Figure 12. The oil sand bitumen around the injection well heated by the steam injected into the model drains down along the steam–bitumen interface with the condensed steam to the production well under the gravity effect. The growth of the solvent or steam chamber is generally upward first to the top of the oil “pay zone” during what is called the chamber rising phase. After 3 h of the experiment, the chamber starts to spread laterally outward sweeping the oil bearing formation, as the viscosity reduced oil drains downward. The pores drained of oil become filled with solvent or steam known as the steam or solvent chamber, which grows laterally in time, known as the chamber spreading phase. The steam accumulated at the top of the model due to the gravity segregation, which results in the temperature of the top significantly higher than that at the bottom. After steam injection for 5 h, when the steam chamber reaches the extent of the model, the steam chamber begins to expand downward, known as the chamber falling phase. After 7 h of the experiment, there is almost no more oil production and the temperature of most parts of the model exceeds 60 °C.

3.4. Production Performance of HS-SAGD and SAGD.
The production performance of the 2-D physical simulation experiment of HS-SAGD is shown in Figures 13–15. The curves of the oil production rate, cumulative oil production, instantaneous oil–solvent ratio, cumulative oil exchange ratio, recovery, and solvent retention rate are drawn on the basis of the experimental data. The experiment of HS-SAGD can be divided into three stages according to the oil production rate: 0–2.5 h is the ramping up stage, 2.5–4.5 h is the steady and peak stage, and 4.5 h is the declining stage. Due to the gravity differentiation, the steam chamber grows faster in the longitudinal direction, and hence, the oil production rate and the solvent to oil exchange ratio increase rapidly in 0–2.5 h. During the chamber spreading phase, the ideal mixing of hot solvent and oil sand bitumen makes the heavy oil drain with a high rate during 2.5–4.5 h. During this stage, the instantaneous oil–solvent ratio remains stable, and the solvent retention rate gradually decreases with the production of heavy oil. From 4.5 h to the end of the experiment, with the production of heavy oil, the oil production rate and the instantaneous oil–solvent ratio gradually decrease and the solvent retention rate remains stable. The ultimate solvent retention rate is 8.5%, and the ultimate oil recovery reaches up to 73.83%. The solvent retention rate of the HS-SAGD simulation experiment is less than 10%, and a large amount of solvent can be recovered to reduce the cost. Also, the ultimate recovery is over 70%, and the technology has high economic benefits and is conducive to environmental protection.

The production performance of the 2-D physical simulation experiment of SAGD is shown in Figures 16–18. The curves of oil production rate, cumulative oil production, cumulative oil–steam ratio, recovery, and water-cut rate are drawn on the basis of the experimental data. The experiment of SAGD can be divided into three stages according to the oil production rate: 0–3 h is the ramping up stage, 3–5 h is the steady and peak stage, and the declining stage is from 5 h to the end of the experiment. During the first stage, the steam chamber expands along the longitudinal direction, and the cumulative oil–steam ratio increases rapidly. The incomplete development of the steam chamber results in some steam advancing rapidly into the production well. The oil sand bitumen between injection and production wells is produced by the steam drive, the steam is produced from the production well in the form of condensed water, and thus the water-cut rate during 0–1 h rises rapidly. During the second stage, the heavy oil is produced at a high speed, and the cumulative oil–steam ratio remains constant.

Figure 13. Oil production rate and cumulative oil production curves of the 2-D physical simulation experiment of HS-SAGD.

Figure 14. Instantaneous oil–solvent ratio and cumulative oil exchange ratio curves of the 2-D physical simulation experiment of HS-SAGD.

Figure 15. Recovery and solvent retention rate curves of the 2-D physical simulation experiment of HS-SAGD.
After 5 h of the experiment, the gravity override is intensified due to the fact that the large quantity of bitumen above the production well was extracted in the early stages. The steam gathers at the top of the model where the heat loss is large, and some steam flows out of the production well in the state of high temperature water before it expands laterally. The oil production rate begins to decline rapidly, and the water-cut rate raises further as a result of the abovementioned reasons. Meanwhile, the effect of viscosity reduced by heat transfer gets worse and the movable oil saturation decreases, which leads to the reduction of the cumulative oil–steam ratio and the increment of oil recovery, the ultimate value of which is 38.35%.

3.5. Component Analysis of the Produced Oil. In order to determine the variation of oil components during the production, the SARA analyses of the oil samples produced by the two-dimensional physical simulation experiments of HS-AGD and SAGD are conducted, and the analysis results are shown in Table 3. Because steam cannot be dissolved in the bitumen or react with the components of the bitumen, the components of oil samples produced in the steady and peak stage of SAGD have no obvious change compared with the original bitumen components. However, in the hot solvent extraction experiment, the composition of the oil samples has changed with the proceeding of the experiment. The content of saturates in the produced oil increases with the solvent dissolving in oil sand bitumen. The proportion of aromatics decreases due to the increase of saturated content, but the total mass of aromatics has no significant change. The solvent extraction leads to the in situ asphaltene precipitation, and resins are extracted to form light components, which leads to the decrease of resins and asphaltene components.

### Table 3. Component Analysis of HS-SAGD- and SAGD-Produced Oil Using the SARA Method

| component | steady and peak stage of SAGD | ramping up stage of HS-SAGD | steady and peak stage of HS-SAGD | declining stage of HS-SAGD |
|-----------|-------------------------------|-------------------------------|-------------------------------|---------------------------|
| saturates | 18.39                         | 44.83                         | 61.35                         | 73.1                      |
| aromatics| 39.63                         | 28.69                         | 21.31                         | 15.56                     |
| resins    | 32.21                         | 20.49                         | 13.82                         | 9.11                      |
| asphaltene| 9.77                          | 5.99                          | 3.52                          | 2.23                      |
| gravity, °API | 7.78                      | 10.48                         | 14.63                         | 18.95                     |

4. CONCLUSIONS AND RECOMMENDATIONS

In this paper, the visualized microscopic seepage experiments and 2-D macroscopic simulation experiments of HS-AGD are carried out, and the results are compared with that of SAGD in detail for the first time. The microscopic seepage experiments are performed to investigate the microseepage characteristics of the hot solvent and steam in the oil sand reservoir and the formation and distribution of the remaining oil in the process of the steam or solvent drive and to demonstrate the oil drainage mechanism in the microscopic view. The visualized two-dimensional simulation experiments are carried out to study the expanding process of the solvent and steam chamber and the production performance of HS-AGD and SAGD to reveal the oil drainage mechanism in the macroscopic view. The main conclusions are as follows.

1. The sweep efficiency of hot solvent vapor is higher than that of steam at the same temperature. After the connection between the injection end and the production end is established, the steam and condensed water are mainly produced from the advantage channels due to the high mobility ratio between steam and oil sand bitumen, resulting in the difficulty to increase the sweep efficiency. However, the condensed solvent diffuses rapidly into the bitumen due to the small
interfacial tension between the solvent and bitumen, which enhances the mobility of bitumen more sufficiently and enlarges the sweep range of the solvent.

2. During the oil sand bitumen production by HS-AGD or SAGD, the expanding process of the solvent and steam chamber can be divided into three phases, including the chamber rising phase, chamber spreading phase, and chamber falling phase. The steam accumulated at the top of the model due to the gravity segregation results in the huge heat loss at the top of the model and the temperature of the steam chamber is significantly lower than that of the solvent chamber.

3. Because steam cannot be dissolved in or react with oil sand bitumen, the components of oil produced in SAGD have little difference compared with the original bitumen components, while the solvent extraction can obviously reduce the content of heavy components in the oil sand bitumen and increase the content of light components, which greatly reduces the viscosity of bitumen, so as to substantially enhance the oil recovery.

4. In SAGD, the viscosity of oil sand bitumen is reduced only by heat transfer. In HS-AGD, the viscosity of oil is reduced by the mass transfer and the sensible heat transfer from the solvent to the bitumen. The in situ asphaltene precipitation induced by heated-solvent extraction upgrades the bitumen, which drains under gravity and is produced through the production well.

5. The oil displacement efficiency of hot solvent surpasses that of steam. The oil recovery of 200 °C hot solvent vapor is about twice as much as that of 300 °C steam due to the different drainage mechanisms of HS-AGD and SAGD. More than 90% of the solvent can be recycled, and the capital cost and the refining cost of HS-SAGD is much lower than those of SAGD.

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### Notes

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