Experimental investigation on the SAGD dilation start-up in shallow heavy oil reservoirs

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Abstract. There are few related researches focused on the steam assisted gravity drainage (SAGD) dilation start-up technology (termed as dilation start-up in this paper), especially with physical modelling experiments. Therefore, in order to better understand the dilation start-up process, several large-scale experiments of SAGD start-up with dual horizontal wells were carried out by using the oil sands from Xinjiang oilfield, northwest China. The dilation process characterized by temperature changes at different positions inside the experimental samples was monitored in real time. The performance differences between dilation start-up and conventional start-up were discussed in detail, and the effects of dilation pressure and dilation time on the dilation process were also studied. The experimental research indicated that dilation start-up can significantly enhance the range of dilation zone and improve the uniformity of dilation zone along the horizontal wellbores. Moreover, it was found that dilation pressure is an essential factor influencing the dilation effect, in that the size and distribution of dilation zone are largely dependent on dilation pressure. The evolution of dilation zone with time shows that a long-time dilation prompts the uniform propagation of dilation zone along the horizontal wellbores.

Key words: oil sands reservoir, steam assisted gravity drainage (SAGD), dilation start-up, geomechanics, dual horizontal wells
1. Introduction

Steam assisted gravity drainage (SAGD) is an effective recovery method for ultra-heavy oil sands reservoirs [1-6]. In the conventional start-up stage (also known as preheating stage), steam is cyclically injected into the injection well (I well) and production well (P well) at the same time in order to heat the inter-well domain by heat conduction until the effective thermal and hydraulic communications are achieved. This conventional start-up usually lasts for several months or even years. During this stage, an enormous consumption of steam is required and a large amount of circulating waste fluid needs to be processed. These operation issues limit the applicability of SAGD for oil sands reservoirs. Therefore, SAGD geomechanical dilation start-up is proposed to shorten the cyclic injection time and improve the efficiency of start-up stage [7-9]. The geomechanical dilation is fully realized by simultaneously injecting high-temperature fluid with the controlling injection pressure into the I well and P well in a short time. Then an ideal dilation zone with high porosity and permeability, which vertically connects the upper I well and the lower P well and is evenly distributed along the horizontal wellbore, is created. The injection capacity is improved significantly and the development of steam cavity is accelerated after geomechanical dilation, which is conducive to shorten the start-up time and enhance the SAGD performance [10-12].

Various methods have been adopted to study the process of SAGD dilation start-up [13-21]. However, there are few experimental investigations on the SAGD dilation start-up at present. Therefore, several large-scale (1050×410×410 mm) true triaxial experiments of SAGD start-up were carried out for the case of oil sands reservoirs in Xinjiang oilfield by using the multi-field coupling experimental system. The dilation process characterized by temperature changes which are monitored by temperature sensors at different positions inside the samples is obtained in real time. The impacts of dilation pressure and injection time on the dilation start-up process are studied.

2. Multi-field coupling experimental system

The triaxial multi-field coupling experimental system shown in figure 1 mainly consists of the triaxial sample chamber, servo-controlled loading system, fluid injection system, control and data acquisition system and sample molding system.

![Figure 1. Triaxial multi-field coupling experimental system, (a) physical equipment, and (b) schematic diagram.](image-url)
Triaxial sample chamber. The triaxial specimen chamber can be loaded a large-scale specimen with the size of 1050 mm × 410 mm × 410 mm. And the different stresses in the three directions of rock sample can be applied, and the variation of stresses in the same direction can also be considered.

Servo-controlled loading system. The servo-controlled confining loading system is used to apply triaxial stresses to the experimental sample. The maximum applied stresses in the X, Y and Z directions are 12 MPa, 10 MPa and 10 MPa, respectively. Moreover, four variation stresses along the Y and Z directions can be applied to different parts of the same experimental sample.

Fluid injection system. The fluid injection system can be controlled by either pressure control or displacement control. The maximum stroke of the booster cylinder during the displacement control is 20 cm, and the maximum injection pressure is 60 MPa.

Control and data acquisition system. The control system is used to specify the control output for the servo-controlled loader and hydraulic cylinders. The data of confining pressure, injection pressure and injection rate during the experiment is recorded in real time through the data acquisition system. The temperature changes inside the sample during the experiments are measured by PT1000 temperature sensors, and then recorded in real time by temperature recorder.

Sample molding system. The sample molding system mainly consists of a molding chamber and a manual-control 5000 kN presser. The function of the molding chamber in the molding system is to form the standard-sized sample after pressing. The maximum pressure of the manual-control presser is 5000 kN and the maximum stroke is 350 mm.

3. Large-scale experiments of SAGD dilation start-up

3.1. Experimental programs

Four large-scale experimental programs shown in table 1 are designed. It is worth noting that the dilation pressure (also known as injection pressure) is greater than or equal to the minimum horizontal stress for the SAGD dilation start-up such as test #3 and test #4. The injection fluid is 2% KCl fluid with a viscosity of 1 mPa·s.

| Programs | SAGD start-up types | Dilation pressure, kPa | Ratio of dilation pressure to $\sigma_{\text{hmin}}$ | $\sigma_v/\sigma_{\text{hmax}}/\sigma_{\text{hmin}}$, kPa | Injection fluid | Injection time, min |
|----------|---------------------|------------------------|-----------------------------------------------|---------------------------------|----------------|-----------------|
| #1       | Conventional start-up | 910                    | 0.35                                          | 4200/3200/2600                  | 100°C KCl fluid | 2621            |
| #2       | Conventional start-up | 1820                   | 0.7                                           | 4200/3200/2600                  | 100°C KCl fluid | 2592            |
| #3       | Dilation start-up     | 2600                   | 1.0                                           | 4200/3200/2600                  | 100°C KCl fluid | 1440            |
The similarities of reservoir physical properties and well layout in the large-scale SAGD start-up experiments are considered as shown in table 2. The schematic diagram of experimental sample is shown in figure 2. The horizontal wellbores are arranged along the direction of the minimum horizontal stress. The distance between the I well and P well is 50 mm, and the distance between the P well and the bottom of sample is also 50 mm. The heel end of the horizontal wellbores is located at 90 mm away from the left boundary in figure 2.

**Table 2.** Similarities of reservoir physical properties and well layout

| Parameters                          | Similar ratio | Field  | Model  |
|------------------------------------|---------------|--------|--------|
| Reservoir thickness, m             | 97            | 40     | 0.41   |
| Horizontal well length, m          | 500           | 450    | 0.9    |
| Distance between I well and P well, m | 100          | 5      | 0.05   |
| Distance between P well and the bottom, m | 100        | 5      | 0.05   |
| Oil saturation, %                  | 1             | 65     | 65     |
| $\sigma_v/\sigma_{\text{max}}/\sigma_{\text{min}}$, kPa | 1             | 4200/3200/2600 | 4200/3200/2600 |

**Figure 2.** Schematic diagram of experimental sample, (a) perspective view, (b) front view, and (c) side view. S1, S2, S3, S4 and S5 represent different cross-sections along the horizontal wellbores, respectively.

The profile of horizontal wellbores with a diameter of 14 mm and a length of 900 mm is shown in figure 3. From figure 3, there are a long tubing and a short tubing for each horizontal wellbore. In the experiments, a slotted screen liner with a diameter of 14 mm is used as the wellbore, and two steel pipe
with a diameter of 6 mm are used as the long tubing and short tubing. The slot width, slot length and slot spacing of the slotted screen liner are 4 mm, 21 mm and 18 mm, respectively. During the experiments, high-temperature fluid is injected simultaneously with the same injection pressure into the toe end of the I well and P well through the long tubings, and then the fluid flows to the heel end along the horizontal wellbores, and finally flows out through the short tubings at the heel end. The geomechanical dilation and the preheating of the reservoir near the wellbores are finally achieved through these experimental processes. Importantly, the dilation pressure is controlled by automatically adjusting the outflow discharge of the short tubing by the fluid injection system.

![Figure 3](image_url)

**Figure 3.** Horizontal wellbore, (a) schematic diagram, and (b) physical equipment. Unit is mm.

The dilation process characterized by temperature changes inside the specimen is monitored in real time by temperature sensors during the experiment. The spiral distribution of temperature sensors is shown in figure 2. A total of 75 temperature sensors is arranged for each sample. These temperature sensors are distributed on 5 cross-sections (S1–S5) along the X direction, and there are 15 temperature sensors in each cross-section.

### 3.2. Preparation of samples

The oil sands are sampled from the ultra-heavy oil reservoirs in the Xinjiang oilfield. For the laying of the horizontal wellbores and the temperature sensors inside the specimen, the oil sands firstly need to be crushed into fine particles by the crusher, and then these particles are remolded by the sample molding system in order to form the standard specimen. During the molding, two horizontal wellbores and 75 temperature sensors need to be laid inside the specimen, respectively. According to figure 4, the P well is laid in the sample after the pressing thickness of oil sands in the molding chamber is 50 mm (figure 4a). Then add continuously the crushed oil sands into the chamber to subsequent pressing, and the temperature sensors are laid when the total height of oil sands reaches 60 mm (figure 4b). The standard sample can be completed by reciprocating these steps. The applied stress during the pressing of oil sands is 9 MPa, and the pressing time for each step is 1 hour. It is noting that grooves are prefabricated when laying the wellbores and the sensors in order to prevent the wellbores and the sensors from being damaged in the subsequent pressing.
In order to compare the properties between the pressing sample and the real oil sands sample, a series of experiments on artificial cores randomly cored from pressed samples and the real cores is conducted, and the experimental results are shown in table 3. From table 3, it is found that the properties of pressing samples are basically consistent with that of the real cores, and thus the pressed samples are reasonable to represent the real rock samples.

Table 3. Comparison of properties between artificial and real samples.

| Properties                          | Artificial samples | Real Samples |
|-------------------------------------|--------------------|--------------|
| Porosity, %                         | 31                 | 31~35        |
| Permeability, mD                    | 2000               | 1500~3000    |
| Elastic modulus, MPa                | 410                | 300~800      |
| Unconfined compressive strength, MPa| 0.6                | 1.0~1.5      |
| Density, g/cm³                      | 1.85               | 1.9~2.0      |

3.3. Experimental process

Firstly, the sample chamber is placed on the triaxial loading stand. According to Table 1, the stresses in the three directions are 4200 kPa (σv), 3200 kPa (σhmax) and 2600 kPa (σhmin), respectively. In order to
prevent the damage to experimental sample caused by the unbalanced loading in different directions, the stresses in the three directions are applied simultaneously. The three principal stresses are firstly increased simultaneously to 2600 kPa, and then the vertical and the maximum horizontal stresses continue simultaneously to increase to 3200 kPa, and finally the vertical stress continues to increase to 4200 kPa. Then the experiment is carried out after 30 min for reaching the stress equilibrium in the experimental sample. Finally, high-temperature fluid is injected simultaneously into the I well and P well from the long tubings to dilate and preheat the sample. The temperature changes at different positions within the rock sample are recorded in real time by the data acquisition system.

4. Experimental results and analysis

4.1. Comparison of experimental results with different start-up programs

The dilation performances of the conventional start-up (#1) and the dilation start-up (#4) at different cross-sections are shown in figure 5. From figure 5, it is evident that a dumbbell-shape dilation zone perpendicular to the direction of the minimum horizontal stress is formed vertically, and then the thermal communication between the I well and P well is realized in different degrees. Moreover, the range of dilation zone of the dilation start-up is obviously greater than that of the conventional start-up.

The SAGD wellpair is able to convert into the production stage from the start-up stage if the minimum temperature in the inter-well domain reaches 80℃, in that crude oil begins to flow. Therefore, 80℃ is the conversion criterion for judging whether the effective start-up is satisfied in our experiments. From figure 5, the maximum temperature in the area between I well and P well is 50℃ at cross-section 1 (S1) of the conventional start-up, which is less than the conversion criterion. While the minimum temperatures are above 80℃ at S1~S4 of the dilation start-up, and it almost meets the conversion criterion.

In addition, there are considerable discrepancies of temperature distribution along the horizontal wellbores between the conventional start-up and dilation start-up from figure 5. In the conventional start-up, the dilation zone is unevenly distributed along the horizontal well and there is almost no dilation zone at the heel (S5). The maximum temperature is 50℃ at the toe (S1) while only 30℃ at the heel (S5) in the conventional start-up, which indicates the large heat loss along the wellbore. However, the dilation zone of the dilation start-up propagates uniformly along the horizontal wellbores with the minimum temperatures of 85℃ (S1) and 77℃ (S5) from the toe and the heel, respectively.
Figure 5. Temperature distribution of (a) #1 conventional start-up with the injection time of 2621 min and (b) #4 dilation start-up with the injection time of 1296 min.

In order to quantitatively describe the communication of dual wells at different cross-sections, a criterion proposed by Lin et al. (2017) [22] is used to evaluate the thermal communication of dual wells during the start-up experiment, and the average communication parameters (CPs) of #1~4 tests are shown in figure 6. The average CPs of five cross-sections of dilation start-up are on average larger than that of conventional start-up, indicating that the thermal communication of dilation start-up is better. It is noteworthy that the CP of #2 conventional start-up is abnormally higher than that of #3 dilation start-up. According to figure 7, it is inferred that the slots of the P well of #2 test during the molding are almost blocked, which results in fluid being injected only into the I well instead of both the I well and
P well. Thus, the dilation zone formed in this case is approximately circular, which is different from the dumbbell in other tests, and this phenomenon leads to an abnormal CP from #2 test.

![Figure 6. Average communication parameters (CPs) of #1~4 tests.](image6)

![Figure 7. Temperature distribution of #2 test at different cross-sections.](image7)

4.2. Impact of dilation pressure

The dilation pressure has a considerable influence on the performance of dilation start-ups (#3 and #4 programs) shown in figures 5b and 8, respectively. The dilation pressures of #3 and #4 programs are
2600 kPa and 2860 kPa, respectively. The big difference is that the temperature in the inter-well domain of #4 program is distributed uniformly from the toe to the heel (S1–S5), while there is a drastically decrease of temperature surrounding the P well in the #3 program, especially at the heel (S5). The #4 program is able to convert into the production stage in that the minimum temperatures in the inter-well domain of S1–S4 reach 80°C. However, only the temperature of S1 meets the convert criteria in the #3 program. These trends show that the high dilation pressure enhances the dilation performance. The optimal dilation pressure is 1.1 times (2860 kPa) of the minimum horizontal stress in the present experiments. Therefore, a large dilation pressure should be applied in the field in order to significantly enhance the dilation effect and shorten the start-up time.

4.3. Impact of dilation time

The evolution of dilation performance of dilation start-up (#3 and #4 programs) with time is monitored, and the results are shown in figure 9. From figure 9, there are two small dilation zones initially formed surrounding the I well and P well at the early stage, respectively. With the increase of dilation time, the dilation zones develop gradually, and then the two dilation zones begin to intersect and eventually communicate completely to form a large dilation zone connecting the I and P wells. Then the dilation zone continues to propagate dominantly in the vertical direction, especially in the area above the I well. Additionally, our observations also indicate that a long time dilation can improve the thermal communication in the inter-well domain and promote the even propagation of dilation zone along the horizontal wellbores. The dilation time with 1440 min for #3 test or 1296 min for #4 test is optimal in the current experiments.
5. Conclusions

(1) A dumbbell-shape dilation zone perpendicular to the direction of the minimum horizontal stress is formed vertically during the SAGD start-up experiment.

(2) Compared with the conventional start-up, the range of dilation zone during the dilation start-up is obviously greater, and the thermal communication along the horizontal wellbores is also more even.

(3) Dilation pressure is an essential factor that affects the development of dilation zone during the dilation start-up. High dilation pressure (i.e., 1.1 times of the minimum horizontal stress in our experiments) is beneficial to enhance the size of dilation zone and improve the uniformity of dilation zone along the horizontal wellbores.
(4) The dilation process with a longer time (i.e., 1440 min for #3 test or 1296 min for #4 test in present experiments) can improve the thermal communication in the inter-well domain and promote the even propagation of dilation zone along the horizontal wells. Therefore, it is necessary and important to increase the dilation time appropriately during the field operations of the dilation start-up.

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