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Research Article

Simulation and Production Optimization on Enhanced Oil Recovery during the Middle and Late Period for SAGD Development in Ultraheavy Oil Reservoirs with Interlayers

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Previous studies on the technique for using the remaining oil are incomplete and inaccurate according to the position of the interlayer of the Steam-Assisted Gravity Drainage (SAGD) technique, and comparative studies of infilled horizontal wells are lacking. In this study, the SAGD well pair in the superheavy oil reservoir in the Z block in the Xinjiang Oilfield, China, was taken as an example. According to the reservoir's geological parameters and production parameters, a typical well group geological model was created for the first time. The model divided the well groups in block Z into three categories according to the position of the interlayer, the production degree of the horizontal section, the oil recovery ratio, and the available degree of reserve control. According to the geological classification results, different typical well groups without an interlayer, with an interlayer located above the steam injection well, and with an interlayer located between the well pairs were classified and analyzed using numerical simulations. This was the first time the infilled horizontal well technique was compared with the infilled vertical well-assisted SAGD technique. In addition, the steam chamber connection law of the infilled vertical well-assisted SAGD was clarified. The results show that for reservoirs without an interlayer, the use of infilled horizontal well-assisted SAGD could speed up the lateral connection of the steam chambers and reduce the residual oil saturation. For reservoirs with a low production degree in the horizontal section and that are affected by an interlayer, an infilled vertical injector could be used with the assisted SAGD technique to increase the oil recovery by 5%–13%. The results of this study provided strong guidance for the next step in using enhanced oil recovery techniques to achieve traditional SAGD production from superheavy oil reservoirs with an interlayer.

1. Introduction

Steam-Assisted Gravity Drainage (SAGD) is a key technique for the development of ultraheavy oil, which has been widely used in Alberta, Canada, and the Xinjiang and Liaohe oilfields in China. The SAGD technique, which was proposed by Butler [1, 2], can achieve an ultimate reservoir recovery of greater than 70%. The SAGD technique is influenced by several factors, particularly the presence of interlayers, which can affect the development of steam chambers, resulting in reduced oil recovery. According to the actual production situation of the oilfield, as an ultraheavy oil reservoir with interlays enters the late stage of development, the differences in the reservoir conditions are enhanced and the reservoir's heterogeneity is increased, resulting in a prolonged SAGD production cycle and decreases in the oil-gas ratio and economic returns. Therefore, for SAGD well pairs with interlayers entering the middle and late stages of oil recovery, it is important to strengthen the understanding of the distribution of the interlayers and to develop suitable replacement techniques to further improve the oil recovery.

Many researchers have studied the effect of reservoir heterogeneity on SAGD recovery through experiments and numerical simulations [3–12]. Their results have shown that an increase in the volume or continuity of the shale barrier layers and a decrease in the distance between the barrier layers and the well pair will increase the influence of the interlayer on the steam chamber development. Shi et al. [13–17] conducted optimization research on the pattern shape, production parameters, and pipe string structure of SAGD dual-horizontal wells in heterogeneous ultraheavy oil reservoirs.

To improve the traditional SAGD technique, Polikar et al. [18, 19] proposed the fast SAGD technique, which involves arranging a parallel horizontal well between the well pair used for SAGD. The well pair is operated in a conventional working method. The offset well starts huff and puff and soak after the steam chamber develops to the top of the oil layer, and then, the offset well starts production until the end. This technique has the advantage of accelerating the lateral connection of the steam chamber, reducing the residual oil saturation, and ultimately improving the oil-gas ratio and recovery factor [20, 21]. Previous studies have comprehensively compared the SAGD technique with the fast SAGD technique using three-dimensional numerical simulations and a high-temperature high-pressure proportional model. The research results of these studies revealed that the fast SAGD technique is more suitable for use in low-quality formations [22]. Shin et al. [23, 24] suggested that the technique requires less steam injection and a shorter production cycle to achieve the same output. Gong et al. [25–27] studied the influence of the reservoir conditions, such as the rhythm, interlayer, thief formation, and fractures, on the development effect of fast SAGD using numerical simulations. Nguyen et al. [24, 28–31] optimized the pattern shape of fast SAGD, the offset horizontal well pretreatment, start-up method, and production time.

In addition, the introduction of vertical wells to optimize SAGD has mainly included the following combinations: a single vertical and a single horizontal well, vertical wells assisted by double horizontal wells, and a single horizontal well and multivertical wells [32, 33]. For the improved SAGD technique using the combination of a single vertical and a single horizontal well, scholars have established a productivity prediction model. The model can effectively reduce the impact of the interlayers during SAGD development [34]. They determined the best pattern shape, optimization of the horizontal well length, dryness fraction of injected steam, liquid withdrawal rate from the production well, and perforated parameters using three-dimensional physical model experiments and numerical simulations [35–37]. The vertical wells assisted by double horizontal well SAGD technique are to arrange one or more vertical wells in positions where the steam chamber is not developed through the SAGD horizontal well section. This method establishes thermal communication with the SAGD well pair through multiple rounds of steam huff and puff in the vertical wells, forming a unified steam cavity to fully utilize the unswept region of the steam chamber and the horizontal drainage channel. Li and Liu [38] carried out an optimization study on the perforation parameters, start-up time, and rotation mode of the SAGD for a double-horizontal well assisted by a vertical well using numerical simulations. Tang et al. [39] optimized the operation parameters in the stages according to the production characteristics and developed a standard for assessing the thermal connection and a conversion standard. For a large oil layer thickness and widespread development of an interlayer, Sun et al. [40, 41] established a mathematical model of the seepage force field and pressure gradient field during the flooding process of a composite well pair with a single horizontal well and multiple vertical wells using an SAGD three-dimensional well pattern.

Many studies have focused on a comparative analysis of the development effect of the improved SAGD technique. Sun et al. [42] demonstrated the feasibility of using a combination of horizontal and vertical wells by comparing it with the dual-horizontal SAGD technique. Rose and Deo [43] compared and analyzed multiple steam injection modes, including traditional SAGD, horizontal well crowding, and the combination of a horizontal well and a vertical well, using large-scale thermal reservoir models. Their results revealed that multiple vertical steam injection wells have a higher injection efficiency than a single well. Tamer and Gates [44] proposed technical countermeasures for vertical well encryption, multibranch horizontal wells, and reservoir reconstruction through classification and analysis of the development mode of an interlayer in the well pair. They also investigated its development effect by analyzing field production data.

However, previous studies on technical countermeasures for improving the SAGD technique did not provide a standard for rapid and accurate classification of the geological conditions; however, detailed technical countermeasures require accurate classification of the geological conditions of the well pair, especially for reservoirs with interlayers. The existing comparison of the technical countermeasures for enhancing oil recovery is not comprehensive, and the infilled horizontal well is not considered when interlayers exist. The key to the vertical well-assisted SAGD technique is the realization of thermal communication, but no detailed analysis and comparison have been conducted on the thermal communication of the vertical well-assisted SAGD technique. The goal of this study was to overcome the above shortcomings. A typical well group geological model was developed for the first time according to the reservoir's geological parameters and production parameters. This was the first study to compare the infilled horizontal well technique with the infilled vertical well-assisted SAGD technique. In addition, this study clarified the steam chamber connection law of infilled vertical well-assisted SAGD.

In this study, the SAGD well pair in the superheavy oil reservoir in the Z block in the Xinjiang Oilfield, China, was taken as an example. First, a typical well group geological model was developed according to the reservoir's geological parameters and production parameters, such as the position of the interlayer, the production degree of the horizontal section, the oil recovery ratio, and the available degree of reserve control. The model divides the well groups in block Z into three categories. Second, different typical well group models were classified and analyzed using numerical simulations according to the classification results of the geological model: without an interlayer, with an interlayer located

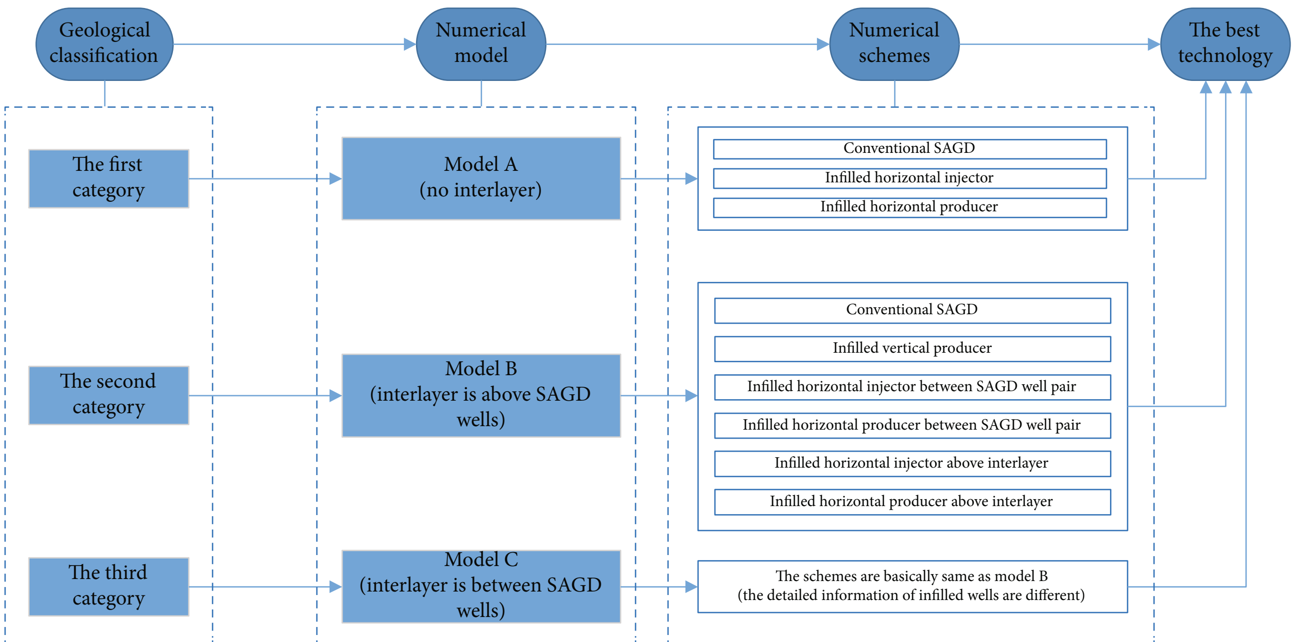


Figure 1: The flow chart of the problem under study.

above the steam injection well, and with an interlayer located between the well pairs. In this paper, the development effects of different schemes for these three SAGD well pairs are discussed, such as using an infilled horizontal well for production or steam injection and using an infilled vertical well for steam injection or production. Finally, the optimization techniques for the middle and late stages of SAGD development of three types of superheavy oil reservoirs with interlayers were determined based on the comparison results. Figure 1 presents a flow chart of this research.

2. Numerical Simulation

The distribution of the remaining oil varies greatly depending on the location of the interlayers in reservoirs in the middle and later stages of SAGD development. In this study, numerical simulation was used to determine the best improved SAGD technique.

2.1. Simulation Scheme. In this study, block Z in the Xinjiang oilfield was taken as the research object. In 2017, 42 well pairs in the Z well area were put into production using the SAGD technique. At present, all of the well pairs have entered the middle and late stages of development. The classification standard of the well pairs in the Z block was determined according to the geological characteristics of the well pair, the production degree of the horizontal section, the oil recovery ratio, and the available degree of reserve control. The 42 well pairs were divided into three types. In the numerical simulations, the position and length of the interlayer were used to represent the heterogeneity of the well pair. Three models were designed in this study to correspond to the three types of well pairs: a well pair without an interlayer, a well pair with an interlayer located above the steam injection wells, and a well pair with an interlayer located between the well pairs. Table 1 shows the classification and characteristics of the well pairs and the numerical simulation models.

To fully compare the effects of the infilled vertical well, infilled horizontal well, and complex well patterns on the residual oil production, a comparative study of the different development techniques was conducted for each type of well pair. For model A, the technical scheme is the traditional SAGD technique, an infilled horizontal well for steam injection, and an infilled horizontal well for production. For model B, the technical scheme is the traditional SAGD technique, an infilled vertical well for steam injection, an infilled horizontal well for steam injection between the SAGD well pairs, an infilled horizontal well for production between the SAGD well pairs, an infilled horizontal well for steam injection above the interlayer, and an infilled horizontal well for production above the interlayer. For model C, the technical scheme is the same as that of model B. The optimal technical countermeasures were finally obtained by comparing the development effects of the different technical schemes.

2.2. Simulation Model. Based on the reservoir parameters of the Z block and the proposed SAGD well pattern, the three models were used to simulate the entire process for the different types of infilled wells using the CMG-STARS software. The dimensions of the simulation model were $56 \times 81 \times 21$, and the block size was 10 m, 1 m, and 1 m for DX, DY, and DZ, respectively. Table 2 presents the reservoir properties and dimensions of the model. In this study, three mechanism models were established based on the reservoir fluid data: model A without an interlayer, model B with an interlayer above the steam injection wells, and model C with an interlayer between the well pair. The schematic of the well configuration and the locations of the interlayers in model

Table 1: Classification and characteristics of the well pair and numerical simulation models.

Classification and characteristics of the well pair		Numerical simulation models	
Geological classification	Feature description	Model name	Model scheme
First category (9 well pairs)	Oil recovery ratio is greater than 5%; oil production rate is 30–50 t/d; production degree of horizontal section is greater than or equal to 80%; available degree of reserve control is 100%.	Model A	There is no interlayer in the model.
Second category (13 well pairs)	Oil recovery ratio is 3%–5%; oil production rate is 20–40 t/d; production degree of horizontal section is greater than 70%; available degree of reserve control is less than 90%.	Model B	In the model, an interlayer is located in the middle of the reservoir and above the steam injection well, 15 m away from the bottom of the reservoir. It has a length of 200 m, width of 40 m, thickness of 1 m, and permeability of 10 mD.
Third category (20 well pairs)	Oil recovery ratio is less than 3%; oil production rate is 15–25 t/d; production degree of horizontal section is less than 80%; available degree of reserve control is less than 90%.	Model C	In the model, an interlayer is located at the toe of the SAGD horizontal well pair and between the well pair. It has a length of 130 m, width of 1 m, thickness of 1 m, and permeability of 10 mD.

Table 2: Parameters of the simulation model.

Parameter	Value	Parameter	Value
Depth (m)	250	Oil viscosity (at 50°C) (mPa·s)	30000
Thickness (m)	30	Oil density (at 50°C) (g/cm^3)	966
Initial reservoir pressure (kPa)	2700	K_v/K_h	0.6
Temperature (°C)	20	Dimension	56 × 81 × 21
Permeability (mD)	2500	Block size (m)	10 × 1 × 1
Porosity (%)	32	Distance between well I and well P (m)	5
Initial oil saturation (%)	75	Distance between well P and bottom of reservoir (m)	1

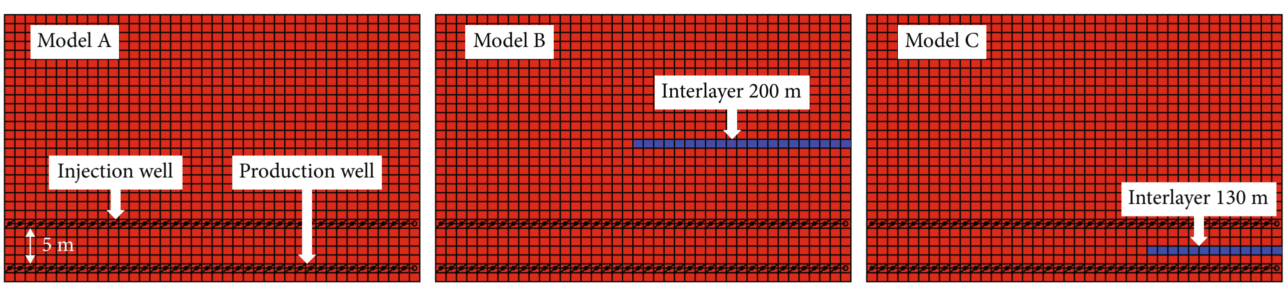


Figure 2: The schematic of well configuration and distribution of interlayer in model A, model B, and model C.

A, model B, and model C is shown in Figure 2. Figure 3 shows the oil viscosity-temperature curve of the model.

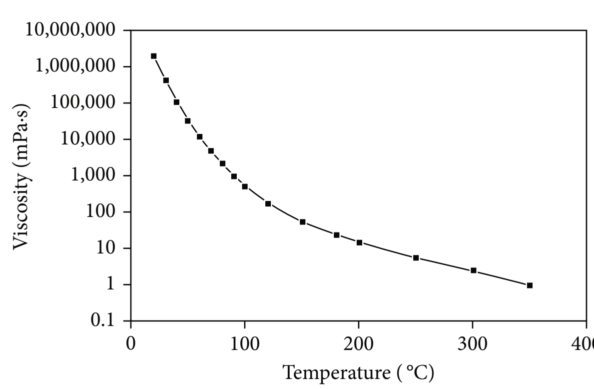


Figure 3: The oil viscosity-temperature curve of the model.

3. Results and Discussion

3.1. Model A: Model without Interlayer

3.1.1. Temperature and Oil Saturation Distribution. There is no interlayer in model A. The steam chamber is uniformly developed throughout the well section, and the oil saturation of the steam chamber was reduced to 0.15–0.2 in the steam chamber development area. The temperature in the steam chamber is 240°C. The temperature profiles and oil saturation profiles at different times for model A are shown in Figure 4.

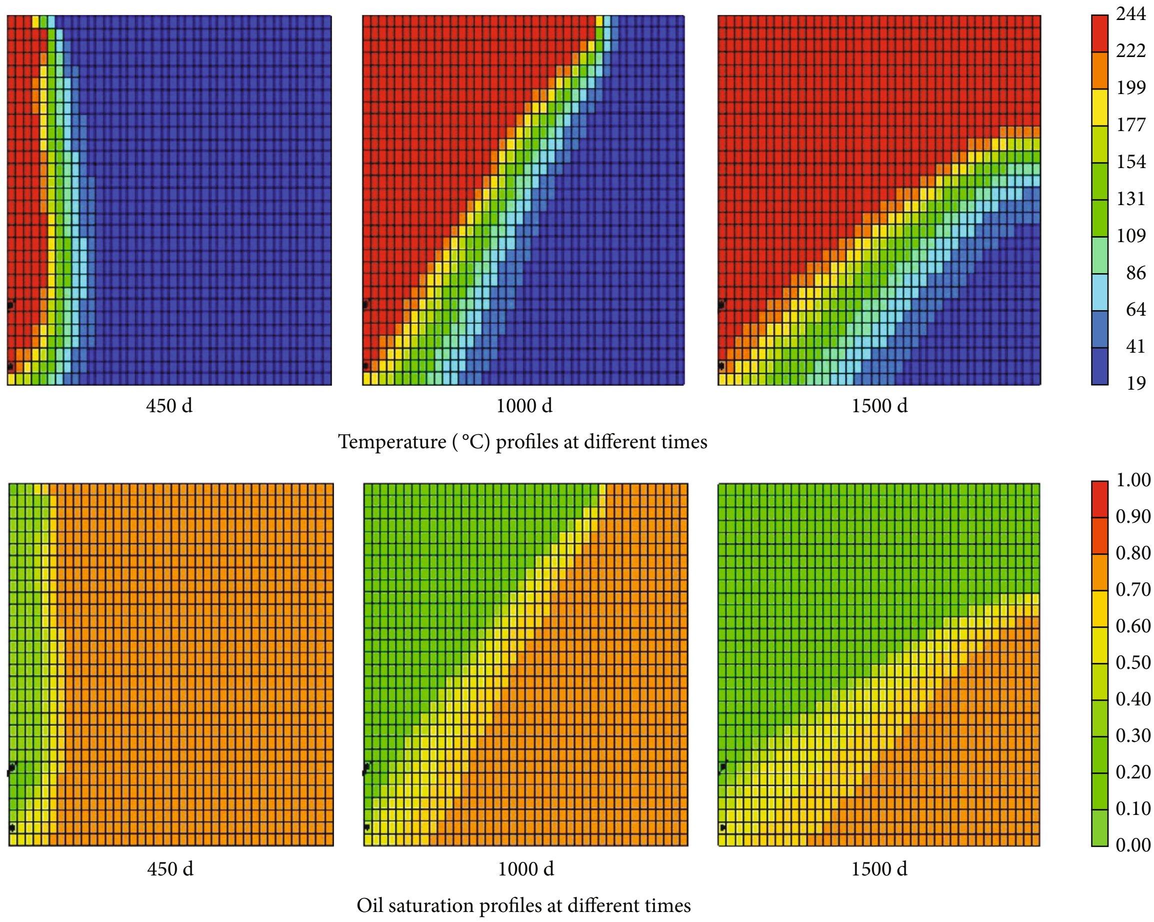


Figure 4: Temperature profile and oil saturation profile at different times of model A ($I = 1$).

The steam expansion chamber is divided into three stages: the rising stage, lateral expansion stage, and descending stage. As can be seen from Figure 4, the production period (from days 0 to 450) was the rising stage of the steam chamber. In this stage, the steam chamber expanded upward under the action of the steam overlap, and the vertical expansion speed of the steam chamber was greater than the horizontal expansion speed. The steam chamber entered the horizontal expansion stage when the steam chamber reached the top of the reservoir, and the production time was 450–1300 days. The steam chamber expanded laterally at the top until it expanded to the boundary of the reservoir. The shape of the steam chamber was similar to an inverted triangle at this time. After 1300 days of production, the steam chamber entered the descending stage, even though steam was still being injected. Figure 4 shows that at 1500 days, the height of the SAGD steam chamber had dropped by 10 m, and the recovery degree had reached 41%. Finally, a triangular low-temperature zone formed in the lower part of the well pair, and the temperature in this area was the original temperature of the oil reservoir. As is shown in Figure 4, the remaining oil saturation field was affected by the expansion of the steam chamber, and there was a triangular cold oil zone between the SAGD well pair.

3.1.2. Thermal Connectivity Analysis. In model A, an infilled horizontal well with a length of 400 m was located 40 m from well P, parallel to well P, and on the same horizontal plane as well P. The infilled horizontal well used for huff and puff was used to realize thermal communication between the SAGD and the horizontal well pair, thus accelerating the lateral expansion of the steam chamber and finally realizing the use of the triangular cold oil zone. In addition, short rounds of huff and puff were used to accelerate the communication between the horizontal offset well and the SAGD well pair. The temperature profile and oil saturation profile after the different rounds of huff and puff for model A are shown in Figure 5.

Figure 5 shows that when the SAGD well pair was produced for 1300 days, the first round of horizontal offset well huff and puff was completed. The production range of the horizontal well was 4 m near the well, and the heating range of the huff and puff was limited. The horizontal well had not yet established a connection with the steam chamber of the SAGD well pair. When the sixth round of steam huff and puff of the horizontal well was completed, the horizontal offset well was injected with 10500 t of steam and produced 3200 t of oil. The cold oil area between the SAGD well pair and the horizontal offset well had been heated to 70°C, and interwell thermal communication was initially established.

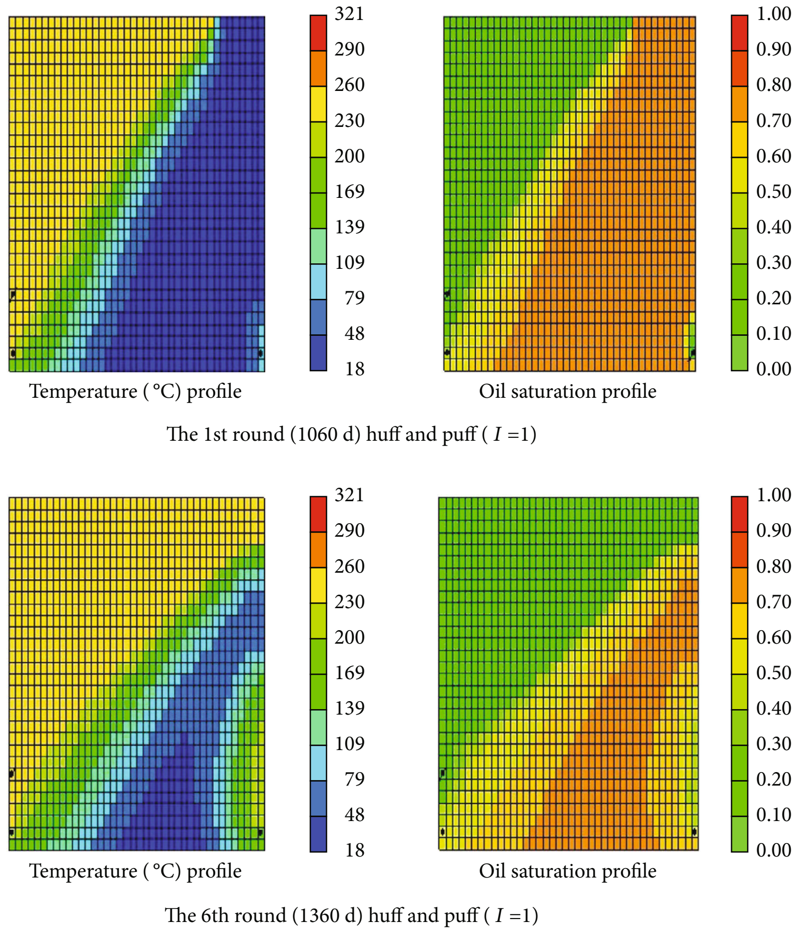


FIGURE 5: Temperature profile and oil saturation profile after the first round of huff and puff for model A ($I = 1$).

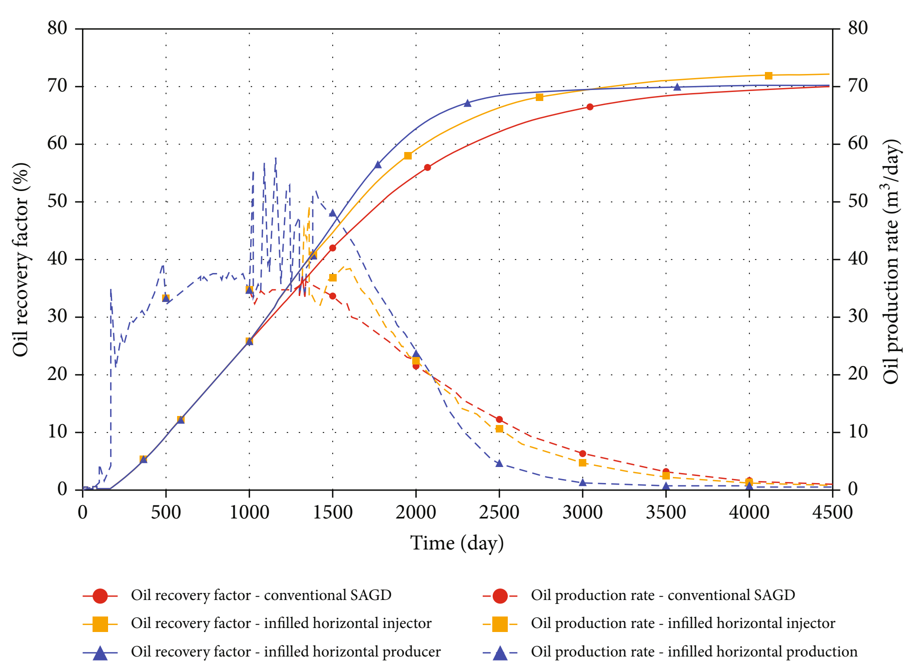


FIGURE 6: Production characteristic of different schemes for model A.

Table 3: Comparison of the production characteristics of model A.

Scheme	Time (d)	Cumulative steam injection (10^4 t)	Cumulative oil production (10^4 t)	Cumulative oil to steam ratio (cOSR) (f)	Oil recovery factor (%)	Oil recovery ratio (%)
Conventional SAGD	3241	286291	73420	0.256	67.4	7.59
Infilled horizontal injector	2900	284000	75147	0.265	69	8.68
Infilled horizontal producer	2374	258839	73674	0.285	67.6	10.39

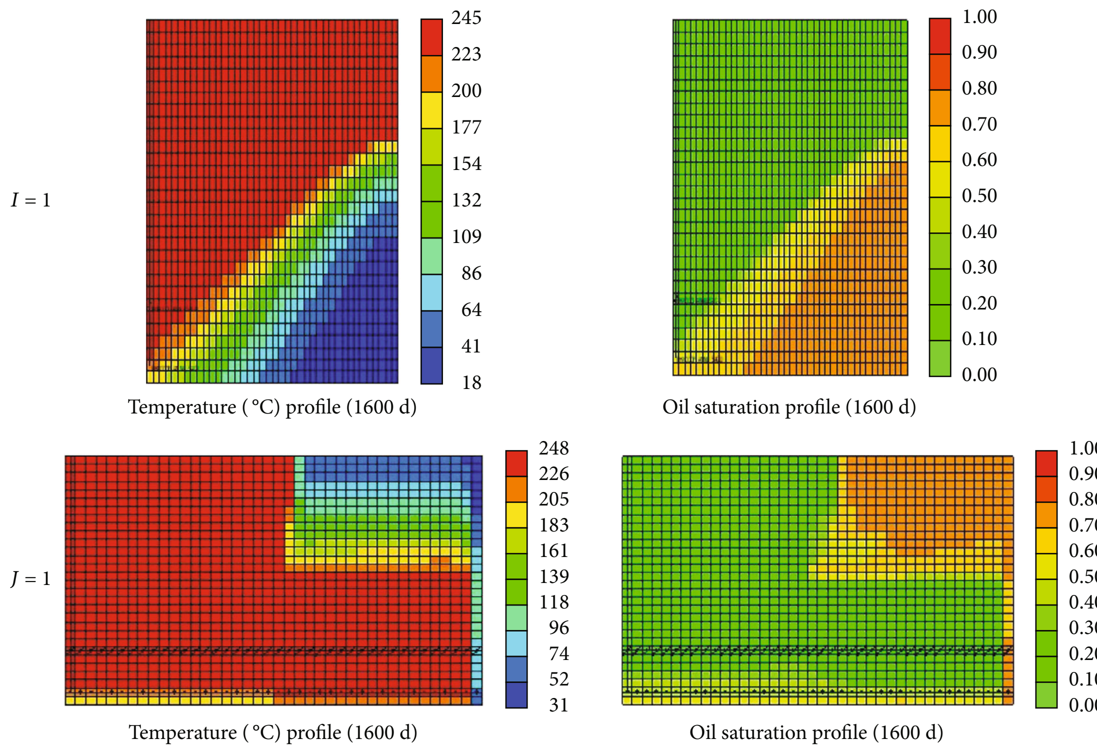


Figure 7: Temperature profile and oil saturation profile of model B.

At this time, it could be transferred to the horizontal offset well for steam injection or oil production.

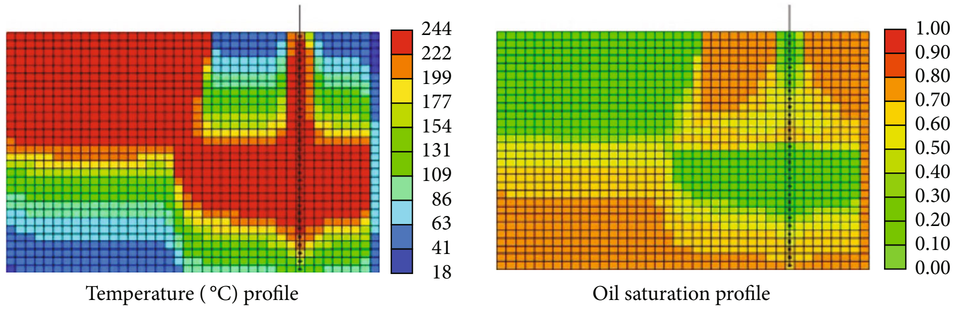
3.1.3. Production Characteristics. We designed two schemes for an infilled horizontal well, in which the infilled horizontal well was used as a production or steam injection well. The comparative analysis is presented in the following.

When the infilled horizontal well was used as an oil production well, heavy oil was produced nearby, the energy consumption and driving force were reduced, and the thermal efficiency was greatly improved. When the infilled horizontal well was used as a steam injection well, crude oil was driven into the SAGD steam chamber within a short distance by the steam, which greatly improved the thermal efficiency. Figure 6 shows that after the conversion on day 1338, compared to the conventional SAGD model, the oil production rate of the half-well pair model was increased from 42 t/d to 62 t/d by using the infilled horizontal well for oil production, and the oil production rate was increased to 47 t/d by using the infilled horizontal well to inject steam.

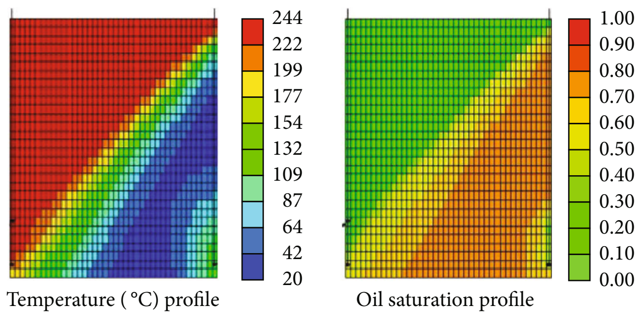
Table 3 shows that the recovery factors of the three methods were only slightly different. The recovery factor was increased by 1.6% when the infilled horizontal well was used to inject steam, which had the largest increase. Under the condition of continuous production from the horizontal well, the production time decreased from 3241 days to 2374 days, the entire well pair operation process was shortened by 867 days, the oil production rate increased by 2.8%, and the oil to steam ratio increased by 0.03. Infilled horizontal well-assisted SAGD production, which has great advantages in oilfield operations, further increased the peak stable production period, speed up the oil production, and reduced the oilfield investment payback period.

3.2. Model B: Interlayer Is Located above Steam Injection Well

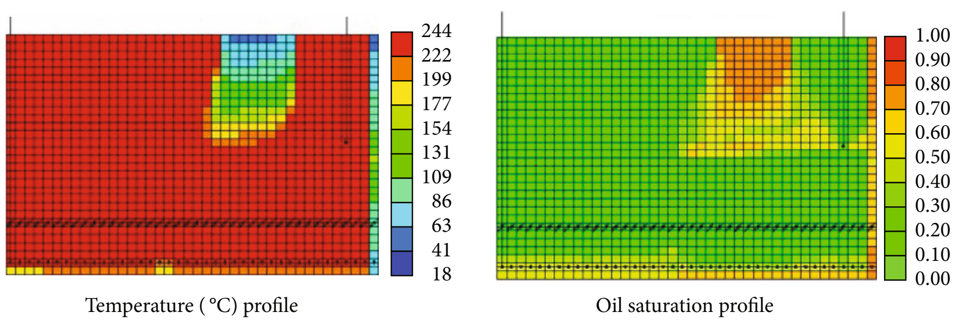
3.2.1. Temperature and Oil Saturation Distribution. The temperature and oil saturation profiles at different times for model B are shown in Figure 7. It can be seen from



(a) The 6th round (1360 d) huff and puff ($J = 1$) of infilled vertical producer



(b) The 6th round (1360 d) huff and puff ($I = 1$) of infilled horizontal injector between SAGD well pair



(c) The 6th round (1360 d) huff and puff ($J = 1$) of infilled horizontal injector above interlayer

FIGURE 8: Temperature profile and oil saturation profile of different schemes for model B.

Figure 7 that when the production reached 1600 d, the steam chamber expansion was similar to that of the model without an interlayer, and it also underwent a steam chamber ascending phase, lateral expansion phase, and descending phase. There was a triangular low-temperature zone at the bottom of the well pair boundary. Because of the occlusion by the interlayer, it was difficult for the steam chamber to expand upward, and the oil saturation remained at the initial saturation after 4.5 years of production. It can be seen from Figure 7 that the temperature of the oil layer above the interlayer increased to >100°C due to the long-term heating of the steam chamber below the interlayer.

3.2.2. Thermal Connectivity Analysis. When there was an interlayer located above the well, the vertical expansion of the steam was hindered by the interlayer. Although the steam could bypass the interlayer in the later stage of production and develop some of the oil reservoirs above the interlayer, it still increased the SAGD development time and reduced the production rate. Based on the above results, three methods involving an infilled well were designed to further improve the recovery rate of the SAGD for model B.

(1) An infilled vertical well was used to improve the production degree of area affected by the interlayer. The infilled vertical producer's affectable radius is generally less than 30 m. In addition, the SAGD steam chamber could extend a certain distance horizontally. Thus, the infilled vertical well was located 20 m from the SAGD well pair and 50 m from the left edge of the interlayer, with a length of 24 m

(2) The infilled horizontal well was used to assist the SAGD technique. An infilled horizontal well with a length of 400 m was located 40 m from and parallel to well P, so it was on the same horizontal plane as well P. This method maximized the use of the triangular cold oil area

(3) An infilled horizontal well with a length of 40 m was arranged above the interlayer. It was located 1 m away

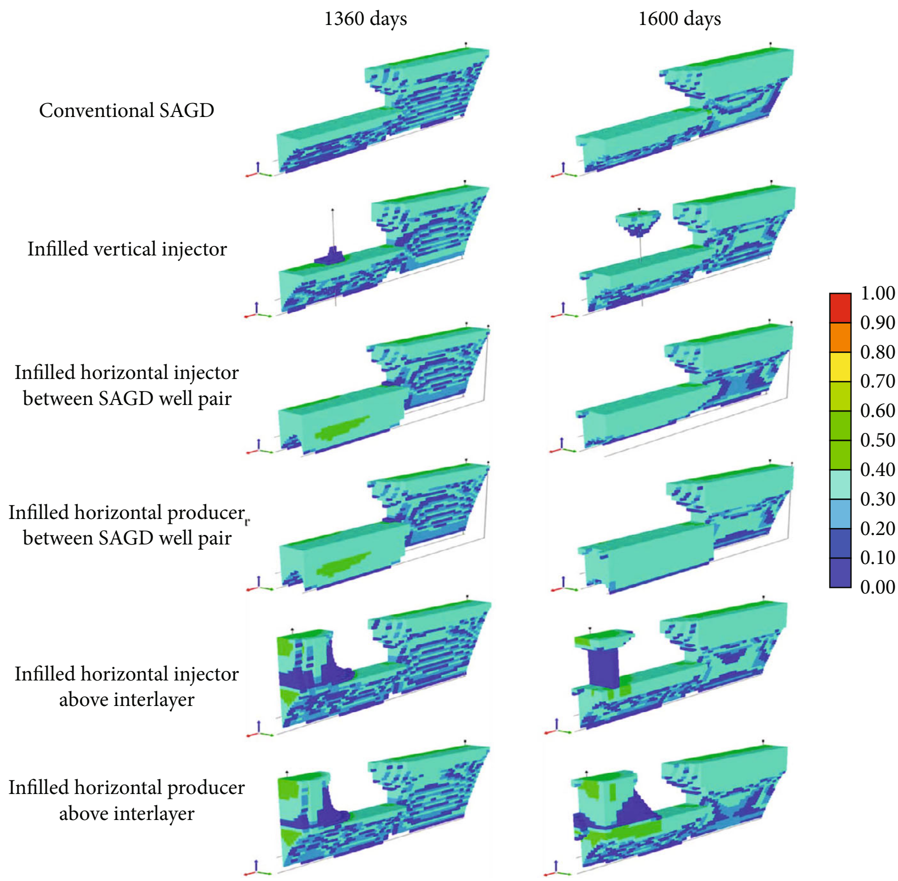


Figure 9: Gas saturation of different schemes for model B at different time.

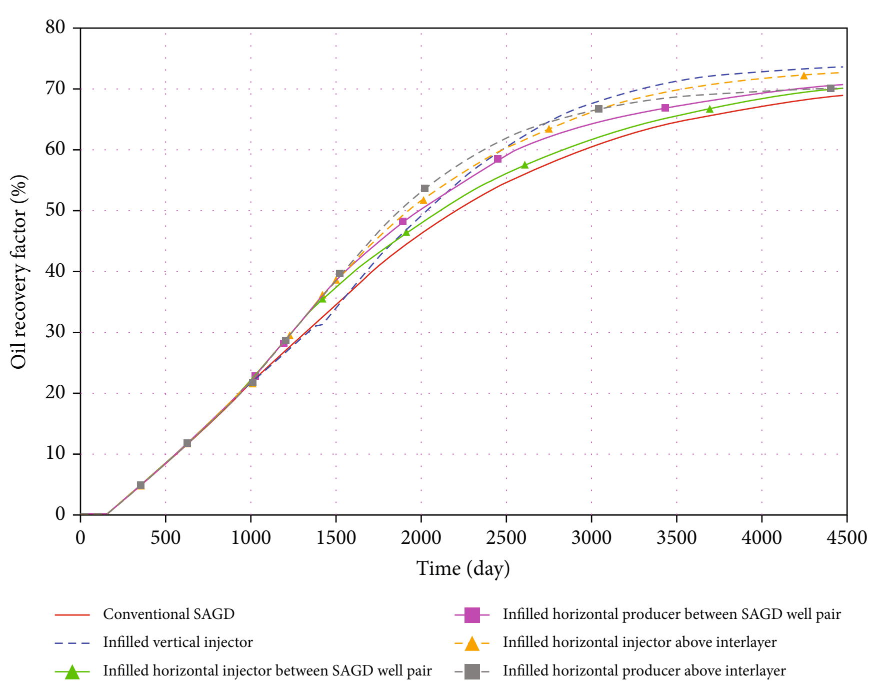


Figure 10: Production characteristics of the different schemes for model B.

Table 4: Comparison of production characteristics for model B.

Scheme	Time (d)	Cumulative steam injection (10^4 t)	Cumulative oil production (10^4 t)	Cumulative oil to steam ratio (cOSR) (f)	Oil recovery factor (%)	Oil recovery ratio (%)
Conventional SAGD	3600	282400	70830	0.251	65	6.59
Infilled vertical injector	3658	302082	78178	0.259	71.7	7.15
Infilled horizontal injector between SAGD well pair	3808	292687	73255	0.250	67.2	6.44
Infilled horizontal producer between SAGD well pair	3154	291185	71101	0.244	65.2	7.55
Infilled horizontal injector above interlayer	3802	303674	77358	0.255	71	6.82
Infilled horizontal producer above interlayer	2663	301456	69447	0.230	63.7	8.73

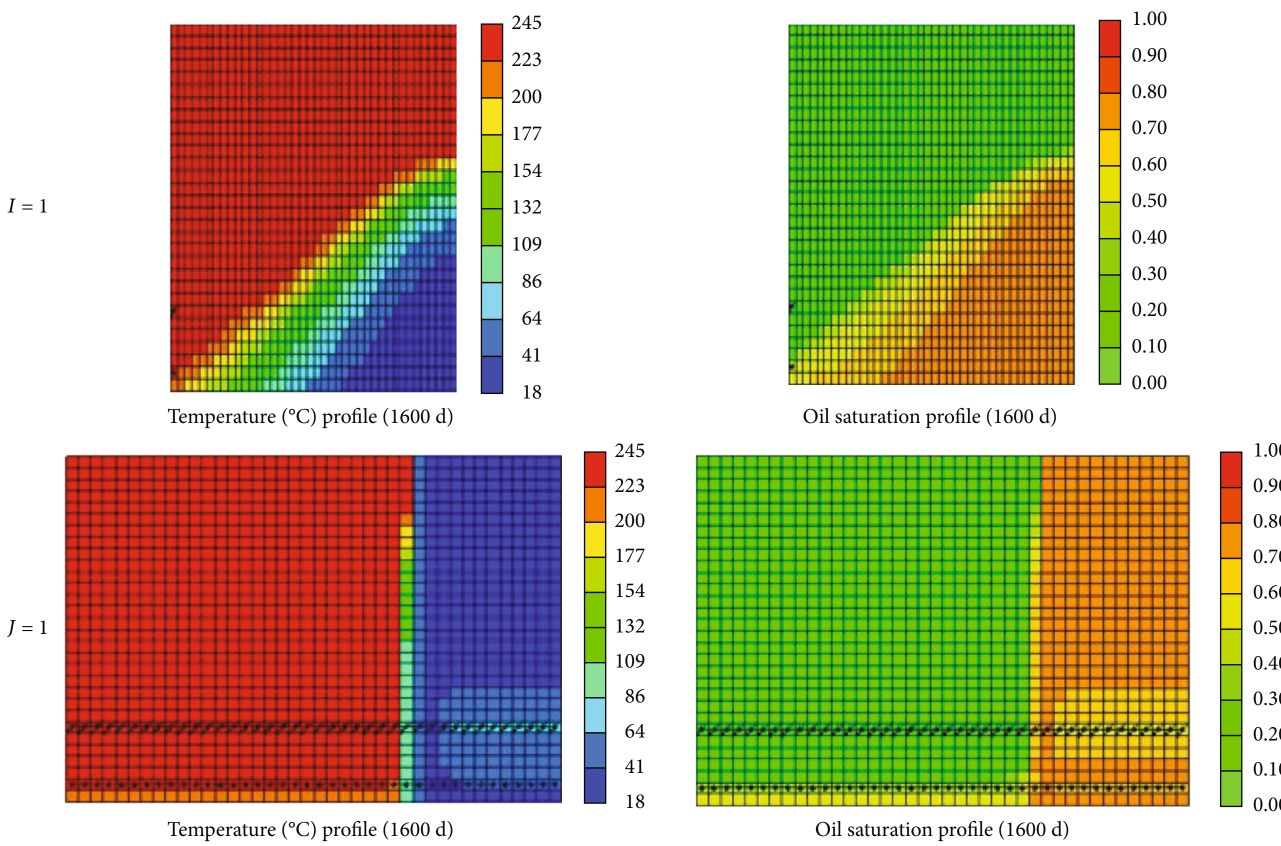
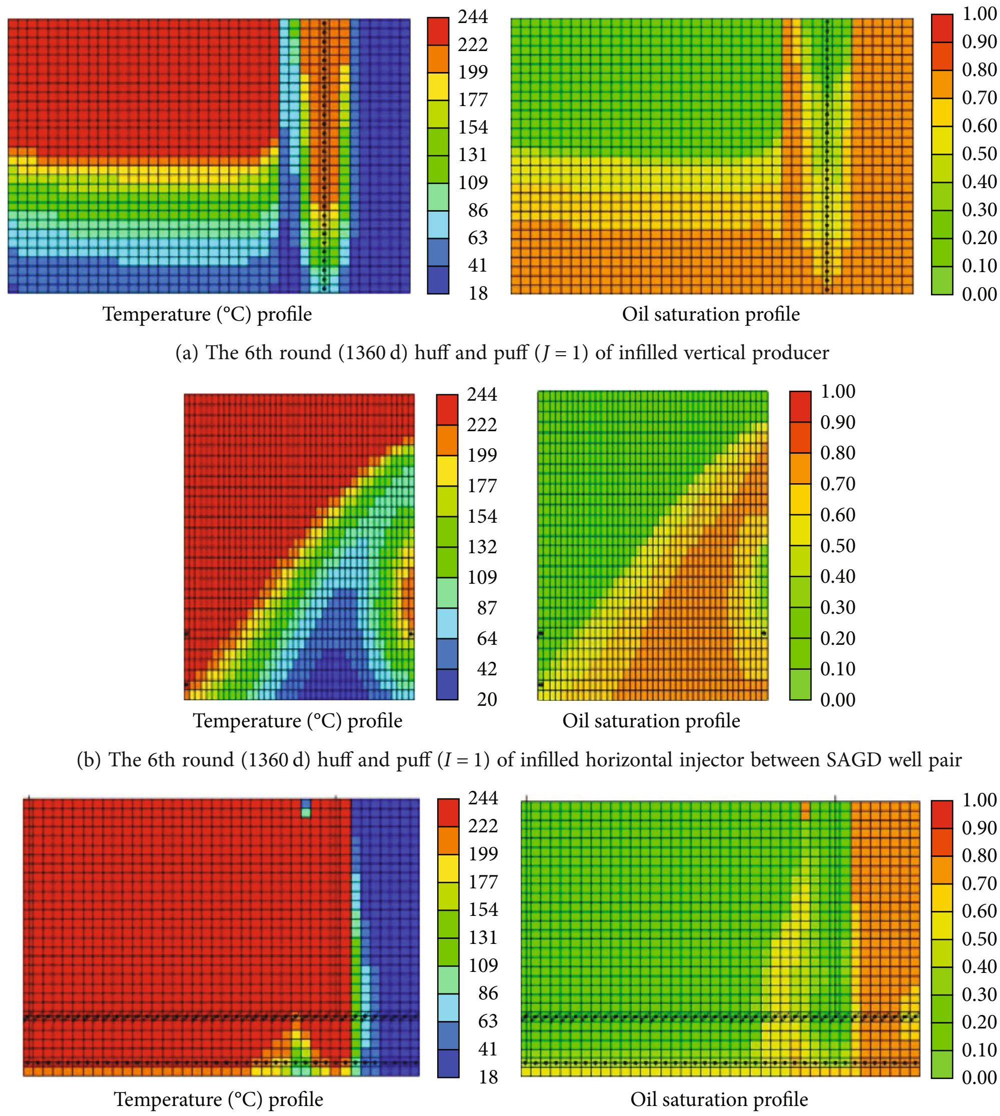


Figure 11: Temperature profile and oil saturation profile for model C.

from the bottom boundary of the interlayer; the well was distributed along the J direction, perpendicular to the plane in which wells I and P were located. The infilled well was 50 m from the left edge of the interlayer and perpendicular to the SAGD well pair

The temperature profiles and oil saturation profiles after different rounds of huff and puff for model B with different enhancement techniques are shown in Figure 8.

Figure 8(a) shows the temperature and oil saturation profiles after the sixth round huff and puff of infilled vertical well. When the production reached 1360 days, the temperature of the low-temperature zone between the infilled vertical well and the SAGD well increased to 120°C, establishing a good communication relationship. Figure 8(b) shows the temperature profile and oil saturation profile after the sixth round of huff and puff of the infilled horizontal well parallel to the SAGD well pair. The cold oil area between the SAGD well pair and the horizontal well has been heated to 60°C, and the interwell communication relationship has been initially established. At this time, it can be transferred to the horizontal well for steam injection or oil production. Figure 8(c) shows



(a) The 6th round (1360 d) huff and puff ($J = 1$) of infilled vertical producer

(b) The 6th round (1360 d) huff and puff ($I = 1$) of infilled horizontal injector between SAGD well pair

(c) The 6th round (1360d) huff and puff ($J = 1$) of infilled horizontal injector above interlayer

Figure 12: Temperature profiles and oil saturation profiles of the different schemes for model C.

the temperature profile and oil saturation profile after the sixth round of huff and puff of the infilled horizontal well. After six rounds of huff and puff, the steam chamber between the SAGD well pair and the horizontal well is completely connected. The heated interlayer forms a separator heating effect, which increases the temperature of the upper oil layer to 120°C. The heated crude oil has a certain flow capacity after its viscosity drops to 200–300 mPa·s. This provides better conditions for subsequent production.

Figure 9 shows the gas saturation of the different schemes for model B at different times. After the sixth round of huff and puff, the infilled wells significantly increased the volume of the steam chamber expansion compared to the traditional SAGD technique. Among them, the expansion speed of the steam chamber volume of the infilled vertical well mode was the lowest, and the volume of the steam chamber was the smallest at 1600 days. For the infilled horizontal producer above the interlayer, the expansion speed of the steam chamber volume was the fastest, and the steam chamber volume was the largest, so the remaining oil in the cold zone could be utilized better.

3.2.3. Production Characteristics. It can be seen from Figure 10 that when there was an interlayer above the well pair, the recovery rate reached 65%, which is equivalent to 68% in the homogeneous model.

When an interlayer existed, the SAGD production time was significantly prolonged. The use of an infilled well increased the oil recovery ratio. By 2022, the recovery degree of the basic model is expected to be 63%, and the recovery degree of the horizontal offset wells above the interlayer using steam injection and oil production will be 64.7% and 66%, respectively.

Table 4 shows that under the limitation of the economic oil to steam ratio of 0.12, the oil recovery factor of the infilled vertical well for the steam injection method is

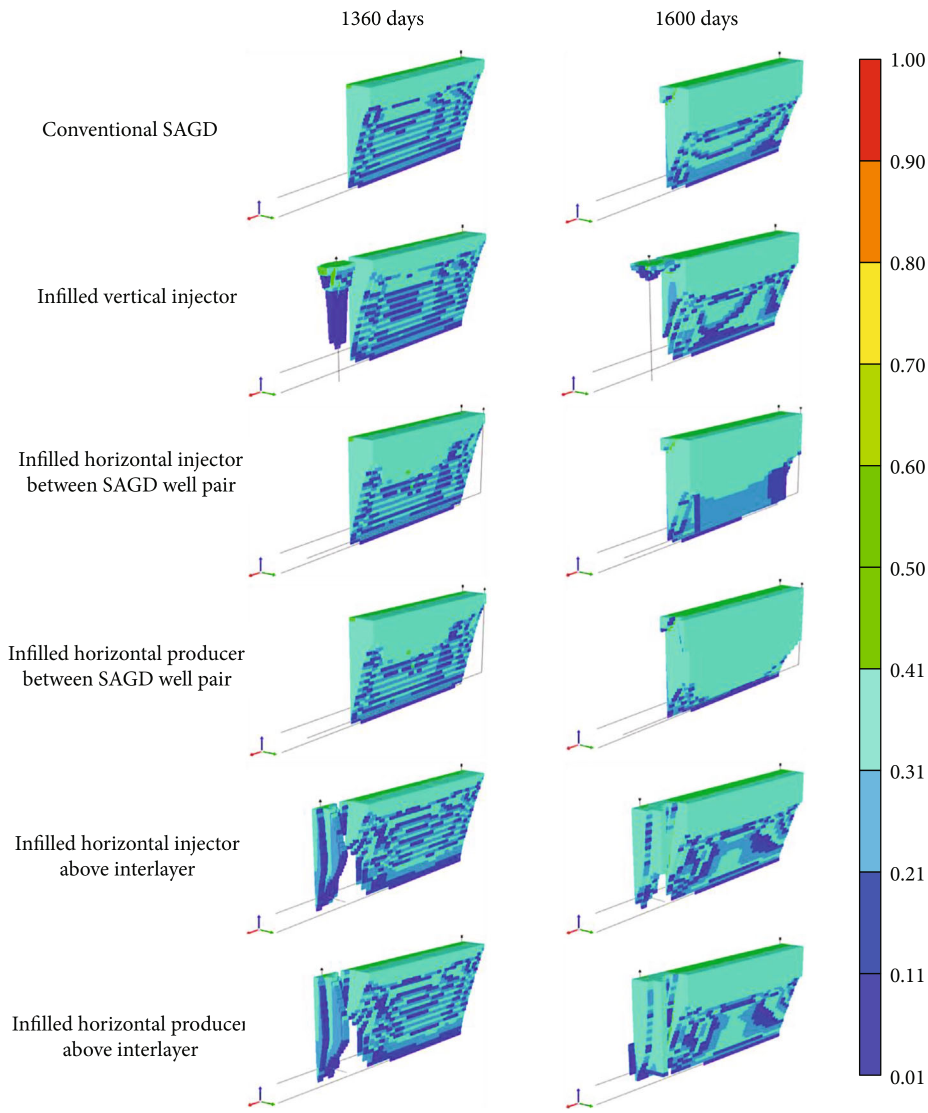


Figure 13: Gas saturation of the different schemes for model C at different times.

increased by 6.7%, and the oil production ratio is increased by 0.59%. The recovery factor of the infilled horizontal well located between the well pair for steam injection is increased by 2.2%, and the oil production ratio is increased by 0.96%. The recovery factor of the infilled horizontal well located above the interlayer used as a steam injector is increased by 6%. When the infilled horizontal well is located above the interlayer and used to produce oil, the horizontal well is easily submerged by the steam chamber, resulting in a limited increase in the oil recovery factor. From the perspective of enhanced oil recovery, the infilled vertical well directly increases the effective utilization of the actual reserves in the upper part of the oil layer. Because vertical wells have more advantages in terms of drilling and production control, their on-site application prospects are even broader.

3.3. Model C: Interlayer Is Located between SAGD Well Pair

3.3.1. Temperature and Oil Saturation Distribution. For model C, the interlayer was located in the middle of the SAGD well pair, so the reservoir located above the well pair and 130 m away from the toe of the well pair was not used, and the steam chamber was not developed in this area. The steam chamber of the other well section was uniformly developed. In the steam chamber development area, the oil saturation of the steam chamber was reduced to 0.15–0.2, and the temperature in the steam chamber was 240°C.

The temperature profile during the 1600 days of production (Figure 11) showed that in the connected area of the horizontal section, the expansion law of the steam chamber was similar to that of model A. There was no steam chamber in the unused area of the horizontal section. The oil reservoir within 5 m of the horizontal well was heated to 70°C due to the heat conduction of the steam injection wellbore and the oil production wellbore. Although there was no developed steam chamber in the horizontal well section close to the steam injection well, the oil saturation decreased to 55%. The oil was mainly produced in the preheating stage of the steam cycle. The crude oil was mainly produced in the preheating stage of the steam cycle. This is because long-tube

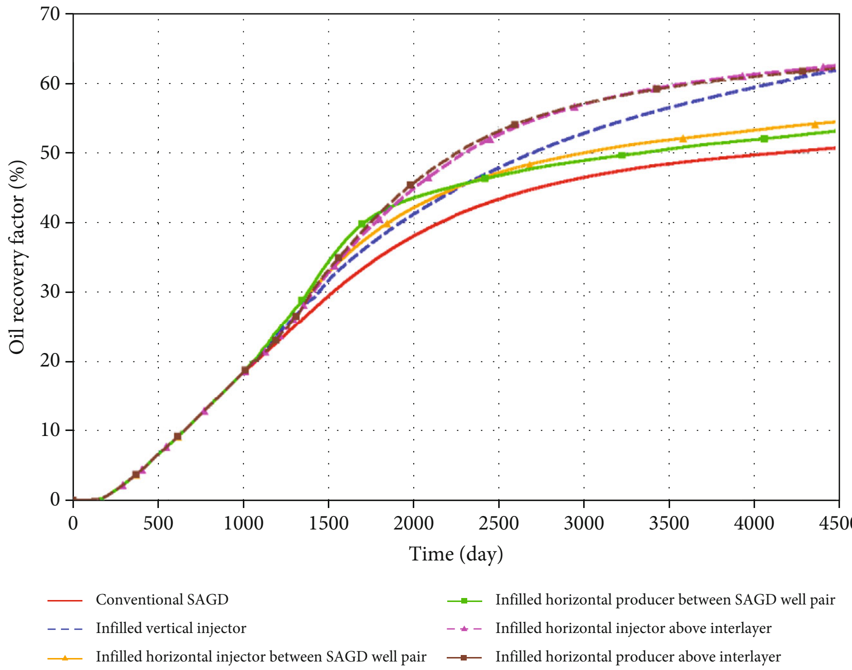


Figure 14: Production characteristics of the different schemes for model C.

steam injection and short-tube liquid production were used in the cycle preheating stage to heat the oil reservoir near the well, and the heated crude oil was produced from the short-tube horizontal well (Figure 11).

3.3.2. Thermal Connectivity Analysis. The existence of an interlayer between the wells hinders the vertical spread of the steam, resulting in a significant reduction in the development effect of the SAGD. We designed three infilled methods to further improve the recovery factor of the SAGD well pair for model C.

(1) An infilled vertical well was used to increase the utilization of the area affected by the interlayer. In addition, during the expansion stage of the SAGD steam chamber, the steam chamber could expand a certain distance laterally, so the horizontal distance between the infilled vertical well and the SAGD well pair was 20 m; the distance from the left edge of the interlayer was 50 m

(2) The infilled horizontal well technique was used, in which a horizontal well was drilled between the original SAGD well pair. The infilled horizontal well had a length of 400 m. The horizontal well and the SAGD steam injection well were at the same height, and 6 m away from the bottom of the reservoir. This type of infilled well maximized the use of the upper oil layer of the interlayer between the well pair

(3) An infilled horizontal well was placed perpendicular to the plane where wells I and P were located. The infilled horizontal well had a length of 40 m, which was at the same height as well I in the SAGD well pair, and 50 m from the left edge of the left boundary

Figure 12(a) shows the temperature profile and oil saturation profile after the sixth round of huff and puff of the vertical offset well. When the production reached 1360 days, the temperature of the low-temperature zone between the vertical well and the SAGD well increased to 70°C, establishing a good communication relationship. Figure 12(b) shows the temperature profile and oil saturation profile after the sixth round of huff and puff of the horizontal offset well parallel to the SAGD well pair. The cold oil area between the SAGD well pair and the horizontal well was heated to 70°C, and the interwell communication relationship had been initially established. At this time, it could be transferred to the horizontal well for steam injection or oil production. Figure 12(c) shows the temperature profile and oil saturation profile after the sixth round of huff and puff of the horizontal offset well perpendicular to the SAGD well pair and above the interlayer. After six rounds of huff and puff, the steam chamber between the SAGD well pair and the horizontal well was completely connected.

Figure 13 shows the gas saturation of the different schemes for model C at different times. After the sixth round of huff and puff, the infilled wells significantly increased the volume of the steam chamber expansion compared to the traditional SAGD technique. Among them, the expansion speed of the steam chamber volume of the infilled horizontal producer mode was the lowest, and the volume of the steam chamber was the smallest at 1600 days. For the infilled horizontal producer above the interlayer, the expansion speed of the steam chamber volume was the fastest, and the steam chamber volume was the largest, and thus, the remaining oil in the cold zone could be utilized better. The infilled vertical injector and infilled horizontal injector above the interlayer could utilize the remaining oil blocked by the interlayer.

Table 5: Comparison of production characteristics for model C.

Scheme	Time (d)	Cumulative steam injection (10^4 t)	Cumulative oil production (10^4 t)	Cumulative oil to steam ratio (cOSR) (f)	Oil recovery factor (%)	Oil recovery ratio (%)
Conventional SAGD	3494	216993	52728	0.243	48.4	5.06
Infilled vertical injector	4480	278275	67438	0.242	61.9	5.04
Infilled horizontal injector between SAGD well pair	3395	224424	56165	0.250	51.5	5.54
Infilled horizontal producer between SAGD well pair	3246	217024	54072	0.249	49.7	5.59
Infilled horizontal injector above interlayer	3601	262094	65359	0.249	60	6.08
Infilled horizontal producer above interlayer	2471	261223	57496	0.220	52.7	7.78

3.3.3. Production Characteristics. Compared with the basic SAGD model, the production degrees of the different offset wells were greatly improved (Figure 14).

By 2022, the recovery degree of the conventional SAGD model will be 48%, the recovery level of the infilled horizontal well for steam injection or oil production above the interlayer will be as high as 59%, and the recovery degree of the steam injection production using a vertical well will be 55.7%. The recovery degree is 51% for the horizontal offset well located between the well pair.

As can be seen from Table 5, for the infilled vertical injector, the oil recovery factor increases by 13.5%, and the oil recovery ratio increases by 5.04%. For the method of using the infilled horizontal wells between the well pair for steam injection or oil production, the remaining oil in the cold oil area can be extracted in the model for conventional SAGD. The recovery factor is greater than that of the basic model, and the oil production rate is increased by 0.5%. When the infilled horizontal well above the interlayer is used for steam injection, the oil recovery factor is increased by 11.6%, and the oil production rate is increased by 1%. Because the infilled horizontal well is at the same height as the injector of the SAGD well pair, it is easily submerged in the steam chamber when used for oil production. The recovery ratio of the infilled horizontal well is limited. From the perspective of enhanced oil recovery, the method of using infilled vertical wells and infilled wells above the interlayer directly increases the effective utilization of the oil reservoirs above the interlayer. The infilled horizontal well located above the interlayer is more difficult to drill.

4. Summary and Conclusions

The following findings were obtained from this study.

(1) For oil reservoirs without interlayers, the method of using infilled horizontal wells between the SAGD well pair can speed up the lateral connection of the steam chamber, reduce the residual oil saturation, increase the final recovery rate, and ultimately reduce the steam to oil ratio

(2) For a well pair with an interlayer located above the SAGD well pair, the infilled vertical injector method can increase the recovery rate by 6.7%. The infilled horizontal well between the well pair for steam injection or oil production can increase the recovery factor by 2.2% and 0.2%, respectively. Using the infilled horizontal well located above the interlayer for steam injection can increase the oil recovery by 6%; the infilled horizontal well can increase the oil recovery factor to a limited extent. It is recommended that in an SAGD well pair with an interlayer above the well, an infilled vertical well should be used for steam injection to increase the oil recovery factor

(3) For an interlayer located in the middle of the well pair, when the infilled vertical well was used for steam injection, the recovery rate increased by 13.5%. When the infilled horizontal well between the well pair was used for steam injection or oil production, the SAGD well pair was not used. The oil layer above the interlayer had a low degree of recovery improvement. When the infilled horizontal well above the interlayer was used for steam injection, the oil recovery rate of the reservoir was increased by 11.6%. The increase was limited. It is recommended that for an interlayer in the middle of the well pair, a vertical well should be used for steam injection to increase the recovery rate

(4) For a well pair with low production levels in the horizontal section that is blocked by interlayers, the infilled vertical well method can increase the recovery rate by 5% to 13%. In addition, vertical wells have advantages in drilling and production control and have good application prospects

Data Availability

All data used to support the findings of this study are available from the corresponding authors on request.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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