Visualization Experimental Study on Well Spacing Optimization of SAGD with a Combination of Vertical and Horizontal Wells

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ABSTRACT: For oil sand reservoirs, the steam-assisted gravity drainage (SAGD) technique is one of the most efficient thermal recovery technologies. However, the high oil viscosity and the severe heat loss seriously affect the production effect of SAGD in developing thin oil sand reservoirs by the traditional SAGD technology. Therefore, it is essential to improve the SAGD technology to enhance the recovery of the thin oil sand reservoir. In this paper, SAGD with a combination of vertical and horizontal well (VH-SAGD) technology was adopted, and the influence of different well spacings (horizontal distance between vertical steam injection wells and horizontal production wells) on the development of steam chambers was investigated. By the similarity criterion, the experimental parameters were obtained. After that, an improved 2D visualization physical model was designed with 9 × 9 high-precision thermocouples installed inside the device to monitor the real-time temperature. This experimental physical model can not only accurately capture the temperature distribution but also display the continuous change process of the chamber inside the model by the visible window. Finally, different well spacing cases (10, 15, and 20 cm) were tested to observe the development of the steam chamber and analyze the production data. Both the temperature distribution and visual window showed that the steam chamber has four obvious stages, and reasonable well spacing can promote the development of the steam chamber. When the well spacing is relatively small, the unswept area of the cold oil on both sides is large, and the area of the steam chamber overlaps more. When the well spacing is relatively moderate, the steam chamber is the most complete and the recovery factor is the highest. When the well spacing is relatively large, although the unswept area of the cold oil on both sides is small, the middle cold oil area is larger than the previous two groups. Therefore, the best well spacing for oil sand reservoirs of about 15 m thickness is 15−20 m, where the VH-SAGD method has a better displacement effect and higher oil recovery. The experimental conclusions can provide theoretical support for the production of thin oil sand reservoirs.

1. INTRODUCTION

Although the heavy oil reserves account for more than 70% of the world’s oil reserves,1−3 it is relatively difficult to exploit heavy oil because of the high viscosity of heavy oil and the serious heterogeneity of the reservoir.4−5 Steam-assisted gravity drainage (SAGD) is an advanced technology for the exploitation of high-viscosity oil.6−9 SAGD uses an upper horizontal well to inject the steam into the reservoir.10−13 During the high-dryness steam injection, the steam overlaps and forms a steam chamber in the stratigraphic reservoir.14−17 With the injection volume increasing, the steam chamber expands upward and laterally to exchange heat with crude oil to form oil drainage channels. The heated crude oil decreases in viscosity and flows downward to the bottom horizontal well under the action of gravity.

Sasaki18 used 2D physical simulation experiments to study the dual-horizontal well SAGD in the growth process of the steam chamber. The shape outline and the temperature distribution of the initial steam chamber are visualized by the thermal video images, and the relationship between the temperature distribution and the intersection of the steam chamber is obtained. Boyle et al.19 studied the three earliest SAGD well groups in the Senlac oilfield in Saskatchewan, Canada, and found that the highest recovery factor of the well group was 52%. Akin20 proposed a linear geometrical and mathematical model for gravity drainage during steam injection in heavy oil reservoirs and tar sands. His experiments observed that the shape of the steam chamber was an inverted triangle whose vertex was fixed at

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the bottom of the production well. Given the response of different reservoir parameters (initial injection capacity, mobile water saturation, and reservoir heterogeneity) to the SAGD process in the Cold Lake, Tavallali et al.\textsuperscript{21} used a fully implicit reservoir thermal simulation system to conduct sensitivity analysis on the SAGD of the improved well type and identify the most promising new well configuration. Zargar et al.\textsuperscript{22} developed an analytical SAGD model with the constant injection rate from three stages (encompassing steam chamber rise stage, sideways expansion stage, and the confinement phases stage) to evaluate the SAGD performance. Canbolat\textsuperscript{23} analyzed the variation of heat transfer behavior by conduction and convection on heavy oil production using heat fluxes via the co-injection of noncondensable gas during SAGD. His results showed that an adequately large concentration at the uppermost part of the chamber decreased the heat flow at the edge. Besides, conduction was the primary heat transfer method only in the steam injection stage. Heidari et al.\textsuperscript{24} put forward a new semi-analytical SAGD model to study the effects of drainage height and reservoir permeability on production performance. In this model, the heat conduction problem ahead of the interface is solved by the heat integration method in an arbitrary orthogonal coordinate system under unsteady-state conditions. Gotawala and Gates\textsuperscript{8} used the linear stability theory to examine the stability of the interface between the steam chamber and oil sands, and the results show that the stability is controlled by the difference between the energy content-weighted Darcy–Rayleigh numbers of the steam/water phases (displacing fluid) and the oil phase (displaced fluid). Also, the chamber edge is unstable when the steam quality at the edge exceeds about 50%. Barillas et al.\textsuperscript{25} idealized a homogeneous model to analyze the effect of permeability barriers and vertical permeability on cumulative oil. The steam optimization results show that heterogeneity and vertical permeability had a major influence on oil recovery and that the optimal steam rate varies depending on the reservoir characteristics.

The Canada Tangleflags North\textsuperscript{26} has a water cut of more than 90% after being produced by a traditional development method. After the SAGD with the combination of vertical and horizontal wells (VH-SAGD, see Figure 1) technology was used to inject steam, the water cut dropped to 60% and the oil production increased. Like the dual-horizontal well SAGD, the VH-SAGD method\textsuperscript{27–29} is used for steam injection from an upper vertical well and oil exploitation from a lower horizontal well. The steam injected from the upper vertical well heats the reservoirs and moves upward and sideways to form a steam chamber. The crude oil and condensate liquid flow into the lower horizontal well under the action of gravity. However, the VH-SAGD method can effectively improve the uneven development of the steam chamber caused by reservoir heterogeneity, and the reservoir engineering scheme adjustment is a more flexible technology than the conventional dual-horizontal well SAGD method. Gao et al.\textsuperscript{30} numerical simulation results showed that the reservoir can be developed efficiently by implementing the SAGD process using existing vertical wells and horizontal wells to be drilled following steam stimulation. Zhang\textsuperscript{31} studied the VH-SAGD technology in ultra-heavy oil reservoirs and improved the horizontal well distribution parameters. To solve the difficulties in setting oil well pumps and insufficient submergence depth, a drilling test to connect the dual-horizontal well SAGD and the vertical well was performed by Nie et al.\textsuperscript{32} Ghahfarokhi and Kleppe\textsuperscript{33} researched the applicability of thermal well-testing analysis in estimating the swept zone after VH-SAGD production. The results of their work show good agreement between the calculated and simulated values of swept volume, swept zone permeability, and skin factor for both vertical and horizontal wells. Forouzanfar et al.\textsuperscript{34} introduced a new methodology for the estimation of the location of horizontal and vertical wells, which can maximize the life-cycle net-present-value of production from a given reservoir.

Due to little visual research on the VH-SAGD and almost no systematic experimental study, it is necessary to carry out systematic experimental work on the VH-SAGD. Based on the improved 2D visual physical experiment, this paper first optimized well spacing by capturing the development behavior of the steam chamber, characterizing the remaining oil distribution, and analyzing the production data.

2. RESULTS AND DISCUSSIONS

2.1. Development Behavior of Steam Chamber. In the actual field scale model, under the condition of large well patterns, injection-production well can be swept. This experiment is used to study the influence of different well spacings on steam chambers. Therefore, only a pair of vertical and horizontal wells are considered to eliminate the influence of other well patterns. In this paper, based on existing experimental...
experience and current methods, a physical model was designed to carry out the experiment. The development of steam chambers was observed, and the production data were analyzed during the experiment. The experimental reservoir reserves are 989 mL, the injection steam temperature is 400 °C, the injection steam speed is 10 mL/min, and the production time is 240 min. The output of oil and water was recorded regularly, and the development of the steam chamber and the change of temperature distribution in each period were monitored.

2.1.1. 10 cm Horizontal Distance. Figure 2 shows the development of the steam chamber and the change of temperature distribution when the horizontal distance between the vertical steam injection well and the horizontal producing well is 10 cm. The red zone reflected the high-temperature area, the yellow zone reflected the area of the steam chamber, the green zone reflected the area swept by the steam, and the blue zone reflected the area where the steam has not reached. As shown in Figure 2, the steam chamber had experienced four stages: formation stage, longitudinal expansion stage, lateral expansion stage, and descent stage. At the beginning of the production stage (t = 10 min), the steam chamber expanded fast along the vertical direction of the vertical injection well. However, the area of the steam chamber was not large and drainage ability was limited. The heavy oil was mainly produced by steam driving with the obvious dragging phenomenon (t = 20 min). The steam chamber expanded rapidly upward, and the oil drainage capacity was gradually enhanced. The heavy oil produced mode transferred from steam flooding to SAGD, and oil drainage channels were gradually formed between the injection-production well (t = 60–100 min). After the steam chamber reached the reservoir top (t = 100 min), steam started to develop laterally, while the cold oil area in the middle decreases gradually (t = 140–240 min).

2.1.2. 15 cm Horizontal Distance. Figure 3 shows the development of the steam chamber and the change of temperature distribution under the 15 cm horizontal well spacing. With the formation of the steam chamber (t = 10 min), the dragging effect of the steam chamber above the production well was more obvious (t = 20 min). Steam flowed to the production well and the oil drainage channel began to form (t = 60 min). This phenomenon indicated that the heavy oil is produced by the combined action of steam flooding and drainage effects. As the steam chamber began to expand horizontally after developing vertically to the top, the lateral extension of steam is more full (t = 100 min). Then, the steam chamber went downward slowly and heated the below cold oil area and heated the heavy oil, and condensate steam was produced from the production well (t = 100–180 min). After
180 min, the steam chamber expanded slowly and the production process entered the depletion stage ($t = 180 - 240$ min).

2.1.3. 20 cm Horizontal Distance. Figure 4 shows the development of the steam chamber and the change of temperature distribution when the horizontal distance is 20 cm. At the beginning ($t = 10 - 60$ min), the injection-production pressure difference made the steam go along with the injection-production wells. Longitudinally, the shape of the steam chamber was slender at the top and wide at the bottom, with a small height. During this period, the heavy oil was mainly driven by steam, and the temperature distribution moved downward. Then ($t = 60 - 100$ min), the steam chamber began to go upward with the increase in temperature. The rising steam heated the top oil, and the heavy oil flowed down the drainage channel to the producer well. In this process, the heavy oil flow was mainly affected by gravity drainage. Subsequently ($t = 100 - 180$ min), as the steam was hindered by the boundary of the model, the steam chambers began to expand laterally. With a large amount of oil being produced at the top of the reservoir, the lateral expansion rate of the steam chamber slowed down and the steam chamber was gradually connected at the top. At this time, the heavy oil was still affected by gravity drainage. At the later stage ($t = 180 - 240$ min), the steam chamber expanded to the cold oil area just above the horizontal well at a slow speed. Due to the close distance between the steam chamber and the horizontal well, the steam broke through to the horizontal well and channeled along the oil drainage channel. The cold oil area directly above the horizontal well decreases gradually, and the development of the steam chamber stagnates.

The result showed that the displacement effect of heavy oil is the best under the 15 cm well spacing. For the smaller horizontal well spacing, the sweep area of the steam chamber was also relatively small and the area of the cold oil area on both sides was larger. For the larger horizontal well spacing, the upward expansion ability of the steam chamber was weakened, and the steam cannot be fully expanded. The area of the cold oil area in the middle was larger than the previous two groups, and there is no effective thermal connection between the two steam injection wells to heat the lower heavy oil.

2.1.4. Area Ratio. Figure 5 shows the dynamic trend of the area ratio (the ratio of the area of the steam chamber to the entire area of the visual window of the sand layer) for the combination of vertical and horizontal wells with different horizontal well spacings. As shown in Figure 5a, in the early stages (about $t = 0 - 40$ min), the area of the steam chamber under the different spacings is roughly the same, and as the steam chamber develops, the area ratio of the 20 cm case was

Figure 3. Case where the horizontal distance between the vertical injection well and the horizontal producing well is 15 cm. (a) Change of the steam chamber. (b) Change of the temperature field.
smaller than that of the 10 cm case and 15 cm case. When the steam chamber on both sides was connected to the 20 cm case, the area ratio was gradually higher than 10 cm. The steam chamber was fully developed when the well spacing is 15 cm.

Figure 4. Case where the horizontal distance between the vertical steam injection well and the horizontal producing well is 20 cm. (a) Change of the steam chamber. (b) Change of the temperature field.

Figure 5. Comparison of the area ratio with different cases. (a) Area ratio change with time. (b) Area ratio under different well spacings.
Therefore, the area ratio was always higher than that of the other two cases (Figure 5b).

### 2.2. Production Dynamic

#### 2.2.1. Oil Production Rate

Figure 6 shows the dynamic trend of the oil production rate for the different well spacings. From the development of the steam chamber shown in Figures 2, 3, and 4, the oil production rate can be divided into four stages. The first stage reflected the formation of the steam chamber (about \( t = 0 \sim 40 \text{ min} \)), and the characteristic of the oil production rate in this stage showed an obvious increasing trend. The second revealed longitudinal development of the steam chamber (about \( t = 40 \sim 120 \text{ min} \)), and the oil production rate showed a decreasing trend until it stabilized. The third stage indicated the lateral expansion of the steam chamber (about \( t = 120 \sim 180 \text{ min} \)), and the oil production rate showed a continuous downward trend until it stabilized again. The last stage represented the descent of the steam chamber (about \( t = 180 \sim 240 \text{ min} \)), and the oil production rate continued to decline continuously. The comparison results showed that the overall oil production rate of the 10 cm case was significantly lower than that of other cases.

#### 2.2.2. Water Cut

The trend of water cut was similar to the trend of the oil production rate with four obvious stages. As shown in Figure 7, the trend of water cut was decreasing in the first stage, increasing until stable in the second stage, increasing again in the third stage, and increasing until stable again in the last stage. In the two early stages, the water cut of the 20 cm case is higher than that of other cases. However, the water cut of the 10 cm case is higher than that of other cases in the two late stages.

#### 2.2.3. Injection-Production Pressure Difference

The heavy oil started to flow because the heavy oil viscosity decreased as the temperature increased. The existence of injection-production pressure difference reflected the displacement of steam in the early stage. On the one hand, the injection-production pressure difference decreased fast in the process of displacement from steam flooding to gravity drainage. Then, the injection-production pressure difference became constant due to the stable gravity drainage established, as shown in Figure 8. On the other hand, the farther the well spacing between injection and production wells, the greater the displacement pressure difference required. Hence, the farthest horizontal well spacing had the maximum injection-production pressure difference in the early stage. In the stable gravity drainage stage, the injection-production pressure difference under different injection-production well spacings became the same because the production rate was very close and reservoir permeability was unchanged.

#### 2.2.4. Cumulative Oil–Steam Ratio

Similar to the dynamic behavior of the oil production rate, the trend of the cumulative oil–steam ratio was increased in the early stage and continued to decrease in the late stages (Figure 9). In the early stage, although the cumulative oil–steam ratio of the 10 cm case was higher than that of the 20 cm case, the trend reversed in the three late stages. There is no doubt that the cumulative oil–steam ratio of the 15 cm case was far higher than that of other cases.

#### 2.2.5. Recovery Factor

Figure 10 shows the dynamic trend of the recovery factor for the combination of vertical and horizontal wells with different horizontal well spacings. On the one hand, although the difference of the recovery factor between the 10 cm case and the 20 cm case can be ignored in the two early stages (about \( t = 0 \sim 100 \text{ min} \)), the recovery factor of the 20 cm case was far larger than that of the 10 cm case in the two late stages (\( t = 100 \sim 240 \text{ min} \)). On the other hand, the recovery factor of the 15 cm case was higher than other horizontal spacings in the whole stages.
3. CONCLUSIONS

Due to little visual research on the VH-SAGD and almost no systematic experimental study and, meanwhile, because the difference and the process of steam chamber development after changing well spacing is not very clear, this paper carried out an experimental investigation on this to observe the production process and explore the production mechanism by using the improved 2D equipment. Based on the improved 2D visual physical experiment, this paper first optimized the well spacing by capturing the development behavior of the steam chamber, characterizing the remaining oil distribution, and analyzing the production data, and the following conclusions were drawn:

1. The process of steam chamber development has four stages: formation stage, longitudinal expansion stage, lateral expansion stage, and descent stage. In the formation stage, steam went along with the injection-production wells, and the steam chamber expanded fast. In the longitudinal expansion stage, the steam chamber went upward with the increase in temperature. The rising steam heated the top oil, and then, the heavy oil flowed down the drainage channel to the producer well. As the steam was hindered by the boundary of the model, the steam chambers began to enter the lateral expansion stage.

2. In this stage, with a large amount of oil being produced at the top of the reservoir, the lateral expansion rate of the steam chamber slowed down. In the descent stage, the steam chamber expanded slowly and stagnates gradually.

3. In the 2D visualization physical experiment, when the well spacing between vertical and horizontal wells is 15 cm, the steam sweep is more sufficient, the combined effect of flooding and drainage is the best, and the recovery factor is the highest. For the actual about 15 m thin oil sand reservoir, the best well spacing between vertical and horizontal wells is 15−20 m.

4. The VH-SAGD can efficiently solve the problems of large reservoir thickness and small longitudinal expansion of injected steam in the thin oil sand reservoir. Reasonable well spacing between vertical and horizontal wells can increase the development of the steam chamber and greatly increase the swept area of the steam chamber.

Furthermore, the findings of this study help for better understanding that changing the vertical well spacing can affect the lateral development of the steam chamber, which can be used to enhance the oil recovery of thin layer oil sand reservoirs especially.

4. EXPERIMENTAL MATERIALS AND METHODS

4.1. Similarity Parameter. Similar scale modeling is the process of transforming a field-scale reservoir prototype into a laboratory-scale reservoir model through similar criteria. The similarity criterion means that the dimensionless form equations of two similar phenomena are the same, and they have the same dimensionless form solution. However, in the actual physical simulation process in laboratories, due to the limitations of experimental conditions, it is possible that the physical model slightly deviates from the reservoir prototype. Therefore, we need to choose the key physical quantities that play a decisive role in the development of the steam chamber.

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role in the physical experiment to satisfy the similarity theory. According to the known relevant actual onsite production parameters, the following three criteria were obtained.

First, gravity is the main driving force, and the viscous force is the main resistance in the SAGD process. Therefore, the ratio of gravity and the viscous force is considered an important index. Second, SAGD thermal recovery mainly relies on steam injection to increase the temperature of and reduce the viscosity of the heavy oil. Therefore, the ratio of steam injection volume to movable oil volume is very important for the SAGD simulation. Thirdly, the criterion number represents the dimensionless production time of the SAGD process, and the main simulated physical parameter is the production time, which is used to realize the conversion between the production time of the prototype and the model.

4.2. Experimental Materials. The degassing and dehydrated heavy oil (asphaltene = 15.1%, resin = 23.78%, aromatic = 43.57%, and saturate = 17.55%) from the McCann River reservoir in Canada was selected for this experiment. The relationship between viscosity and temperature was measured by an MCR302 rheometer of Anton Paar, as shown in Figure 11. The oil sand samples from CNPC’s Canadian oil sand work area were adopted. Distilled water was used for the experiment. Steam was produced by a steam generator.

4.3. 2D Visualization Experiment. 4.3.1. Parameters and Schemes. According to similarity criteria, the adaptive parameters of the 2D experimental model were determined, as shown in Tables 1 and 2. In the model, the thickness of the reservoir was 15 cm, and the thickness of the upper clay was 32 cm. A silicone band with a width of 3 cm was placed between the clay layer and the reservoir. Each production well was located below the injection well, whose distance was 3 cm. The well spacing of the production well was 2 cm from the bottom edge. The length of the perforation interval of the vertical steam injection well was 7 cm. The parameters of the 2D experimental scheme are shown in Table 3. The relative position of the well group is shown in Figure 12. The development of the steam chamber, the change of the temperature distribution under this condition, and the production data during the experiment were studied with a 2D visual physical device.

4.3.2. Apparatus. ISCO high precision plunger pump: produced by Teledyne ISCO in the United States, which belongs to ISCO D series plunger pumps; it can provide high pressure, low velocity, high precision, no pulse flow, and other functions for pumping work such as metering, feeding, burdening, distribution, and so on. The control panel has a number of interfaces for analog pressure, analog flow rate input and output, and digital signal input. Steam generator: generates and injects high-temperature and high-dryness steam into the model. The temperature range is 0−450 °C, and the pressure range is 0−25 MPa. 2D visual large plate model: the internal size of the model is 500 mm × 500 mm, the working pressure range is 0−3 MPa under normal pressure, and the maximum working temperature is 280 °C. As shown in Figure 13, the visible parts of

Table 2. Parameters of the 2D Reservoir Model and Experimental Model

| parameters                        | 2D reservoir model | 2D experimental model |
|-----------------------------------|--------------------|-----------------------|
| physical dimension (m)            | 50 × 15            | 0.5 × 0.15            |
| horizontal distance of the injection-production well (m) | 10/15/20          | 0.1/0.15/0.2         |
| porosity (%)                      | 33.42              | 40.3                  |
| permeability (10−3 μm²)           | 3252               | 31201                 |
| initial oil saturation (%)        | 74.16              | 73.9                  |
| viscosity at 50 °C (mPa·s)        | 15623              | 961                   |
| density at 50 °C (kg/m³)          | 1082               | 946                   |
| steam injection rate (t/d)        | 0.35               | 0.0144 (10 mL/min)    |

Table 3. Parameters of the Different Well Spacings of the 2D Experimental Scheme

| parameters                        | 10 cm horizontal distance | 15 cm horizontal distance | 20 cm horizontal distance |
|-----------------------------------|---------------------------|---------------------------|---------------------------|
| reservoir thickness (cm)          | 15                         | 15                        | 15                        |
| thickness of the clay (cm)        | 32                         | 32                        | 32                        |
| silica band width (cm)            | 3                          | 3                         | 3                         |
| producer well to injection well bottom distance (cm) | 3                         | 3                         | 3                         |
| producer well to bottom edge distance (cm) | 2                          | 2                         | 2                         |
| perforation section of vertical steam injection well (cm) | 7                          | 7                         | 7                         |

Figure 12. Relative position of the well group. (a) 10 cm horizontal distance, (b) 15 cm horizontal distance, and (c) 20 cm horizontal distance.
the device are made of two high-temperature and high-pressure resistant borosilicate glass with a thickness of 40 mm bonded together. The temperature can be above 400 °C, and the pressure can be above 3 MPa. High-precision and high-temperature thermocouples were installed in the 2D physical devices, and the temperature data of each part of the model were collected in real time. In this experiment, a total of 81 temperature measuring points were arranged in 9 rows and 9 columns, and the temperature changes inside the model were monitored in real time.

4.3.3. Procedures. The flow diagram of 2D experiments is shown in Figure 14, and the procedures follow as:

1. According to the experimental scheme, two vertical steam injection wells and a horizontal production well were installed in the designated position.
2. The sandpack model with proper porosity and permeability was prepared. Silica sands with 60 mesh were used

Figure 13. 2D physical model. (a) 2D visualization appearance of a large flat plate. (b) 2D visualization interior of a large plate.

Figure 14. Flow diagram of 2D experiments.
to pack the 2D model first, and then, the bolts on the back of the model were tightened to compress the sand layer for proper porosity and permeability. Finally, it was pressurized to test the antileaking performance.

(3) After pressurization, the model was saturated with distilled water after vacuuming for 6 h. Then, the model was saturated with an oil sample in an environment of 50 °C, the backpressure valve is opened, and the pressure value is set as 1 MPa. Until there was no water and oil produced, the initial oil saturation, porosity, and permeability were calculated.

(4) After the model achieved a stable state, the simulation of SAGD exploitation was carried out. The injection rate of steam (water equivalent) was set to 10 mL/min.

(5) During the experiment, the data and image acquisition system captured the temperature changes of 81 temperature sensors and steam chamber development dynamics images, respectively. At the same time, the produced oil and water were collected and recorded.

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■ NOMENCLATURE

\( g \), gravitational acceleration, \( m/s^2 \)
\( h \), thickness of the reservoir, \( m \)
\( i \), gas injection intensity, \( t/d \)
\( K \), permeability, \( 10^{-3} \mu m^2 \)
\( L \), length of the horizontal well, \( m \)
\( n \), viscosity temperature characteristic parameter of the crude oil
\( t \), production time, \( s \)
\( \phi_{p} \), measure of the exploitation degree, \% 
\( \alpha \), thermal diffusivity, \( m^2/s \)
\( \Delta S \), oil saturation, \% 
\( \mu_o \), dynamic viscosity of the formation crude oil, \( mPa\cdot s \)
\( \nu_s \), kinetic viscosity of steam, \( m^2/s \)
\( \pi_f \), darcy formula modified with \( \psi \Delta S \)
\( \pi_w \), ratio of flow to storage capacity
\( \rho_o \), density of the crude oil, \( kg/m^3 \)
\( \psi \), porosity, %

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