Convection beyond the Steam Chamber Interface in the Steam-Assisted-Gravity-Drainage Process

Fei Wang, Zhengda Yang, Xinwei Wang, and Riyi Lin*

ABSTRACT: In the steam-assisted-gravity-drainage (SAGD) process, heat energy is transferred from the steam chamber to the farther cold reservoir by conduction and convection mechanisms, so as to reduce the oil viscosity. In previous research works, although it was proved that convection is an indispensable part of the heat-transfer process, there is still a controversy about the formation mechanism of heat convection. In this study, an analytical mathematic model was proposed to explore the convective heat transfer in SAGD operation. Typically, this model integrates three heat convection forms that are generated by pressure difference, gravity, and thermal expansion of connate water. Subsequently, the simulation results are compared with field data to evaluate the accuracy of the new model, and they are reasonably consistent with UTF field data. The results indicate that convective heat transfer plays a predominant role in the immediate vicinity of the steam chamber interface. Furthermore, this paper derives a mathematic model of oil production to explore the effect of heat convection on oil production under different operation conditions. The results demonstrate that heat convection has an adverse impact on oil production, but it is inevitable. This study also displays that some parameters, such as the lateral spreading rate, the thermal diffusivity, the viscosity coefficient, and the curvature of oil relative permeability curve, can significantly affect the oil production rate. Based on this study, the effect of convection mechanism on the heat-transfer process and oil production will be further clarified, and the parameters in the SAGD process can be optimized, so as to effectively enhance and predict oil production.

1. INTRODUCTION

According to statistics, about two-thirds of the total crude oil resources are heavy oil and bitumen that are known for their extremely high viscosity under original reservoir conditions. For this reason, heavy oil is difficult to be mined out from the ground by conventional methods. Two requirements are essential to any thermal recovery technology: on the one hand, reducing the oil viscosity by heating the bitumen, while on the other hand, providing a driving force to transfer the flowing bitumen to the production wellbore. Therefore, the increase of the flowability of heavy oil is the key to enhance the oil production capacity. So far, this goal has been achieved through some technologies, one of which is steam-assisted-gravity-drainage (SAGD).

Generally, in the SAGD operation, a pair of horizontal wells parallel to each other are placed 5 m above the bottom of the bitumen reservoir, and the vertical separation between the two wells is usually between 5 and 7 m. The saturated steam is injected from the injection well into a vapor chamber at a constant temperature of 150–300 °C and below the fracture press. Afterward, when it comes in contact with the oil–sands at the interface of the steam chamber, steam releases its latent heat to heat the bitumen. Because of the drastic decrease of oil viscosity, the heated oil drains downward along the inner interface of the steam chamber to the production well eventually, as illustrated in Figure 1, where it is transported out to the ground. Therefore, heat transfer is the key step in SAGD operation.

Both heat conduction and heat convection processes contribute to heat transfer. However, heat convection is neglected by researchers for a long time, including the famous “Butler theory.” With further studies in recent years, more and more evidence proved that heat convection is an indispensable factor in the SAGD process. For a long time, researchers dispute the dominant mechanism in the heat-transfer process beyond the edge of steam chambers.

Although most researchers supported conductive heat transfer, researchers still hold the point that heat...
conduction and convection exist in the heat-transfer process, and there are three types of convection mechanisms. For a long time, the convection formed by the steam condensate and flowing along the steam chamber is considered as the only convection form. However, as reported by the Alberta Oil Sands Discovery Center, the vast majority of oil sands in Alberta is water-wet and the water film is a continuum that separates the sand grains and the bitumen.26,33 The single-phase phenomenon is also observed in subsequent experiments that utilize the semipermeable membranes to measure the effective permeability of connate water in the bitumen reservoir that is simulated with a sand pack. It is found that connate water is capable of flowing at the saturation condition as low as 0.17 under the pressure difference, ranging from 0.88 to 0.15 kPa.34 The field data obtained from the Underground Test Facility (UTF) Phase A SAGD pilot on November 1987 also verified this view.35–37 It is confirmed that, when the water-injection rate changes from 12 to 8 m³/d, water moves through the bitumen zone by examining the pressure data from the observation wells. The test results imply that, if there is an appropriate pressure difference and the water saturation exceeds irreducible water saturation in an oil sand reservoir, water could move through the reservoir and simultaneously generate convective heat transfer. Therefore, the convection caused by the pressure gradient is considered in this paper. In addition, there is a lack of understanding about the heat convection by connate water that is induced by thermal expansion. In porous media, the excess fluid pressure that is created by fluid thermal expansion against a matrix is described as aquathermal pressuring that has been discussed by many researchers.38,39 In aquathermal pressuring, once the temperature increases at an elevated temperature,39 for example, when the temperature increases from 0 to 179 °C at 1.0 MPa, the water density decreases from 1000.3 to 887.1 kg/m³. Therefore, the excess fluid pressure gradient that is caused by the liquid volume expansion constrained by a matrix provides the potential for fluid flow.39 Therefore, in the SAGD process, ignoring the effect of connate water flow that is an important effects of heat convection on oil production are analyzed. Moreover, the effects of reservoir properties as well as the operation parameters on oil production are explored, which contribute to the heavy oil production in the SAGD process.

2. CONDUCTIVE AND CONVECTIVE HEAT-TRANSFER THEORY

The diagrammatic sketch of heat transfer at the edge of the steam chamber is illustrated in Figure 2. Both heat conduction and convection exist beyond the steam chamber interface.
form to deliver heat to the cold reservoir would adversely affect the heat efficiency calculation.

According to Carlsow and Jaeger’s formula and Butler’s quasisteady theory, the heat-transfer process in a reservoir can be presented as follows

$$K \left( \frac{\partial^2 T}{\partial z^2} \right) + [\mu t_en - \mu c_wc_w \left( \frac{\partial T}{\partial z} \right)] = 0$$  \hspace{1cm} \text{(1)}

where $\rho_t$ is the water density, $c_w$ refers to the water capacity, $\rho_s$ marks the reservoir density, $c_p$ represents the reservoir heat capacity, $K$ stands for the reservoir thermal conductivity, $V_c$ means the convection velocity, and $U_z$ is the lateral spreading rate.

The solution to eq 1 by considering only the conduction is as follows

$$T^* = \frac{T - T_i}{T_{st} - T_i} = \exp \left( - \frac{U_z \xi}{\alpha} \right)$$  \hspace{1cm} \text{(2)}

Oil saturation beyond the steam chamber interface is presented as

$$S_o = S_{ow} + (S_{io} - S_{ow})(1 - T^*)$$  \hspace{1cm} \text{(3)}

where $S_o$ is the oil saturation, $S_{ow}$ represents the residual oil saturation, $S_{ow}$ stands for the initial oil saturation, and $T^*$ marks the dimensionless temperature.

Based on Corey’s equations, the relative permeability can be determined as

$$k_{ro} = k_{roc}(1 - S_{wD})^a$$ \hspace{1cm} \text{for oil}  \hspace{1cm} \text{(4)}

$$k_{rw} = k_{rwc}(S_{D})^b$$ \hspace{1cm} \text{for water}  \hspace{1cm} \text{(5)}

$$S_{wD} = \frac{S_w - S_{wc}}{1 - S_{wc} - S_{ow}}$$  \hspace{1cm} \text{(6)}

where $k_{roc}$ is the relative permeability of oil, $k_{roc}$ refers to the relative permeability of oil at connate water saturation, $k_{roc}$ means the relative permeability of water at residual oil saturation, $a$ and $b$ stand for Corey coefficients, $S_o$ indicates the water saturation, and $S_{ow}$ is the connate water saturation.

In Butler’s model, the following formulas are applied to calculate the oil density, water density, and heat capacity of water, respectively.

$$\rho_o = 1024 - 0.645T$$  \hspace{1cm} \text{(7)}

$$\rho_w = 1001.7 - 0.1616T - 0.00262T^2$$  \hspace{1cm} \text{(8)}

$$c_w = 4.182 - 1.5 \times 10^{-4}T + 3.44 \times 10^{-7}T^2$$  \hspace{1cm} + $4.26 \times 10^{-8}T^3$$  \hspace{1cm} \text{(9)}

The convective velocity can be written as

$$V_c = V_{cp} + V_{cg} + V_{ce}$$  \hspace{1cm} \text{(10)}

where $V_{cp}$, $V_{cg}$, and $V_{ce}$ mark the convective velocity generated by condensate under the pressure difference, gravity, and water thermal expansion, respectively, which are given by

$$V_{cp} = -\lambda \frac{\partial P}{\partial z}$$  \hspace{1cm} \text{(11)}

$$V_{cg} = \lambda \mu g \cos \theta$$  \hspace{1cm} \text{(12)}

$$V_{ce} = \frac{(1 - \phi) \sigma_s U_z}{1 - \alpha_s(T - T_r)} (T - T_r)$$  \hspace{1cm} \text{(13)}

where $g$ is the gravity coefficient, $\theta$ stands for the interface angle, $\phi$ refers to the reservoir porosity, $\alpha_s$ represents the water thermal expansion coefficient, and $\lambda$ marks the water mobility, and it can be derived as follows

$$\lambda_s = \frac{k k_{osc}}{\mu_s}$$  \hspace{1cm} \text{(14)}

The same can be derived for oil mobility as

$$\lambda_o = \frac{k k_{ocw}}{\mu_o}$$  \hspace{1cm} \text{(15)}

where $k$ is the absolute permeability.

In Butler’s theory, the relationship between viscosity and temperature is formulated as

$$\mu_s = \frac{\rho_{st} k_{st}}{\rho_s k_{st}} = \frac{\rho_s}{\rho_{st}} \left( \frac{T_{st} - T_r}{T - T_r} \right)^m$$  \hspace{1cm} \text{(16)}

Based on the model of Zhang et al., the relationship of pressure and kinematic viscosity is similar to that of temperature and viscosity, so it can be expressed as

$$\frac{\mu_{st}}{\mu} = \left( \frac{P - P_{st}}{P - P_i} \right)^n$$  \hspace{1cm} \text{(17)}

Combining eq. 16 and 18, the relationship between pressure and temperature can be presented as

$$\left( \frac{P - P_{st}}{P - P_i} \right)^n = \left( \frac{T - T_i}{T_{st} - T_r} \right)^m$$  \hspace{1cm} \text{(18)}

By differentiating eq 19, the pressure gradient can be derived as follows

$$\frac{\partial P}{\partial z} = -\frac{m U_z (P_{st} - P_i)}{n \alpha} (T^*)^{m/n}$$  \hspace{1cm} \text{(19)}

Substituting eq 20 into eq 11, $V_{cp}$ can be derived as

$$V_{cp} = \frac{m U_z (P_{st} - P_i)}{n \alpha} (T^*)^{m/n}$$  \hspace{1cm} \text{(20)}

The apparent thermal diffusivity combining the conductive and heat convective heat fluxes is proposed as

$$\alpha^* = \frac{U_z}{\alpha} - \frac{V_{cp}}{k}$$  \hspace{1cm} \text{(21)}

Equation 22 can be solved by an iteration method. For a given temperature, the fluid properties can be determined. Based on eq 22, the apparent thermal diffusivity $\alpha^*$ can be calculated. Then, by replacing $\alpha$ with $\alpha^*$, a new temperature could be found using eq 2. Comparing the new temperature with a formerly given temperature and resetting to a new value until the difference between these two temperatures is small enough, the accurate temperature at this point is determined. According to eq. 3 and 22, the conductive heat flux and convective heat flux can be presented as


\[ F_{\text{cond}} = -k \frac{\partial T}{\partial x} = \left( \frac{T_a - T_f}{\alpha^*} \right) K \frac{U_x}{\alpha^*} \exp\left( -\frac{U_x}{\alpha^*} \xi \right) \]  

(23)

\[ F_{\text{conv}} = \rho \mu \omega_p (T - T_f) \]  

(24)

### 3. OIL MOBILITY AND OIL PRODUCTION THEORY

As a function of distance, oil mobility can be obtained by substituting eqs 3, 4, 6, and 16 in eq 15.

\[ \lambda_o = \frac{k k_{\text{rocf}}}{\nu \rho} \left[ 1 - \exp\left( -\frac{U}{\alpha^*} \xi \right) \right] \left[ \exp\left( -\frac{U}{\alpha^*} \xi \right) \right]^{12} \]  

(25)

Figure 3 exhibits the oil-phase mobility profile versus distance based on properties listed in Table 1 and eq 15.

![Figure 3. Oil-phase mobility distribution vs distance beyond the steam chamber interface.](image)

The curve indicates that the peak mobility does not appear at the edge of the steam chamber but at a distance beyond the steam chamber interface. The position of the highest value can be calculated by differentiating eq 25 with respect to the distance and setting the result equal to zero. The result

\[ \xi_{\text{max}} = \frac{\alpha^*}{U_x} \ln \left( 1 + \frac{a}{m} \right) \]  

(26)

reveals that the location of the peak value is positively related to the apparent thermal diffusivity \( \alpha^* \) and the Corey coefficient \( a \), while it is negatively related to the lateral spreading rate of the steam chamber \( U_x \) and the viscosity coefficient \( m \).

By substituting \( \xi_{\text{max}} \) in eqs 25 and 2, the maximum of oil mobility and its corresponding temperature are then given by

\[ \lambda_{o_{\text{max}}} = \frac{k k_{\text{rocf}}}{\nu \rho} \frac{a^m}{(m + a)^{m+a}} \]  

(27)

\[ T_{o_{\text{max}}} = \frac{m}{m + a} \]  

(28)

The results prove that, corresponding to the maximum of the oil mobility, the temperature is constant if the reservoir properties of Corey coefficient \( a \) and viscosity coefficient \( m \) are determined. In contrast to the location of the peak value, the changes in the thermal diffusivity \( \alpha^* \) and the lateral spreading rate \( U \) have no impact on the peak value as well as on the maximum corresponding temperature.

According to the Darcy law, the oil production rate can be calculated as

\[ dq = \lambda_o \rho o \sin \theta L d \xi \]  

(29)

### 4. RESULTS AND DISCUSSION

#### 4.1. Modeling Validation

Table 1 lists the physical parameters that are consistent with the representative properties of the Dover UTF Phase B reservoir in the Athabasca reservoir. In this table, thermal conductivity is assumed to be 1.45 W/m·°C. The steam injection pressure is set to 1.73 MPa. The properties of water and oil, including the density, heat captivity, and viscosity, are determined as a function of temperature.

In terms of the temperature distribution at the edge of the steam chamber, the curves in Figure 4 compare four different analytical models. As shown in Figure 3, the curves of all these models display a similar pattern to that of the field data, and the differences mainly occur at the distance of 3 m from the boundary of the steam chamber. Compared with the Irani and Ghannadi model, the new model and the Sharma and Gates model coincide with the field data much better, and there is only a small gap between the two models, because both the new model and Sharma and Gates model consider water as the

### Table 1. Fluid and Reservoir Properties

| hydraulic properties parameters | values* |
|----------------------------------|---------|
| \( k \) (m²)                    | 6.0 x 10⁻¹² |
| \( k_{\text{rocf}} \) (m²/s)   | 0.9     |
| \( k_{\text{roco}} \) (m²/s)  | 0.02    |

| thermal properties parameters | values |
|------------------------------|--------|
| \( \alpha_e \) (1/K)         | 803.42 x 10⁻⁶ |
| \( \alpha_m \) (m²/s)        | 7 x 10⁻⁷ |
| \( K \) (W/m·°C)            | 1.45   |
| \( \mu_a \) (cP)             | 1.2    |
| \( \rho_s \) (kg/m³)         | varies |
| \( \mu_w \) (cP)             | varies |

| chamber properties parameters | \( T_r \) (°C) | \( T_s \) (°C) | \( U_x \) (cm/day) | \( P_r \) (MPa) | \( P_s \) (MPa) |
|------------------------------|---------------|---------------|-------------------|---------------|---------------|
|                             | 10            | 205           | 1.7              | 1.47          | 1.73          |

| characteristic parameters | m | n | a | b |
|----------------------------|---|---|---|---|
|                            | 2.35| 2 | 1 | 2 |

*Values were cited in refs. 3, 14, 17, 24, 42. Hydrostatic pressure evaluated on the basis of an average depth of 150 m. Saturation pressure related to 205 °C, evaluated based on Williamson. 46
only phase in the heat-transfer process and set the water saturation beyond the steam chamber interface as a function of temperature, while Irani and Ghannadi proposed a multiphase flow model wherein water saturation is assumed to be constant. However, the Sharma and Gates model only investigates the convection that is caused by the pressure difference, whereas the new model analyzes more comprehensively. Therefore, the temperature profile that is described by the new model is more accurate. It should be noted that the Butler model is the only one that neglects the convective heat transfer, and the temperature of the Butler model is the lowest compared with these models. The maximum of temperature difference with field data even reaches 16 °C at the distance of 0.6 m beyond the edge of the steam chamber, meaning that heat convection hugely contributes to the temperature enhancement in the vicinity of steam chamber edge. The convection-active region is smaller than 3 m from the steam chamber interface, and the temperature is higher than 100 °C in this area, illustrating that the crude oil will possess a high mobility. It can be concluded that, if the surrounding temperature is above 100 °C, convection can significantly improve the efficiency of the heat-transfer process.

Figure 5 demonstrates the conductive heat flux distribution versus temperature for three models and the field data. Only the new model displays a similar trend with the field data, thus increasing noticeably with decreasing temperature before reaching the maximum at the temperature of 150 °C, and then the curve of the new model consistently falls to zero at the location where the temperature is equal to the initial reservoir temperature. Compared with the new model, the heat flux profile depicted by the Sharma and Gates model is a straight line, illustrating only a downward trend with dropping temperature. Whereas the Irani and Ghannadi model coincides with the experimental data very well, except for the high-temperature region, in which both the Sharma and Gates model and the Irani and Ghannadi model present a great error from the field data, because the Irani and Ghannadi model is derived based on a postulation that the oil saturation remains constant and is nearly equal to the maximal oil saturation in the reservoir, while it is considered as a variable that varies linearly with $T^*$ over the whole temperature bracket in other two models. It should be noted that the maximum of the conductive heat flux appears in the vicinity of steam chamber interface and is nearly twice the value of the heat flux at the boundary of steam chamber. It can be explained that the powerful convective heat transfer is generated under the conditions of high pressure and high temperature near the steam chamber boundary, and the majority of heat energy is then transferred by heat convection. Therefore, heat conduction plays a relatively small role. As the distance increases, heat convection reduces remarkably with the decrease of pressure and temperature, so heat conduction dominates the heat-transfer process eventually.

The comparison of convective heat flux versus temperature for three different models with field data is presented in Figure 6. The curves of all three models display a similar pattern to that of field data. The convective heat flux reaches the maximum at the steam chamber interface and then drops radically with the decline of temperature to zero at the temperature around 80 °C. However, when the temperature is below 50 °C, all models cannot match the experimental data. Compared with other two models, the new model has the smallest error from field data over the whole temperature range, especially at the zone where the temperature is below 150 °C. In this region, the curve of the new model is relatively flat, with only the decrease of 10 W/m² at the temperature ranging from 140 to 80 °C, while the counterparts of the other two models are 20 W/m² (Sharma and Gates model) and 15 W/m² (Irani and Ghannadi model), respectively. The results indicate that the new model captures the features of convective heat transfer beyond the steam chamber interface. It can be found that the convective heat flux approximately and exponentially decreases as the temperature declines, and the value drastically drops in the high-temperature region, whereas
it slowly changes in the low-temperature region, because steam pressure and aquathermal pressure are considered as the main driving forces to generate heat convection, and both factors are sensitive to temperature. The convective heat flux is maximal at the edge of the steam chamber and can be explained based on the above analysis.

Figure 7 presents the comparisons of UTF field data and the results calculated by the new model, including the total heat flux, conductive heat flux, and convective heat flux. All the three curves show similar trends with their corresponding field data, suggesting that the new model reveals the law of the relationship between convective heat transfer and convective heat transfer beyond the steam chamber boundary. Heat convection has the largest proportion of heat flux at the steam chamber interface, more than twice the value of conductive heat flux. When the temperature is below 80 °C, it drops significantly to zero. In contrast, the curve of conductive heat flux shows a different trend, the value tends to increase with the decrease of temperature, and the conductive heat flux gradually decreases after reaching the maximum at the temperature of 150 °C. The intersection of the two curves is called the critical point, with the temperature of 182 °C. Heat convection is predominant in the region where the temperature is higher than the critical point. However, when the temperature is below the critical point and the proportions of conductive heat flux are considerably high, conduction is the principal mechanism in the heat-transfer process. Compared with heat conduction, heat convection has a relatively narrow action range, and only when the temperature is higher than 100 °C, it is more obvious, whereas heat conduction exists at a temperature bracket ranging from the steam injection temperature to the original reservoir temperature. These results also indirectly verify the conclusions in Figure 4.

4.2. Effect of Heat Convection on Oil Production with the New Model. 4.2.1. Oil Production Profile beyond the Steam Chamber Interface. In terms of distribution of oil production rate, Figure 8 compares the conduction-only case and the actual case, including both heat conduction and heat convection. Both cases show a similar pattern, increasing dramatically and peaking at about 2 m beyond the steam chamber interface, and then the two curves drop radically until there is no oil production at a distance of 10 m. The maximum values appear in the immediate vicinity of the steam chamber boundary, instead of the steam chamber interface because of oil mobility. The temperature drops remarkably with increasing distance from the steam chamber interface (See in

Figure 8. Comparison of oil production distribution of the conduction-only case and the actual case vs distance.

Figure 4), and it is negatively correlated with oil relative permeability. In the high-temperature region, it is in the vicinity of the steam chamber interface, temperature contributes relatively more to the decrease of oil viscosity than to the decline of oil permeability with the increase of distance. After reaching the maximum, the effect of temperature on the two oil characteristic parameters is reversed. Compared with the actual case, the peak value of conduction-only case is relatively closer to the steam chamber interface, and an explanation can be as follows. When the hot condensate enters the reservoir, oil saturation reduces dramatically and practically approaches the residual saturation. At the same time, oil relative permeability slumps with decreasing oil saturation. The effect of heat convection caused by water flow into oil sands on oil relative permeability is greater than the effect of temperature enhancement caused by convection on oil viscosity. It is noted that the total oil production of conduction-only case is more than that of the actual case, compared with the actual case, because the effective permeability of oil decreases as the oil relative permeability decreases in the convection-active zone. Therefore, mobile oil is limited. It can be concluded that heat convection has an adverse impact on oil production, but it is inevitable.

4.2.2. Effect of the Lateral Interface Angle of the Steam Chamber. The effects of heat convection on oil production for different lateral spreading angles are plotted in Figure 9. Both cases increase steadily with the increase of angle before reaching the maximal value, and the gap between the two curves narrows as the angle grows, although heat convection plays a negative role in oil production. In the early stage of SAGD operation, the expansion angle of the steam chamber is
nearly close to 90°, which provides the favorable condition for heat convection caused by the gravity and benefits to make heated oil flow down in two cases. Therefore, the oil production of the two cases reaches the peak value (i.e., 0.015 m²/day for the actual case and 0.0158 m²/day for the conduction-only case). As the steam chamber enters the horizontal expansion period, the angle gradually declines. Although the heat convection caused by the pressure gradient and the gravity increases as the interface angle decreases, the component of the gravity along the steam chamber interface decreases, which drives the heated oil drainage into the production well. Therefore, oil production presents a downward trend (i.e., 0.0074 and 0.0079 m²/day for the actual case and the conduction-only case at the angle of 30°, respectively), and the value of the two cases tends to be consistent with decreasing angle.

4.2.3. Effect of Lateral Spreading Rate of the Steam Chamber. In terms of the changes in oil production for different lateral spreading rates, Figure 10 compares the actual case and the conduction-only case. Both curves decline with the increase of spreading rate. The difference between the two cases is found at the velocity of 1 cm/day and then narrows as velocity increases. Because of the negative effect of heat convection, when the lateral spreading rate is slow, the value of the conduction-only case is slightly bigger than that of the actual case, because when the steam chamber interface moves slower than the water movement velocity of heat convection and the thermal front rate of heat conduction, the temperature distribution can be considered as stable with time. Therefore, the effect of heat convection is much more obvious. As the lateral spreading rate increases and ultimately exceeds the convection velocity, convective heat transfer disappears and there is only heat conduction beyond the steam chamber boundary. Therefore, both cases obtain equal oil production at the velocity of 3 cm/day. As displayed in Figure 10, the lateral spreading rate has a significant impact on oil production. As it increases from 1 to 5 cm/day, the value of the actual case declines from 0.022 to 0.004 m²/day with a drop of 82% because too fast spreading rate is difficult to maintain a stable temperature profile, and the farther cold bitumen cannot be fully warmed up. Therefore, mobile oil is limited.

4.2.4. Effect of Pressure Difference. The effect of heat convection on oil production with varying pressure differences is illustrated in Figure 11. In order to obtain different pressure differences, the original reservoir pressure varies from 1.45 to 1.68 MPa, whereas the steam injection pressure is kept constant (1.73 MPa, corresponding to 205 °C). As shown in the graph, the oil production of the two cases is basically the same at the pressure difference of 0.05 MPa and then the value of the actual case decreases gradually. On the contrary, the values of conduction-only case remain roughly unchanged. It can be explained that, when the temperature difference is not large enough, heat convection hardly exists. In this situation, heat convection is the only mechanism in heat-transfer process. In contrast, if there is an increase of pressure difference, the effect of convection increases significantly. It should be noted that, although it presents a downward trend with the increase of pressure difference, the value of oil production changes slightly in the actual case. Compared with the conduction-only case, when the pressure difference reaches the maximum of 0.28 MPa, there is only 4 percent reduction, because convective heat-transfer flux reduces exponentially with the distance from the steam chamber boundary, and heat convection only occurs in the area where the temperature is above 100 °C (see in Figure 6). Although heat convection is detrimental to oil production, it only makes up a small proportion of the total oil production, while the main part is produced outside the convection-active region (see in Figure 8). Therefore, the pressure difference cannot affect oil production significantly.

4.3. Effect of Reservoir Properties on Oil Production with the New Model. 4.3.1. Effect of Lateral Spreading Rate on Oil Production. The curves in Figure 12 display the effect of lateral spreading rate on oil flow flux distribution versus distance beyond the edge of the steam chamber. All
lines rise significantly from zero at the edge of the steam chamber and then the values fall back to zero after peaking at their respective maximums of the oil flux. The faster the boundary moves, the closer the peak value is to the steam chamber edge, because as the spreading rate increases, the temperature in the vicinity of the steam chamber boundary grows more rapidly. The former analysis revealed that the peak value of the oil flux and its corresponding temperature have no relationship with the lateral spreading rate and the thermal diffusivity as well. Thus, the largest oil flux appears closer to the steam chamber interface. The area enclosed by the curve and horizontal axis refers to the cumulative oil flux that rises with the decrease of the spreading rate. It can be explained that, if the steam chamber boundary moves quickly and the range of heated oil declines accordingly, the temperature distribution range is compressed.

4.3.2. Effect of Thermal Diffusivity on Oil Production. Figure 13 displays the volumetric oil flux distribution versus distance with varying thermal diffusivities. The results prove that, as the thermal diffusivity increases, the location corresponding to the peak value gets farther away from the steam chamber interface. The larger diffusivity reveals that more heat can be transferred farther into the reservoir, and the range of high-temperature profile is wider. Therefore, the location of the temperature corresponding to the largest oil production rate is farther from the lateral steam chamber. In addition, the high thermal diffusivity can enlarge the production region of heated oil, which is beneficial to improving oil production.

4.3.3. Effect of the Viscosity Coefficient m on Oil Production. Figure 14 presents the effect of the viscosity parameter m on the oil volumetric rate distribution versus distance from the boundary of the steam chamber. As the viscosity parameter increases, both the peak value and the oil production decline, and the location corresponding to the maximum of the oil flux is closer to the steam chamber interface. The viscosity parameter is the characterization of the viscosity sensitivity of the oil to temperature. The larger the viscosity parameter is, the more the viscosity of oil changes with temperature. Thus, the mobility of crude oil rises drastically at the edge of the steam chamber where the temperature is high. The heated oil flows quickly along the inner interface of the steam chamber into the production well and takes away lots of thermal energy, so only a small part of heat is retained and transferred into the farther cold reservoir, thus leading to the decline of temperature in the whole region beyond the steam chamber interface ultimately reducing oil production.

4.3.4. Effect of the Corey Coefficient a on Oil Production. Figure 15 displays the effect of Corey coefficient a on the oil production rate profile beyond the edge of the steam chamber. As the Corey coefficient increases, the changes in the maximum of the oil production rate and the oil production show a similar trend with that of the viscosity coefficient m, but the distance of the location corresponding to the peak value from the steam chamber edge get farther. The Corey coefficient a implies the curvature of the relative oil permeability curve. The larger the curvature is, the smaller the oil relative permeability is, and the lower the oil production is, referring to that only a small part of the oil is replaced by the steam condensate, and it is known that the thermal capacity of water is almost 5 times more than oil, so the majority of energy would be able to transferred to improve the temperature deep in the reservoir rather than near the edge of the steam chamber. Therefore, when the Corey coefficient a is greater, the peak value is farther away from the steam chamber edge.

5. CONCLUSIONS

- An analytical model is proposed in this paper, which combines three forms of heat convection. It can reasonably represent the heat-transfer process beyond the steam chamber boundary compared with other models.
• There is a critical point beyond the steam chamber interface. Heat convection is the predominant mechanism in the heat-transfer process between the steam chamber interface and the location of the critical point.

• Heat convection has an adverse impact on oil production, but it is inevitable, because when the temperature is high, the relative permeability of oil decreases faster than oil viscosity, and the decline of oil phase mobility causes the decrease in oil production.

• Lower lateral spreading rate is more beneficial to improving the oil production. Besides, the reservoir has excellent properties, including high thermal diffusivity, great viscosity coefficient, and small curvature of the oil relative permeability curve, thus showing the potential to produce more oil.

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### NOMENCLATURE

- \( q_o \): oil production rate, m³/day
- \( S_{wa} \): water saturation, no unit
- \( S_{nw} \): connate water saturation, no unit
- \( S_{w} \): normalized water saturation, no unit
- \( S_{or} \): initial oil saturation, no unit
- \( S_{rw} \): residual oil saturation, no unit
- \( T_r \): reservoir temperature, °C
- \( T_{sw} \): steam temperature, °C
- \( U_x \): velocity of the advancing front of steam chamber, m/s
- \( V_{w} \): water convective velocity normal to the steam chamber edge, m/s
- \( V_{wp} \): water convective velocity caused by pressure difference, m/s
- \( V_{wo} \): water convective velocity caused by gravity, m/s
- \( V_{w} \): water convective velocity caused by thermal expansion of water, m/s
- \( \alpha_t \): thermal diffusivity, m²/s
- \( \alpha_{T} \): water thermal expansion coefficient, 1/K
- \( \alpha^* \): apparent thermal diffusivity, m²/s
- \( \lambda_o \): oil mobility (m³/s)/kg
- \( \lambda_w \): water mobility (m³/s)/kg
- \( \mu_o \): dynamic viscosity of oil, cp
- \( \mu_w \): dynamic viscosity of oil at steam temperature, cp
- \( \nu_w \): kinematic viscosity of oil, m²/s
- \( \nu_{w} \): kinematic viscosity of water at steam temperature, m²/s
- \( \xi \): distance measured from the steam chamber interface in the direction normal to it, m
- \( \theta \): steam chamber interface angle, °
- \( \rho_o \): oil density, kg/m³
- \( \rho_w \): water density, kg/m³
- \( \rho_w \): water density, kg/m³
- \( \rho_o \): oil density, kg/m³
- \( \rho_w \): sand matrix density, kg/m³
- \( \phi \): porosity of the reservoir, no unit

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