Solution and Analysis of Wellbore Temperature and Pressure Field Coupling Model under Lost Circulation
Ao Yang, Zhongxi Zhu,* Nan Zhang, and Yuchen Ye

ABSTRACT: The fluid in the annulus is in a variable mass flow state under the lost circulation condition, significantly affecting wellbore pressure distribution and the heat transfer efficiency between wellbore and formation. Therefore, based on the hydrodynamics and energy conservation law, a coupling model of transient wellbore temperature and pressure field under lost circulation conditions is established, which fully considers the casing program, bottom hole assembly, and heat source generated in drilling, as well as the influence of the temperature and pressure coupling in wellbore on the physical parameters of drilling fluid. The calculation results of the model in this paper are in good agreement with the field measured data and the previous research results, which verifies the rationality and accuracy of the model in this paper. The effects of the loss rate and the lost circulation zone location on the wellbore temperature and pressure distribution are analyzed, and the variation rule of the physical parameters of drilling fluid under the lost circulation condition is studied. The numerical simulation results show that the density and viscosity of drilling fluid in the annulus and bottom hole pressure increase with the increase in the circulation time; the annulus temperature decreases gradually with the increase in cycle time and tends to become stable after 8 h of the cycle. The annulus temperature and bottom hole pressure decrease with the increase in loss rate and closeness of the loss zone to the well bottom. When the loss zone is in the upper open-hole section, an inflection point consistent with the location of the loss zone appears on the annular temperature difference curve between the loss circulation and the nonloss circulation, and the position of the loss zone can be judged according to the inflection point.

1. INTRODUCTION
With the increase in oil and gas exploration and development, the research frontier of the petroleum industry has gradually shifted to the development of land deep oil and gas reservoirs and deep-water drilling. Complex geological conditions result in drilling operations facing engineering problems such as abnormally high temperature, high pressure, and narrow safe density window, resulting in frequent downhole complex accidents such as lost circulation. In addition, borehole temperature is not only an important parameter for wellbore stability analysis and drilling design but also has a significant impact on drilling fluid properties and cementing quality. Moreover, under the loss condition, the fluid in the annulus is in an unsteady-state flow, and the leaked fluid also reduces the formation temperature near the wellbore and changes the original temperature and pressure distribution in the wellbore, which seriously affects the physical parameters such as drilling fluid density and viscosity, making the loss situation more complex. Therefore, studying the variation law of wellbore temperature and pressure in the process of lost circulation is of great significance for safe and efficient drilling.

In drilling engineering, the research methods of wellbore temperature field are mainly divided into the analytical method and numerical method. Holmes used the steady-state linear heat transfer approximation to replace the heat transfer between the annulus fluid and the formation and derived an analytical model to calculate the steady-state heat transfer between the fluid in the drill string and the fluid in the annulus. The calculation results show that the maximum temperature of the fluid in the annulus does not appear at the well bottom. Based on this research result, Kabir assumes that the heat exchange process between the fluid in the drill string and the fluid in the annulus belongs to steady-state heat transfer, and the heat exchange between the annulus fluid and the near wellbore area belongs to pseudo-steady-state heat transfer. Combined with the energy conservation law, a one-dimensional transient heat transfer model based on dimensionless time has been established. Based on the above model and considering the different construction environment, mode, and other factors, researchers have established different analytical models to study the temperature and pressure fields in lost circulation conditions.
models to analyze the temperature distribution law of wellbore fluid, heat sources, and different casing program on the wellbore temperature distribution cannot be fully considered. As a result, the analytical model is difficult to effectively complete the research on the wellbore temperature distribution during deep-water drilling and drilling into deep reservoirs. This also makes more and more scholars prefer to use numerical methods to study the transient heat transfer process between wellbore and formation.

Although the research on wellbore heat transfer of drilling fluid under no-loss circulation conditions has become mature, there are few studies on variable mass heat transfer of annulus fluid under loss circulation. In 2014, Li et al. established the first variable mass heat transfer model in the wellbore under the lost circulation condition and also proposed a method to judge the position of the loss zone according to the temperature gradient curve. However, due to its failure to fully consider the heat source generated in the drilling process and the influence of the casing program on the wellbore temperature distribution, the model has a large error in the drilling process of deep and ultradeep wells. In 2020, Wang et al. on the basis of the Chen model, supplemented the influence of the internal heat source generated in the drilling process and casing program on the temperature distribution in the wellbore and established the numerical model predicting the wellbore temperature profile under the lost circulation. In 2020, Zhang proposed a wellbore temperature distribution model based on two-dimensional bottom hole regional loss. It is considered that compared with one-dimensional regional loss, the loss of drilling fluid in a two-dimensional region has a more significant impact on the annulus temperature profile of drilling fluid; however, the location of the loss zone cannot be judged by this model.

The above models never consider the influence of temperature pressure coupling in the wellbore on the physical parameters of drilling fluid after loss circulation. Based on the Chen model and Wang model, first, considering the mutual effect of physical parameters of the drilling fluid and wellbore temperature and pressure, a coupling model of wellbore temperature and pressure field under loss circulation is established. The partial differential equation is discretized by the finite difference method, and the discrete equation is solved by the Gauss–Seidel algorithm. In addition, the effects of temperature pressure coupling in wellbore on physical parameters of drilling fluid, convective heat transfer coefficient, and circulating pressure loss under lost circulation are analyzed.
pressure in wellbore under lost circulation is studied. The research results can provide theoretical guidance for an efficient leaking stoppage and safe drilling.

2. MATHEMATICAL MODEL

During the drilling operation, the drilling fluid enters the drill string at temperature \( T_{\text{in}} \) flows to the well bottom through the drill string, then enters the annulus by the drill bit, and finally returns to the surface with rock cuttings. During this process, the fluid in the wellbore not only absorbs the heat generated by its flow and drill string rotation but also is heated by the lower high-temperature formation and returns to the ground at temperature \( T_{\text{out}} \).\textsuperscript{2,12,14,22}

Different from the normal condition, the lost circulation makes the drilling fluid invade the formation, resulting in a decrease in the volume flow of the drilling fluid in the upper annulus. It is necessary to comprehensively consider the influence of variable mass flow on the wellbore heat transfer process under the loss circulation. The fluid flow and heat transfer model under loss circulation is shown in Figure 1.\textsuperscript{13}

In the process of establishing the model, according to the flow characteristics and heat transfer law of the fluid in the wellbore under the condition of loss circulation, the following assumptions are put forward:

(1) The heat exchange in the axial direction of the formation is ignored.
(2) The physical parameters (density, specific heat capacity, etc.) of the drill string, casing, and formation rock are not affected by temperature and pressure.
(3) The axial heat conduction and radial temperature gradient of drilling fluid is ignored.\textsuperscript{12}

2.1. Circulating Pressure Loss. In the process of drilling fluid circulation, the circulating pressure loss is expressed as\textsuperscript{45}

\[
\frac{dP}{dz} = \frac{2\rho_m \nu^2}{d} \quad (1)
\]

where \( P_l \) is the circulating pressure loss of drilling fluid (Pa), \( \rho_m \) is the drilling fluid density (kg/m\(^3\)), \( f \) is the friction coefficient (dimensionless), and \( d \) is the flow diameter (m).

The calculation of friction coefficient mainly depends on the flow state of fluid; however, in the process of lost circulation, the volume flow of annulus fluid in the upper part of the loss zone decreases, which changes the flow state of annulus fluid. Therefore, it is necessary to accurately calculate the flow state of fluid on each grid node. Equations 2 and 3 are the calculation methods of friction coefficient of drilling fluid under laminar flow and turbulent flow conditions, respectively.\textsuperscript{14}

\[
f = \frac{16}{Re} \quad (2)
\]

where \( Re \) is the Reynolds number (dimensionless).

\[
\frac{1}{\sqrt{f}} = \frac{4}{(n)^{0.75}} \log(Re(\sqrt{f})^{1-n}) - \frac{0.4}{(n)^{2}} \quad (3)
\]

where \( n \) is the flow-behavior index (dimensionless).

2.2. Wellbore-Formation Heat Transfer Model. In the process of drilling fluid flowing from the wellhead to the well bottom in the drill pipe, the energy change of fluid microelement is mainly reflected in (1) the convective heat transfer between the fluid in the drill string and the fluid in the annulus, (2) net heat in the axial direction, and (3) heat generated by fluid flow and rock breaking by the drill bit.

\[
S_m + S_b = Q_m C_m \frac{\partial}{\partial z}(\rho_m T_p) - \pi d_{po} h_{12} (T_p - T_a) = \frac{\pi}{4} d_{po}^2 C_m \frac{\partial}{\partial t}(\rho_m T_p) \quad (4)
\]

where \( Q_m \) is the drilling fluid displacement (m\(^3\)/s), \( T_p \) is the fluid temperature in the drill string (°C), \( T_a \) is the fluid temperature in the annulus (°C), \( d_{po} \) is the inner diameter of the drill string (m), \( C_m \) is the specific heat capacity of the drilling fluid (J/(kg·°C)), \( h_{12} \) is the total convective heat transfer coefficient (W/(m\(^2\)·°C)), \( S_m \) is heat generated by fluid flow (W/m), and \( S_b \) is heat generated by rock breaking (W/m).

Under the condition of no loss, the energy change of fluid microelement in the annulus is mainly reflected in (1) the convective heat transfer between the fluid in the annulus and the fluid in the drill string, (2) convective heat transfer between fluid in annulus and wellbore, (3) net heat in the axial direction, and (4) heat generated by fluid flow and drill string rotation.

\[
S_m + S_t + (Q_m - Q_t) C_m \frac{\partial}{\partial z}(\rho_m T_t) = \pi d_{po} h_{12} (T_a - T_p) + \pi d_{po} h_{32} (T_i - T_a) = \frac{\pi}{4} (d_w - d_{po})^2 Q_m C_m \frac{\partial}{\partial t}(\rho_m T_t) \quad (5)
\]

where \( T_i \) is the formation temperature (°C), \( d_{po} \) is the outer diameter of the drill string (m), \( d_w \) is the wellbore radius (m), \( h_{32} \) is the convective heat transfer coefficient of the borehole wall (W/(m\(^2\)·°C)), and \( S_t \) is the heat generated for drill string rotation (W/m).

Under the loss circulation, the energy change of fluid microelement in the annulus at the lower part of the loss zone is the same as that under the normal circulation condition, while the change in drilling fluid flow caused by fluid entering the formation needs to be considered in the upper part of the loss zone.

\[
S_m + S_t + (Q_m - Q_t) C_m \frac{\partial}{\partial z}(\rho_m T_t) - \pi d_{po} h_{12} (T_a - T_p) + \pi d_{po} h_{32} (T_i - T_a) = \frac{\pi}{4} (d_w - d_{po})^2 Q_m C_m \frac{\partial}{\partial t}(\rho_m T_t) \quad (6)
\]

where \( Q_t \) is the loss rate (m\(^3\)/s).

The radial heat transfer in the formation is

\[
k_r \frac{\partial^2 T_i}{\partial r^2} + \frac{k_r}{r} \frac{\partial T_i}{\partial r} = \rho Ci_r \frac{\partial T_i}{\partial t} \quad (7)
\]

where \( k_r \) is the thermal conductivity of rock (W/(m·°C)), \( \rho _{ci} \) is the rock density (kg/m\(^3\)), and \( C_i \) is the specific heat capacity of rock (J/(kg·°C)).

2.3. Auxiliary Equation. 2.3.1. Convective Heat Transfer Coefficient. To simplify the calculation, the total convective heat transfer coefficient \( h_{12} \) is used to calculate the transient heat transfer between the drilling fluid in the drill string and the drilling fluid in the annulus.\textsuperscript{45} Table 1 shows the calculation method of convective heat transfer coefficient.\textsuperscript{36}
Table 1. Calculation Formula of Convective Heat Transfer Coefficient

| region          | flow pattern | calculation formula                   |
|-----------------|--------------|---------------------------------------|
| inner wall       | laminar      | \( h_1 = \frac{4.12 k_m}{d_{p}} \)  |
|                 | turbulent    | \( h_1 = \frac{0.0107 R_e^{0.67} P_{0.33} k_m}{d_{p}} \) |
| outer wall       | laminar      | \( h_2 = \frac{4.12 k_m}{d_{p}} \)  |
|                 | turbulent    | \( h_2 = \frac{0.0107 R_e^{0.67} P_{0.33} k_m}{d_{p}} \) |
| well wall        | laminar      | \( h_3 = \frac{4.12 k_m}{d_{p}} \)  |
|                 | turbulent    | \( h_3 = \frac{0.0107 R_e^{0.67} P_{0.33} k_m}{d_{p}} \) |

where \( h_1 \) and \( h_2 \) are the convective heat transfer coefficients of the drill string inner wall and the drill string outer wall, respectively, \( (W/(m^2 \cdot °C)) \), \( k_m \) is the thermal conductivity of drilling fluid \( (W/(m \cdot °C)) \), and \( k_p \) is the thermal conductivity of the drill string \( (W/(m \cdot °C)) \).

2.3.2. Heat Source During Drilling. Equations 11–13 represent the heat generated by fluid flow, drill string rotation, and rock breaking by the drill.\(^{23}\)

\[
S_m = \Delta P \cdot Q \quad (9)
\]

\[
S_t = \Delta M \cdot \omega \quad (10)
\]

\[
S_b = (1 - E_b) \Delta M_b \cdot \omega \quad (11)
\]

where \( M \) is the axial drill string torque \( (N \cdot m) \), \( \omega \) is the drill string rotary speed \( (r/s) \), \( E_b \) is the rock breaking efficiency of the bit (dimensionless), and \( M_b \) is the torque at the bit \( (N \cdot m) \).

2.3.3. Physical Parameters of Drilling Fluid. Considering that the thermophysical parameters of drilling fluid change with temperature and pressure during drilling fluid circulation, eqs 11 and 12 represent the functional relationship of density and viscosity of water-based drilling fluid under the coupling action of temperature and pressure, respectively.\(^{47}\)

\[
\rho_f(P, T) = \rho_{in0} \exp [A(P - P_0) - B(P - P_0)^2 - C(T - T_0) - D(T - T_0)^2 + E(T - T_0)(P - P_0)] \quad (12)
\]

\[
\mu_f(P, T) = \mu_{in0} \exp [F(P - P_0) - G(T - T_0) - H(T - T_0)^3] \quad (13)
\]

where \( \rho_{in0} \) is the density of surface drilling fluid \( (kg/m^3) \), \( P_0 \) is the surface pressure \( (MPa) \), \( T_0 \) is the surface temperature \( (°C) \), \( \mu_{in0} \) is the viscosity of surface drilling fluid \( (mPa \cdot s) \), \( A \) is equal to 4.9224 \( \times \) 10\(^{-10} \), \( B \) is equal to \(-9.6877 \times 10^{-19} \), \( C \) is equal to \(-3.1296 \times 10^{-5} \), \( D \) is equal to \(-1.7432 \times 10^{-6} \), \( E \) is equal to 4.9186 \( \times \) 10\(^{-13} \), \( F \) is equal to 2.18 \( \times \) 10\(^{-9} \), \( G \) is equal to \(-9.32 \times 10^{-3} \), and \( H \) is equal to 1.09 \( \times \) 10\(^{-5} \).

3. MODEL SOLVING

3.1. Initial and Boundary Conditions.

(1) Known drilling fluid injection temperature

\[
T_p(z = 0, t) = T_{in} \quad (14)
\]

(2) The temperature of drilling fluid in the drill string at the well bottom is equal to that in the annulus

\[
T_p(z = H, t) = T_s(z = H, t) \quad (15)
\]

(3) The formation temperature changes linearly at an infinite distance from the wellbore

\[
T_i(z, r \to \infty, t) = T_s + HT_8 \quad (16)
\]

where \( T_i \) is the surface temperature \( (°C) \), \( H \) is the well depth \( (m) \), and \( T_8 \) is the formation temperature gradient \( (°C/m) \).

3.2. Model Solving Method. Figure 2a shows that the wellbore and formation are divided into \( n \) equally spaced grids in the axial direction, respectively. Figure 2b shows that \( m \) variable spacing grids are divided radially for the wellbore and formation with the drill string as the center.\(^{48}\) In this case, \( r_j \) is the inner diameter of the drill string, \( r_1 \) is the outer diameter of the drill string, \( r_2 \) is the well diameter, when \( j > 2, r_j = r_2 e^{(j-2) a} \), where \( a \) is an equal ratio factor.

Based on the finite difference method, the wellbore transient temperature control equation is discretized and fully implicit. Among them, the first-order space derivative in the governing
equation adopts the first-order upwind scheme, and the first-order time derivative adopts the two-point backward difference. The second spatial derivative adopts the three-point central difference. Equation 17 can be expressed as a difference scheme of any node.

\[
A_{ij}T_{ij}^{n+1} + B_{ij}T_{ij}^{n+1} + C_{ij}T_{ij}^{n+1} + D_{ij}T_{ij}^{n+1} + E_{ij}T_{ij}^{n+1} = F_{ij}T_{ij}^{n+1} \tag{17}
\]

The equations of all control bodies are expressed in the matrix form of eq 18 and solved by the Gauss–Seidel algorithm. The temperature \(T_{ij}^{n}\) of each control body at \(t_0\) can be obtained. Then, the drilling fluid physical parameters at \(t_0\) can be obtained according to the current time pressure \(p_0\). All the above can be used as the initial parameters of drilling fluid physical parameters at \(t = t_0 + \Delta t\) to solve the temperature and pressure distribution at each node at \(t\). The specific solution process is shown in Figure 3.\(^{30}\)

\[
\Delta T = \dot{C} \tag{18}
\]

4. MODEL VALIDATION

To verify the accuracy of the model, the drilling data of Xinjiang Oilfield in Table 2 are substituted into this model and another classical model, and the calculation results are compared. The annulus temperature distribution curve is shown in Figure 4. The simulation results show that since the Chen model does not consider the influence of heat source on annulus drilling fluid temperature, the bottom hole temperature is 13.5 °C lower than that of the actual model and 10.7 °C lower than that of the Wang model. The calculation results of this model are close to those of the Wang model. However, the Wang model considers that the physical parameters of drilling fluid are constant, which leads to the calculation result being 2.8 °C lower than that of this model. In addition, the error between this model and the Wang model is no more than 5%, which shows that the calculation results of this model are reasonable and accurate.

Table 3 shows the comparison between the calculated values of drilling fluid outlet temperature and circulating pressure loss and the measured values on the construction site. The calculation results are in good agreement with the field measurement results. The maximum error of wellhead temperature is 3.9% and the maximum error of circulating pressure loss is 4.6%. The accuracy of the model in this paper meets the needs of practical engineering and the actual situation of the construction site.

5. RESULTS AND DISCUSSION

5.1. Influence of Loss Circulation on Convective Heat Transfer Coefficient. In the process of drilling fluid circulation, the flow condition is mainly affected by bottom hole assembly, casing program, and drilling fluid volume flow.
Therefore, the effect of loss circulation on the convective heat transfer coefficient is more significant. Figure 5 shows the calculation results of the annular convective heat transfer coefficient when the location of the loss zone is located at 4000 and 5590 m and the loss rate is 20% of the displacement. It can be seen from Figure 5 that during the lost circulation process, the fluid volume flow in the annulus above the loss zone decreases and the flow state changes, resulting in the convection heat transfer coefficient of the drill string outer wall and borehole wall being lower than that in the normal circulation.

5.2. Annulus Temperature Profile under Loss Circulation. When loss occurs at the well bottom (5590 m) and the loss rate is 25% of the displacement, the annulus temperature profile under the lost circulation condition is shown in Figure 6. The simulation results show that with the increase in well depth, the annulus temperature increases first and then decreases. The highest temperature is about 800–1000 m from the well bottom. This is because when the local formation temperature is higher than the wellbore temperature, the drilling fluid absorbs heat from the formation; otherwise, it releases heat into the formation. In addition, with the increase in circulation time, the bottom hole temperature gradually decreases. When the circulation time reaches 8 h, the temperature change in the annulus gradually tends to be stable.

5.3. Influence of Loss Circulation on Wellbore Pressure. When loss occurs at the bottom of the well (5590 m) and the loss rate is 25% of the displacement, the simulation results of circulating pressure loss and pressure distribution in the wellbore are shown in Figure 7. The simulation results show that in the case of lost circulation, the circulating pressure loss in the annulus is reduced by 0.85 MPa. This is because the loss circulation reduces the flow of drilling fluid above the loss zone so that the circulating pressure loss in the wellbore under the loss circulation condition is lower than that under the normal circulation of drilling fluid, resulting in the reduction of the pressure in the wellbore.

5.4. Drilling Fluid Physical Parameter Profile. Figure 8 shows the simulation results of drilling fluid density and viscosity in the annulus during the lost circulation. The simulation results show that with the increase in well depth, the density and viscosity of drilling fluid in the annulus decrease first and then increase. This is because under the

Table 3. Simulation Results of Drilling Fluid Outlet Temperature and Circulating Pressure Loss of Well XX

| well depth (m) | displacement (L/s) | drilling fluid injection temperature (°C) | outlet temperature (°C) | circulating pressure loss (MPa) |
|---------------|--------------------|------------------------------------------|-------------------------|-------------------------------|
|               |                    |                                          | measured value | calculated value | error (%) | measured value | calculated value | error (%) |
| 5400          | 20.8               | 49.6                                     | 50.4             | 52.4             | 3.9       | 13.95          | 14.6           | 4.6     |
| 5450          | 26.2               | 59                                       | 59.8            | 59.4             | 0.6       | 18.13          | 18.8           | 3.7     |
| 5530          | 25.2               | 60.9                                     | 60.7            | 60.9             | 0.3       | 17.79          | 18.5           | 3.9     |
| 5570          | 21.8               | 59.1                                     | 58              | 57.5             | 0.8       | 14.62          | 14.5           | 0.8     |
| 5590          | 21.7               | 61.4                                     | 59.9            | 58.6             | 2.1       | 15.4           | 15.1           | 1.9     |
coupling effect of pressure and temperature, the annulus temperature gradually increases with the increase in well depth and the drilling fluid expands, resulting in a decrease in density and viscosity. On the contrary, when the well depth exceeds the highest point of the annulus temperature, the annulus...
temperature gradually decreases and the annulus pressure gradually increases, resulting in the compression of the drilling fluid and the increase in the density and viscosity of the drilling fluid.

**5.5. Effect of Loss Rate on Annulus Temperature.** Figure 9 shows the effect of different loss rates on the annulus temperature distribution when the bottom hole (5590 m) has lost and the circulation time is 8 h. The simulation results show that compared with normal circulation, the fluid temperature in the annulus decreases significantly when loss occurs. On the one hand, when lost circulation occurs, the drilling fluid enters and reduces the temperature of the formation near the loss zone, reducing the temperature difference between the fluid in the annulus and the formation. On the other hand, the lost circulation also leads to a decrease in fluid volume flow in the upper part of the lost circulation zone and a reduction in the heat generated by fluid friction resistance. At the same time, the flow velocity of the fluid decreases, resulting in the highest point of annulus temperature moving up. In addition, with the increase in loss rate, more drilling fluid enters the formation, resulting in a further reduction in fluid temperature in the annulus.

**5.6. Influence of Loss Zone on Annulus Temperature.** Figure 10 shows the effect of loss zone on annulus fluid temperature distribution when the circulation time is 8 h. When there is a loss zone (4300 m), the loss rate is 40% of the displacement; when there are two loss zones (4000 m and 5590 m), the loss rate is 20% of the displacement respectively. The results show that the closer the loss circulation zone is to the well bottom, the lower the annulus temperature is.

Figure 11 shows the annulus temperature difference between non-lost circulation and lost circulation. The simulation results show that when the loss occurs in the upper open-hole section, the annulus temperature at the lost circulation zone decreases greatly, resulting in the appearance of an inflection point consistent with the location of the loss zone on the temperature difference curve. In the case of lost circulation, the position of the lost circulation zone can be judged according to the inflection point by predicting the annulus temperature.

**5.7. Analysis of Factors Influencing Bottom Hole Pressure.** Figure 12 shows the variation law of bottom hole pressure with cycle time under loss circulation. The simulation results show that the bottom hole pressure increases with the increase in the drilling fluid circulation time. When the drilling fluid circulation time is close to 8 h, the bottom hole pressure gradually tends to be stable. In addition, with the increase in loss rate and the gradual downward movement of lost circulation zone, the bottom hole pressure decreases accordingly. When the loss rate increases from 10 to 40%, the bottom hole pressure decreases by 0.4 MPa; when the position of the lost circulation layer moves down from 4300 to 5300 m, the bottom hole pressure decreases by only 0.1 MPa. It can be seen that the effect of loss rate on bottom hole pressure is more significant.

**6. CONCLUSIONS**

According to the hydrodynamics and energy conservation law, a coupling model of wellbore temperature and pressure field is established. The influence of temperature pressure coupling in wellbore on drilling fluid physical parameters and convective heat transfer coefficient under loss circulation is analyzed, and
the main factors affecting annulus temperature and pressure distribution are researched. The conclusions are as follows:

1. Under the loss circulation, the density and viscosity of drilling fluid decrease first and then increase with the increase in well depth. To improve the accuracy of calculation, the physical parameters of drilling fluid need to be considered as a function of temperature and pressure.

2. Different from the normal circulation condition of drilling fluid, the lost circulation reduces the volume flow in the upper part of the lost circulation zone, the annulus pressure loss, and convective heat transfer coefficient, resulting in a large decrease in the annulus temperature near the lost zone. Also, when the loss occurs in the upper open-hole section, the temperature difference curve has an inflection point at the near loss zone, and the location of the loss zone can be judged by referring to the inflection point.

3. Compared with the position of loss zone, the influence of loss rate on annulus temperature and bottom hole pressure is more significant. The temperature and pressure distribution in the wellbore can be calculated using this model according to the real-time loss rate at the construction site to appropriately adjust the drilling fluid density and ensure safe drilling.

### AUTHOR INFORMATION

**Corresponding Author**
Zhongxi Zhu — Key Laboratory of Drilling and Production Engineering for Oil and Gas, National Engineering Research Center for Oil & Gas Drilling and Completion Technology, Yangtze University, Wuhan 430100 Hubei, China; orcid.org/0000-0001-9175-7444; Email: zhuzhongxi@yangtzeu.edu.cn

**Authors**
Ao Yang — Key Laboratory of Drilling and Production Engineering for Oil and Gas, National Engineering Research Center for Oil & Gas Drilling and Completion Technology, Yangtze University, Wuhan 430100 Hubei, China; orcid.org/0000-0001-8167-9761
Nan Zhang — Engineering Technology Research Institute of PetroChina, Xinjiang Oilfield Company, Karamay 834000, China
Yuchen Ye — Engineering Technology Research Institute of PetroChina, Xinjiang Oilfield Company, Karamay 834000, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c04185

**Author Contributions**
N.Z. and Y.Y. curated the data. Z.Z. and A.Y. performed the methodology and numerical simulation and wrote the original draft. Y.Y. supervised the experiment. Z.Z. and A.Y. wrote, reviewed, and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding**
This research was funded by the National Natural Science Foundation of China (Grant No. 51204024) and the Hubei Provincial University Outstanding Young and Middle-aged Science and Technology Innovation Team Plan (Grant No. T201804).

**Notes**
The authors declare no competing financial interest.

### ACKNOWLEDGMENTS
The authors wish to acknowledge the China Scholarship Council and National Engineering Laboratory of Petroleum Drilling Technology, Leak Resistance, and Sealing Technology Research Department.

### REFERENCES

1. Hu, W.; Bao, J.; Hu, B. Trend and progress in global oil and gas exploration. *Pet. Explor. Dev.* 2013, 40, 439–443.

2. Zou, C.; Zhai, G.; Zhang, G.; Fang, Y. C.; Gray, K. E. Mitigating lost circulation: A numerical assessment of wellbore strengthening. *J. Pet. Sci. Eng.* 2017, 157, 657–670.

3. Jia, L. C.; Chen, M.; Hou, B.; Sun, Z.; Jin, Y. Drilling fluid loss model and loss dynamic behavior in fractured formations. *Pet. Explor. Dev.* 2014, 41, 105–112.

4. Tao, P. D.; Santana, C. L.; Feng, Y. C.; Gray, K. E. Mitigating lost circulation: A numerical assessment of wellbore strengthening. *J. Pet. Sci. Eng.* 2017, 157, 657–670.

5. Cai, W. J.; Deng, J. G.; Luo, M.; Feng, Y. C.; Li, J.; Liu, Q. Recent advances of cementing technologies for ultra-HTHP formations. *Int. J. Oil Gas Coal Technol.* 2022, 29, 27–51.

6. Pournemat, S.; Hajidavalloo, E.; Daneh-Dezfuli, A.; et al. Effect of temperature variation on the accurate prediction of bottom-hole pressure in well drilling. *Energy Sources, Part A Recovery Utilization and Environmental Effects* 2020, 9, 1–22, DOI: 10.1080/15567036.2020.1797943.

7. Li, M.; Liu, G.; Li, J. Thermal effect on wellbore stability during drilling operation with long horizontal section. *J. Nat. Gas Sci. Eng.* 2015, 23, 118–126.

8. Zhu, Z. X.; Wang, C. F.; Guan, Z. G.; Lei, W. N. Thermal Characteristics of Borehole Stability Drilling in Hot Dry Rock. *ACS Omega* 2021, 6, 19026–19037.

9. Dokhani, V.; Ma, Y.; Yu, M. J. Determination of equivalent circulating density of drilling fluids in deepwater drilling. *J. Nat. Gas Sci. Eng.* 2016, 34, 1096–1105.

10. Zhang, R.; Li, J.; Liu, G.; Yang, H.; Jiang, H. Analysis of Coupled Wellbore Temperature and Pressure Calculation Model and Influence Factors under Multi-Pressure System in Deep-Water Drilling. *Energies* 2019, 12, 3533.

11. Zhang, Z.; Xiong, Y.; Yu, H.; Sun, Z. Effect of the variations of thermophysical properties of drilling fluids with temperature on wellbore temperature calculation during drilling. *Energy* 2021, 214, No. 119055.

12. Zhang, Z.; Xiong, Y. M.; Mao, L. J.; Lu, J. S.; Wang, M. H.; Peng, G. Transient temperature prediction models of wellbore and formation in well-kick condition during circulation stage. *J. Pet. Sci. Eng.* 2019, 175, 266–279.

13. García, A.; Santoyo, E.; Espinosa, G.; Hernandez, I.; Gutierrez, H. Estimation of temperatures in geothermal wells during circulation and shut-in in the presence of lost circulation. *Transp. Porous Media* 1998, 33, 103–127.

14. Holmes, C. S.; Swift, S. C. Calculation of Circulating Mud Temperatures. *J. Pet. Technol.* 1970, 22, 670–674.

15. Kabir, C. S.; Hasan, A. R.; Kouba, G. E.; Ameen, M. M. Determining Circulating Fluid Temperature in Drilling, Workover, and Well Control Operations. *SPE Drill. Completion* 1996, 11, 74–79.

16. Al Saedi, A.; Flori, R. E.; Kabir, C. S. New analytical solutions of wellbore fluid temperature profiles during drilling, circulating, and cementing operations. *J. Pet. Sci. Eng.* 2018, 170, 206–217.

17. Hasan, A. R.; Kabir, C. S. Wellbore heat-transfer modeling and applications. *J. Pet. Sci. Eng.* 2012, 86–87, 127–136.
(18) Hasan, A. B.; Kabir, C. S.; Lin, D. Analytic Wellbore-Temperature Model for Transient Gas-Well Testing. SPE Reservoir Eval. Eng. 2005, 8, 240–247.

(19) Raymond, L. R. Temperature Distribution in a Circulating Drilling Fluid. J. Pet. Technol. 1969, 21, 333–341.

(20) Keller, H. H.; Couch, E. J.; Berry, P. M. Temperature Distribution in Circulating Mud Columns. Soc. Pet. Eng. J. 1973, 13, 23–30.

(21) Romero, J.; Touboul, E. In Temperature Prediction for Deepwater Wells: A Field Validated Methodology, SPE Annual Technical Conference and Exhibition, 1998.

(22) Mou, Y.; et al. Effect of the radial temperature gradient and axial conduction of drilling fluid on the wellbore temperature distribution. Acta Phys. Sin. 2013, 62, 537–546.

(23) Li, M.; Liu, G.; Li, J.; Zhang, T.; He, M. Thermal performance analysis of drilling horizontal wells in high temperature formations. Appl. Therm. Eng. 2015, 78, 217–227.

(24) Li, G.; Yang, M.; Meng, Y. F.; Wen, Z. M.; Wang, Y. M.; Yuan, Z. T. Transient heat transfer models of wellbore and formation systems during the drilling process under well kick conditions in the bottom-hole. Appl. Therm. Eng. 2016, 93, 339–347.

(25) Yang, H. W.; Li, J.; Liu, G. H.; Wang, C.; Li, M. B.; Jiang, H. L. Numerical analysis of transient wellbore thermal behavior in dynamic deepwater multi-gradient drilling. Energy 2019, 179, 138–153.

(26) Liu, X. K.; Liu, L. M.; Yu, Z. C.; Zhang, L.; Zhou, L.; Zhang, Z.; Guo, F. Study on the coupling model of wellbore temperature and pressure during the production of high temperature and high pressure gas well. Energy Rep. 2022, 8, 1249–1257.

(27) Zhu, Z. X.; Zhang, Y. J.; Lei, W. N.; Dai, A. G. Temperature and Borehole-Wall Stress Fields of Gas Drilling. Chem. Technol. Fuels Oils 2019, 54, 804–811.

(28) Zhu, Z. X.; Wang, C. F.; Ye, Y. C.; Lei, W. N. Analysis of borehole stability in gas drilling using a thermal elastoplastic coupling model. Energy Sci. Eng. 2021, 9, 2388–2399.

(29) Zhu, Z. X.; Wang, C. F.; Guan, Z. G.; Lei, W. N. Study on Distribution of Wellbore Temperature in Gas Drilling with Gradient Equations. GeoFluids 2021, 11.

(30) Yang, H. W.; Li, J.; Liu, G. H.; Wang, J. S.; Luo, K. D.; Wang, B. Development of transient heat transfer model for controlled gradient drilling. Appl. Therm. Eng. 2019, 148, 331–339.

(31) Chang, X.; Zhou, J.; Guo, Y. T.; He, S. M.; Wang, L.; Chen, Y. L.; Tang, M.; Jian, R. Heat Transfer Behaviors in Horizontal Wells Considering the Effects of Drill Pipe Rotation, and Hydraulic and Mechanical Frictions during Drilling Procedures. Energies 2018, 11, 2414.

(32) Zhang, Z.; Xiong, Y. M.; Guo, F. Analysis of Wellbore Temperature Distribution and Influencing Factors During Drilling Horizontal Wells. J. Energy Resour. Technol. 2018, 140, 11.

(33) Sun, W. T.; Wei, N.; Zhao, J. Z.; Zhou, S. W.; Zhang, L. H.; Li, Q. P.; Jiang, L.; Zhang, Y.; Li, H. T.; Xu, H. M.; et al. Wellbore Temperature and Pressure Field in Deep-water Drilling and the Applications in Prediction of Hydrate Formation Region. Front. Energy Res. 2021, 9, No. 696392.

(34) Shi, Y.; Song, X. Z.; Wang, G. S.; McLennan, J.; Forbes, B.; Li, X. J.; Li, J. C. Study on wellbore fluid flow and heat transfer of a multilateral well CO2 enhanced geothermal system. Appl. Energy 2019, 249, 14–27.

(35) Hajidavalloo, E.; Joxaei, A. F.; Azimi, A.; Shekari, Y.; Ghabadpour, S. Thermal simulation of two-phase flow in underbalanced drilling operation with oil and gas production. J. Comput. Appl. Mech. 2018, 49, 314–322.

(36) Abdelhafiz, M. M.; Hegele, L. A.; Oppelt, J. F. Numerical transient and steady state analytical modeling of the wellbore temperature during drilling fluid circulation. J. Pet. Sci. Eng. 2020, 186, No. 106775.

(37) Yang, M.; Tang, D. Q.; Chen, Y. H.; Li, G.; Zhang, X. G.; Meng, Y. F. Determining initial formation temperature considering radial temperature gradient and axial thermal conduction of the wellbore fluid. Appl. Therm. Eng. 2019, 147, 876–885.

(38) Dong, W. T.; Shen, R. C.; Liang, Q. M. Model Calculations and Factors Affecting Wellbore Temperatures During SRV Fracturing. Arab. J. Sci. Eng. 2018, 43, 6475–6480.

(39) Chen, Y.; Yu, M.; Miska, S.; et al. Fluid flow and heat transfer modeling in the event of lost circulation and its application in locating loss zones. J. Pet. Sci. Eng. 2017, 148, 1–9.

(40) Wang, J.; Li, J.; Liu, G.; Song, X. Development of a wellbore heat transfer model considering circulation loss. Arab. J. Geosci. 2020, 13, No. 85.

(41) Zhang, Z.; Xiong, Y. M.; Pu, H.; Peng, G.; Wang, J. P. Borehole temperature distribution when drilling fluid loss occurs in the two-dimensional area at the bottom-hole during drilling. J. Nat. Gas Sci. Eng. 2020, 83, No. 103523.

(42) Xiao, D.; Hu, Y. F.; Meng, Y. F.; Li, G.; Wang, T. D.; Chen, W. X. Research on wellbore temperature control and heat extraction methods while drilling in high-temperature wells. J. Pet. Sci. Eng. 2022, 209, No. 109814.

(43) Yang, M.; Yang, L. C.; Wang, T.; Chen, Y. H.; Yang, C.; Li, L. X. Estimating formation loss pressure using a coupled model of circulating temperature-pressure in an eccentric annulus. J. Pet. Sci. Eng. 2020, 189, No. 106918.

(44) Shah, S. N. Effects of Pipe Roughness on Friction Pressures of Fracturing Fluids. SPE Prod. Eng. 1990, 5, 151–156.

(45) Willhite, G. F. Over-all Heat Transfer Coefficients in Steam And Hot Water Injection Wells. J. Pet. Technol. 1967, 19, 607–615.

(46) Marshall, D. W.; Benton, R. G. A Computer Model to Determine the Temperature Distributions In a Wellbore. J. Can. Pet. Technol. 1982, 21, No. PETSOC-82-01-05.

(47) He, M.; et al. Solution and Analysis of Fully Transient Temperature and Pressure Coupling Model for Multiphase Flow. Pet. Drill. Tech. 2015, 43, 25–32.

(48) Eickmeier, J. R.; Ersoy, D.; Ramey, J. H. Wellbore Temperatures And Heat Losses During Production Or Injection Operations. J. Can. Pet. Technol. 1970, 9, No. PETSOC-70-02-08.

(49) Tao, W. Numerical Heat Transfer, 2nd ed.; Xian Jiaotong University Press: Xian, 2001.

(50) Song, X.; Guan, Z. Coupled modeling circulating temperature and pressure of gas–liquid two phase flow in deep water wells. J. Pet. Sci. Eng. 2012, 92–93, 124–131.