Numerical Simulation Study on Temperature Field of Dry Hot Rock Gas Drilling Wellbore

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Abstract. In this paper, gas drilling is used for dry hot rock drilling. According to the first law of thermodynamics and the basic principles of heat transfer, a mathematical model for the temperature field of dry hot rock gas drilling wellbore is established. The model is solved by the full implicit finite difference method. Then, relevant sensitivity analysis was carried out. The model can be used for the temperature distribution of drill string, annulus and formation under actual dry hot rock well circulation conditions.

1. Introduction

During the drilling of hot dry rocks, the high temperature and high pressure environment places higher requirements on the performance and life of downhole drilling tools and electronic instruments. The influence of downhole circulation temperature on dry hot rock drilling projects has become increasingly prominent. The application of gas drilling technology to the dry hot rock geothermal drilling process can overcome the lack of high temperature resistance of liquid drilling fluid, effectively solve the formation loss, and avoid thermal wall fracture problems.

Many scholars at home and abroad have done a lot of research work on the temperature distribution and dynamic change of wellbore and formation and the prediction of formation temperature during drilling. Ramey first proposed a comprehensive steady-state and transient heat transfer model in 1962 [1]. Willhite [2] improved on the basis of the Ramey model, and since then the wellbore temperature field calculation model has been widely used. Keller [3] established a wellbore cycle temperature field model considering the heat transfer process between casing strings, cement rings, drilling fluids, and formations, and solved it using the finite difference method. Romero [4] studied the temperature distribution in deep wells of offshore drilling wells, established a one-dimensional wellbore and three-dimensional formation unsteady-state heat transfer model, and obtained numerical solutions by finite difference methods. In China, Shigui Li, Shiming He, Cunxin Wang, etc. respectively carried out numerical simulation studies on the wellbore temperature field of gas wells and analyzed the sensitivity of the temperature field.

Due to the large differences in lithology, thermophysical parameters, and temperature and pressure systems between the upper caprock and the lower dry hot rock formations of dry hot rock drilling, existing wellbore temperature models have simplified the geothermal gradient and heat transfer process a lot, but the calculation results can not accurately describe the temperature change law of the dry-hot rock drilling wellbore and formation. Therefore, it is necessary to carry out research on the temperature field of the drilling wellbore under the two temperature and pressure systems of the upper caprock and the lower dry hot rock stratum based on the characteristics of the dry and hot rock formations. This is
useful for accurately predicting the wellbore and formation temperature during drilling and grasping the wellbore and the formation temperature distribution and dynamic change law are of great significance to the safe and fast drilling of drilling operations.

2. Heat transfer model of downhole temperature field

2.1. Physics Model of Wellbore Circulation

During the drilling of dry hot rocks, the fluid is injected into the drill pipe at normal temperature and flows downward along the drill pipe. After the water from the drill bit is ejected, it enters the annulus and flows upward along the annulus to the ground. There are three types of heat exchange during the whole cycle. The fluid inside the drill pipe, the wall of the drill pipe, the annulus fluid, and the well wall are mainly covered by convective heat transfer and heat transfer in the heat conduction mode. The effects of thermal radiation also need to be considered in the Hot and dry rock strata.

2.2. Mathematical model of wellbore and formation heat transfer

According to the first law of thermodynamics and the basic principles of heat transfer, the fluid in the drill pipe, the annulus fluid and the formation control body are taken to establish a one-dimensional fluid and two-dimensional transient mathematical model of the formation fluid. The basic assumptions in the model establishment process are as follows: (1) the fluid in the wellbore is a steady state fluid; (2) the physical parameters of the rock do not change with temperature; (3) the thermal conductivity of the downhole medium is constant and not affected by temperature; (4) The influence of radial temperature gradient and axial heat conduction on wellbore temperature distribution is ignored. Heat transfer model in wellbore.

(1) Heat transfer model in drill pipe

\begin{equation}
U_a \pi d_1 (T_a - T_c) - \rho_m q C_m \frac{\partial T_c}{\partial z} + Q_1 = \frac{\pi d_1^2}{4} \rho_m C_m \frac{\partial T_c}{\partial t}
\end{equation}
Where, \( T_c \) and \( T_a \) is the temperature in drill pipe and annulus respectively; \(^\circ\)C; \( d_i \) is the inside diameter of drill pipe, m; \( \rho_m \) is the wellbore fluid density, kg/m\(^3\); \( q \) is the wellbore fluid displacement, m\(^3\)/s; \( C_m \) is the specific heat capacity of wellbore fluid, J/(kg*\(^\circ\)C); \( Q_3 \) is the heat generated per unit length of drill pipe, W/m; \( U_{ac} \) is the comprehensive heat transfer coefficient between annulus and drill pipe, W/ (m\(^2\)*\(^\circ\)C).

(2) Annular heat transfer model of cap section

\[
h_b \pi d_a (T_f - T_a) + \rho_m q C_m \frac{\partial T_a}{\partial z} - U_{ac} \pi d_1 (T_a - T_c) + Q_2 \frac{\pi (d_a^2 - d_2^2)}{4} \rho_m C_m \frac{\partial T_a}{\partial t} \tag{2}
\]

Where, \( T_f \) is the formation temperature \(^\circ\)C; \( d_a, d_2 \) is the inside diameter of casing and the outside diameter of drill pipe, m; \( h_b \) is wall convection heat transfer coefficient, W/(m\(^2\)*\(^\circ\)C); \( Q_2 \) is the heat generated per unit length in the annulus, W/m.

(3) Annular heat transfer model of dry hot rock section

\[
U_T \pi d_a (T_f - T_a) + \rho_m q C_m \frac{\partial T_a}{\partial z} - U_{ac} \pi d_1 (T_a - T_c) + Q_2 \frac{\pi (d_a^2 - d_2^2)}{4} \rho_m C_m \frac{\partial T_a}{\partial t} \tag{3}
\]

Where, \( U_T \) is the combined convection-radiation heat transfer coefficient, W/ (m\(^2\)*\(^\circ\)C).

2.2.1. Formation heat transfer model.

\[
\frac{\partial^2 T_f}{\partial r^2} + \frac{1}{r} \frac{\partial T_f}{\partial r} = \frac{\rho_f C_f}{\lambda_f} \frac{\partial T_f}{\partial t} \tag{4}
\]

Where, \( r \) is the formation radius, m; \( \rho_f \) is the formation density, kg/m\(^3\); \( C_f \) is the specific heat capacity of the formation, J/(kg*\(^\circ\)C); \( \lambda_f \) is formation thermal conductivity, W/ (m\(^2\)*\(^\circ\)C).

2.3. Mathematical model initial and boundary conditions

(1) At the beginning, the initial injection temperature is the temperature of the fluid at the wellhead of the drill pipe, the initial temperature of the annulus is the outlet temperature at the same depth, and the fluid temperature distribution in the drill pipe and the annulus are undisturbed ground temperature;

(2) The temperature of the drilling fluid in the drill pipe, the wall of the drill pipe, and the drilling fluid in the annulus at the bottom of the well is equal, that is \( T_c (z = H, t) = T_a (z = H, t) \);

(3) At the interface between the formation and the annulus liquid, that is, on the wall of the well, the heat flow from the formation and the annulus should be equal;

(4) The formation temperature far from the borehole is not disturbed, it is the original formation temperature; the surface and the atmosphere are adiabatic.

3. Numerical solution method

3.1. Model discretization

The finite difference method is used to discretize the time and space differential equations in the established mathematical model of the temperature field, so that the mathematical model is modeled as a finite difference equation.

As shown in the figure 2, the two-dimensional grid represents the wellbore and adjacent strata. Due to the radial heat transfer from the stratum to the borehole wall, the temperature around the borehole wall changes the most violently. The stratum around the borehole wall is discretized, the grid is densely divided around the well wall, and the grid is sparsely far away from the well wall to accurately describe the temperature change around the well wall.
3.2. Discrete Partial Differential Equations

From the perspective of the stability of the equation, the partial differential equation is fully implicitly processed. Under the same grid, the calculation result of the central difference is smaller than the result of the first-order difference. Among them, the first-order space derivative in the differential equation uses the central difference, the first-order time derivative uses backward difference, and the second-order space derivative uses three-point central difference.

\[ \alpha_1 (T_c)^{k+1}_{i,j} + \beta_1 (T_c)^{k+1}_{i,j} + \gamma_1 (T_c)^{k+1}_{i+1,j} + \delta_1 (T_a)^{k+1}_{i,j} + \lambda_1 = \mu_1 (T_c)^k_{i,j} \quad (0 \leq i \leq m) \]
\[ \alpha_2 (T_a)^{k+1}_{i-1,j} + \beta_2 (T_a)^{k+1}_{i,j} + \gamma_2 (T_a)^{k+1}_{i+1,j} + \delta_2 (T_f)^{k+1}_{i,j} + \lambda_2 = \mu_2 (T_a)^k_{i,j} \quad (0 \leq i \leq i_s) \]
\[ \alpha_3 (T_a)^{k+1}_{i,j} + \beta_3 (T_a)^{k+1}_{i,j} + \gamma_3 (T_a)^{k+1}_{i+1,j} + \delta_3 (T_f)^{k+1}_{i,j} + \lambda_3 = \mu_3 (T_a)^k_{i,j} \quad (0 \leq i \leq m) \]
\[ \alpha_4 (T_f)^{k+1}_{i,j-1} + \beta_4 (T_f)^{k+1}_{i,j} + \gamma_4 (T_f)^{k+1}_{i,j+1} = \lambda_4 (T_f)^k_{i,j} \quad (0 \leq j \leq n) \]

**Figure 2.** Meshing of wellbore temperature field.

The depth direction of the well is represented by \( i \) and the radial direction is represented by \( j \). The number of nodes in the cap zone is \( i_s \), then the number of annulus nodes in the dry and hot rock zone is \( i-i_s \). Based on the above grid division, the model equations of the five regions can be discretized as follows:

4. Calculation example of temperature field in dry hot rock drilling cycle

4.1. Basic calculation parameters

Example data: ground atmospheric pressure \( 10^5 \text{pa} \); the surface temperature is \( 20 \^\circ\text{C} \), the geothermal gradient of cap section (mud shale) is \( 2.5 \^\circ\text{C}/100\text{m} \), and the geothermal gradient of hot dry rock strata (granite) is \( 5.0 \^\circ\text{C}/100\text{m} \). The inlet temperature of drill pipe is \( 40 \^\circ\text{C} \), the depth of well is \( 5000\text{m} \), the depth of cap section is \( 3000\text{m} \), and the depth of dry hot rock section is \( 3000\text{m}-6000\text{m} \). The drill bit diameter is \( 149\text{mm} \), the outer diameter of drill pipe is \( 88.9\text{mm} \), the inner diameter of drill pipe is \( 66.1\text{mm} \), and the gas injection volume is \( 180\text{m}^3/\text{min} \). The thermophilic data are shown in the table 1.
Table 1. Basic calculation parameters.

| Physical parameters       | air       | Drill pipe | Cap rock | Dry hot rock |
|---------------------------|-----------|------------|----------|-------------|
| density /\(\text{kg/m}^3\) | 1.164     | 264        | 285      | 285         |
| Specific heat /\(\text{J/(kg} \cdot \text{°C})\) | 1005      | 400        | 830      | 920         |
| Thermal conductivity /\(\text{W/(m}^2 \cdot \text{°C})\) | 0.026     | 43.75      | 2.24     | 3.15        |

4.2. Analysis of calculation results

Can be seen from figure 3, the temperature and annulus temperature in the drill pipe near the wellhead are both higher than the formation temperature, and the temperature in the drill pipe is higher than the annulus temperature, so the heat transfer direction near the wellhead is the drill pipe to the annulus and then to the formation. As the depth increases, the heat release temperature in the drill pipe decreases, while the heat absorption temperature in the annulus increases. When the hole reaches a depth of 1500 meters, the temperature curve in the drill pipe intersects the temperature curve of the annulus, that is, the heat release in the drill pipe reaches a balance with the heat absorption of the annulus, and the temperature in the annulus is 55°C. As the depth of the well increases, the heat transfer direction is from the formation to the annulus, and the annulus temperature is higher than the temperature in the drill string. When the well reaches a depth of 3000 meters, that is, the boundary between cap layer and dry and hot rock segment, the geothermal gradient increases, and the temperature in drill string and annulus increases sharply with the increase of geothermal gradient. In the dry and hot rock section, the proportion of radiant heat transfer increases, and the wellbore temperature increases with the influence of lower heat transfer, but it is always lower than the formation temperature, and the temperature difference with the formation is maintained at about 3°C. As can be seen from the profile of the whole wellbore and formation temperature, firstly, the temperature of the wellbore annulus changes the most rapidly at the junction of cap and dry hot rock. Secondly, the maximum temperature of the whole wellbore is not at the bottom of the well, but about 100m away from the bottom of the well. Moreover, due to the joule Thomson effect at the bit, the temperature at the bottom of the well drops suddenly.

4.3. Sensitivity analysis

4.3.1. The cycle time. FIG. 4 is the functional relationship curve of fluid temperature and circulation time in the annulus, which reflects the law of fluid temperature in the annulus changing with circulation time. From the general trend, the influence of circulation time on the wellbore annulus temperature is obvious. Under the condition that other parameters remain unchanged, the fluid temperature in the annulus decreases with the increase of circulation time. The influence of fluid circulation time on the annulus temperature is relatively low in the cathing interval of about 0-2000 meters, while the influence of fluid circulation time on the annulus temperature is relatively obvious in the dry hot rock formation. However, with the increase of circulation time, the degree of temperature change in the annulus tends to be slow.

4.3.2. Cyclic displacement. FIG. 5 is the functional relationship curve of fluid temperature and circulating displacement in the annulus, which reflects the law of fluid temperature in the annulus changing with circulating displacement. Can be seen from the figure, with the increase of circulating displacement, the temperature in the annulus of the wellbore decreases, but in the shallow section, that is, 0-1000 meters, the circulating displacement has little effect on the annulus temperature. The decrease in annulus temperature is due to the increase in circulating flow rate of circulating fluid in the wellbore caused by the increase in circulating displacement, which enhances the wellbore cooling effect and also strengthens the joule Thomson effect at the bit, resulting in a significant sudden drop in the temperature at the bottom of the well.
4.3.3. The gas specific heat. FIG. 6 is the functional relationship curve of fluid temperature and specific heat of gas in the annulus, which reflects the law of fluid temperature in the annulus changing with specific heat of gas. In this paper, the specific calorific values of air, nitrogen and methane are selected for discussion. As can be seen from the figure, when other parameters remain unchanged, the change of specific heat of gas in the common gas circulating medium has a significant impact on the temperature in the wellbore annulus. When the specific heat of gas increases by about 52.3%, the bottom hole temperature decreases by 9°C; when the specific heat of gas decreases by about 18.4%, the bottom hole temperature increases by 4°C. Specific heat is affected by temperature and pressure, so a reasonable estimate of this parameter is needed.

4.3.4. Geothermal gradients in the dry-hot rock segment. FIG. 7 is the functional relationship curve of fluid temperature in the annulus and geothermal gradient in the dry-hot rock segment, which reflects the law of fluid temperature in the annulus changing with geothermal gradient in the dry-hot rock segment. As can be seen from the figure, the change of ground temperature gradient has a significant impact on the annular temperature of the wellbore. The annular temperature of the dry-hot rock segment increases with the increase of the low temperature gradient, and the bottom hole temperature increases or decreases by about 10°C when the local temperature gradient increases or decreases by 1°C every 100 meters. Therefore, the prediction of geothermal gradient plays an important role in the study of wellbore temperature field.

4.3.5. The annular clearance. FIG. 8 is the functional relationship curve of fluid temperature in the annulus and annulus clearance, which reflects the law of fluid temperature change with annulus clearance. When the wellbore size of 149mm remained unchanged, the changed wellbore sizes were 88.9mm, 114.4mm, and 127.0mm. As can be seen from the figure, with the increase of the size of the wellbore, that is, the reduction of annulus clearance, the temperature of the wellbore annulus also decreases. The decrease of annulus temperature is caused by the increase of circulating flow rate of circulating fluid in the wellbore, which enhances the cooling effect of the wellbore.

![Figure 3. Wellbore temperature distribution.](image1)

![Figure 4. Annulus temperature distribution under different cycle times.](image2)
5. Conclusion

(1) The model can be used to calculate the wellbore temperature field and formation temperature changes at any time during the cycling process. In the dry and hot rock section, the proportion of radiant heat transfer increases, and the wellbore temperature increases with the influence of lower heat transfer, but it is always lower than the formation temperature, and the temperature difference with the formation is maintained at about 3 °C. As can be seen from the profile of the whole wellbore and formation temperature, firstly, the temperature of the wellbore annulus changes the most rapidly at the junction of cap and dry hot rock. Secondly, the maximum temperature of the whole wellbore is not at the bottom of the well, but about 100m away from the bottom of the well. Moreover, due to the joule Thomson effect at the bit, the temperature at the bottom of the well drops suddenly.

(2) Through sensitivity analysis, it can be seen that changes in circulation time, circulating displacement, gas specific heat and annulus clearance all have an impact on the wellbore temperature field. Therefore, relevant parameters need to be accurately obtained to predict the wellbore temperature field change. As far as formation parameters are concerned, the change of geothermal gradient has the most obvious influence on wellbore temperature field. Therefore, the study of detecting formation temperature gradient on wellbore temperature field is particularly critical.

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