Temperature of the Core Tube Wall during Coring in Coal Seam: Experiment and Modeling

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ABSTRACT: Temperature is the primary factor affecting the law of coal gas desorption. When the core method is used to measure the coal seam gas content (CSGC), the temperature of the coal core sample (CCS) will increase because the heat generated by the core bit cutting and rubbing the coal is transferred to the CCS through the core tube. To solve the above problems, the temperature of the core tube wall during coring at core depths of 10, 20, and 30 m was measured by a self-designed temperature measuring device. The thermodynamic models of the core bit and the core tube during coring were established. The thermal flux of the system at different stages was inverted numerically by the dichotomy method. The reliability of the model was verified by comparing the numerical simulation results with the field measurement results. The main influencing factors during coring were studied by numerical simulations. The results show that the temperature change of the core tube wall goes through four stages: slowly rising, fast rising, slowly rising, and slowly falling, which correspond to the process of pushing the core tube, drilling the CCS, and the early stage and later stage of withdrawing the core tube, respectively. The maximum temperature of the core tube wall appears in the first 5 min of withdrawing the core tube and increases with the increase of core depth. When the core depth is 30 m, the maximum temperature of the core tube wall reaches 105.17 °C. The temperature of the measuring point at the end of drilling the CCS and the maximum temperature during coring linearly increase with the core depth, friction heat generated while pushing the core tube, and coal strength. This study can provide a basis for further research on the dynamic distribution characteristics of temperature in the CCS during coring, which is of profound significance to calculate the gas loss amount and CSGC.

1. INTRODUCTION

In China, coal seam gas content (CSGC) is not only an indispensable basic parameter for the evaluation of coal seam gas risk degree, the control of gas disaster, and the exploitation and utilization of coalbed methane (CBM) resources but also a main index for the prediction of coal and gas outburst risk and the test of regional outburst prevention measures.1,2 Therefore, the accurate determination of CSGC is significant for the safety of coal mine and CBM exploitation.3 The methods of determining CSGC mainly include the direct method and the indirect method.4,5 Due to the high cost and long period of the indirect method, the direct method is the primary method to measure CSGC.6 The Direct Method of Determining Coalbed Gas Content in the Mine stipulates that the determination of CSGC must adopt the core tube sampling or other effective verified fixed-point sampling methods, and the use of the core tube sampling is recommended.7

However, the friction between the core bit and the core tube and the coal wall during coring produces heat, and the heat generated from the core bit and the core tube wall is transmitted to the coal core sample (CCS), resulting in an increase in the temperature of the CCS. With the increase of the coal core temperature, the gas adsorption capacity decreases, which accelerates the gas desorption of CCS and increases the gas loss amount during coring.8−14 Because the CCS is in a variable temperature environment during coring, the error of calculating the gas loss amount during coring by using the law of gas desorption under a normal temperature and pressure is large, which leads to gas outburst in low-gas mines.15,16 Therefore, it is necessary to study the variation law of CCS temperature and gas desorption in the coring process to accurately calculate the gas loss and CSGC. In order to achieve this goal, the heating law of the core tube caused by the heating between the core drill bit and the core tube and the coal mass is very important.

Many scholars have studied the heat generated during drilling. Larsen-Basse17 found that the cutting friction generated

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between the drill bit and the wall of hole in the process of drilling rock can cause the temperature of the drill bit reaching about 500 °C. The instantaneous high temperature of the drill bit reached 1000 °C, while 70−95% of the energy obtained by the drill bit was consumed in heating.18 Abbas19 et al. found that the absorption coefficient of the drilling tool affected the cutting temperature by simulating the heat distribution of twist drill pipe drilling. When the cutting edge breaks hard rock, most of the cutting work is converted into cutting heat, resulting in a rapid increase in bit temperature.20 Srimaruthi21 et al. systematically studied the influence of bit design parameters on cutting temperature and concluded that the bit screw angle, the drilling location, and lithology had a significant impact on the increase of temperature caused by the clog of the drain hole. Delgadillo22 et al. found that the spindle speed and thrust speed of the drill had a great influence on bit heating, and the temperature of bit rose rapidly to 100 °C within 5 s during dry drilling. The heat generated during drilling rock was mainly affected by the geometrical shape of the drilling tool, thermal properties, and drilling parameters, such as cutting force, cutting speed, and propulsion speed.23−26 At the same time, the average rising temperature of cutting edge was proportional to the square root of propulsion speed when other conditions were the same.27,28

It is difficult to directly measure the temperature of CCS during coring in the laboratory for the following reasons. First, CCS entering the core tube is a dynamic process. Second, large coal is difficult to obtain. Third, the stress state of coal is difficult to achieve in the laboratory. To obtain the temperature variation characteristics of coal core during the coring process, the temperature of the core tube wall surface during coring for a core depth of 10, 20, and 30 m was measured by a self-designed temperature measuring device. The thermodynamic models of the core bit and the core tube during coring were established.

The thermal flux of the system at different stages was inverted numerically by the dichotomy method. The reliability of the model was verified by comparing the numerical simulation results with the field measurement results. In addition, the numerical simulation results revealed the effects of coring depth, friction heat flux generated while pushing the core tube, and coal seam strength on the temperature of the core tube wall during coring.

2. RESULTS AND DISCUSSION

2.1. Field Test Results. The temperature variations of measuring points on the core tube wall during coring for a core depth of 10, 20, and 30 m are shown in Figure 1a−c, respectively. As can be seen from Figure 1, the temperature variation of measuring points on the core tube wall is basically consistent under different core depths. The temperature of the core tube wall goes through five stages during coring: I initial temperature stage, II slowly temperature rising stage, III rapidly temperature rising stage, IV slowly temperature rising stage, and V slowly cooling stage. Taking the core depth of 10 m as an example, (1) in the stage of I, the temperature of the core tube wall is relatively stable, which corresponds to the process of installing a temperature measuring tube, and the tube wall temperature is determined by the ambient temperature of the test site. (2) In the stage of II, the temperature of the core tube wall rises slowly, which corresponds to the process of pushing the core tube. The main reason for the increase of core wall temperature is the residual coal slag in the borehole, or under the influence of gravity and geostress, the borehole may deform or even collapse, resulting in a slow rise of core wall temperature to produce certain heat through the coring process. (3) In the stage of III, the temperature rises rapidly, which corresponds to the process
of drilling CCS. In this process, the core bit generates a lot of heat when cutting coal, which rapidly increases the temperature of the core tube wall. At the end of drilling CCS, the temperature of the tube wall reaches the extreme point. (4) In the stage of IV, the temperature rises slowly, which corresponds to the first 5 min when withdrawing the coal core tube. In this process, the temperature of the core drill bit is higher than that of the core tube, and then the heat will continue to transmit to the core tube, resulting in a slow rise in the temperature of the measuring point. (5) In the stage of V, the temperature falls slowly, which corresponds to the process of withdrawing the core tube. Due to the process of drilling CCS, the temperature of the air in the hole is high, which makes the temperature of the core tube wall drop slowly.

The key temperature parameters of the core tube wall during coring are discussed as follows and can be seen in Table 1.

1. The time of pushing the core tube is less than that of withdrawing the tube, and the heating rate during pushing is higher than the cooling rate during withdrawing for the same core depth. This is because the time required to install the core tube is shorter than the time required to withdraw the drill pipe, which shows that the time of pushing the core tube is less than that of withdrawing the tube. At the initial stage of withdrawing the core tube, the temperature of coring bit is higher than that of the core tube wall, and the heat is transferred to the core tube wall, resulting in a rise in the temperature of the measuring point to the maximum temperature. At the same time, the temperature of hole-gas is high after the process of drilling CCS. Therefore, the cooling rate during withdrawing is lower than the heating rate during pushing.

2. It takes 3 min to drill the CCS under different core depths. This is because the length of the core pipe is 1.5 m in this test, and the drilling parameters of the drill are the same, so the time required of drilling CCS for the same length and quality is the same.

3. The maximum temperature of the measuring point on the core tube wall increases with the increase of the core depth. For example, when the core depths are 10, 20, and 30 m, the maximum temperatures of the measuring point on the core tube wall are 63.13, 83.09, and 105.17 °C, respectively.

### 2.2. Thermodynamic Theory and Numerical Simulations of the Coring Process

The coring process can be regarded as the rotating jump fracture process of drill bit under the action of axial pressure and rotary cutting force. The coal body during drilling must undergo surface micro-cracks, elastic deformation, plastic deformation, and other processes, resulting in cracks and expansion, and eventually leading to brittle fracture. The brittle fracture stage is the main stage in which a large number of new surfaces and coal spalling become debris, and the thermal work conversion mainly occurs in this stage. The heat generated is distributed between the bit and coal and is reflected in their temperature rise. When the bit breaks into the coal seam, the axial displacement of the bit is very small in unit time, so the work done by the axial force can be almost ignored. Friction and wear between drill bit and coal is the main factor leading to the temperature rise of drill bit. Therefore, the rising of the temperature for the bit is mainly composed of two parts, one is the shear heat generated by the coal shear failure under the action of the bit edge and the other is the heat generated by the friction between the bit and the coal and the debris not discharged in time.

The increase of temperature for the core bit is not only affected by the drilling speed and torque, bit diameter, physical characteristics of coal, and stress state of coal but also by the number of cutting edges, cutting angle, leading edge surface, trailing edge surface, side edge surface, and other factors. In addition, the operation level of drilling rig operators is also an important factor affecting the temperature change of the coring bit. If human factors are excluded, material parameters, drilling parameters, coal seam stress state, and physical properties are the main factors affecting the core bit temperature during drilling.

### 2.2.1. Core Bit—Core Tube Heat Conduction Theory

The heat generated by the coring bit cutting coal will be transferred from the coring bit to the coring tube wall. During coring, in the temperature test of measuring points on the core tube, we tested the three stages of core pushing tube, core drilling, and core pulling tube. The generated heat not only exchanges with the outside world but also transmits between the core bit and the core tube.

The differential equation of transient temperature field in the core bit—core tube in the Cartesian coordinate system satisfies Formula 1.
\[ \rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) - \rho Q = 0 \]  
\text{(1)}

where \( \rho \) is the material density, kg/m\(^3\); \( c_p \) is the specific heat capacity of the materials, J/kg°C; \( k_x, k_y, \) and \( k_z \) are the thermal conductivities of the material along the \( X, Y, \) and \( Z \) directions, respectively, W/(m·K); \( Q \) is the density of the heat source inside the object, W/(m\(^3\)·K); \( Q \) is the given heat flux on the boundary; \( T \) is the given external ambient temperature in the natural convection condition on the \( \Gamma_3 \) boundary. In forced convection condition, it is the adiabatic wall temperature of the boundary layer; \( \Gamma_1, \Gamma_2, \) and \( \Gamma_3 \) boundaries are also called the first, second, and third boundary conditions; and \( h \) is the convective heat-transfer coefficient, W/(m\(^2\)·°C).

The friction heat generated between the core bit and the coal wall in the process of advancing the core tube can be simplified as the second boundary condition of constant heat flow. During CCS drilling, the heat generated by the coring bit during coal cutting can be simplified as the second boundary condition of constant heat flow. When withdrawing the core bit and the core tube, the gas between the core bit and the wall undergoes convection heat transfer, which can be simplified as the third boundary condition with a constant convective heat-transfer coefficient.

2.2.2. Core Bit—Core Tube Physical Model Establishment.

According to the size of the core tube, which is shown in Figure 2, and the size of the core bit, the connection model between the core bit and the core tube was established, as shown in Figure 3.

The core tube model, the core bit model, and the overall model of the core tube and the core bit are as shown in Figure 3a–c, respectively. The coring system includes four parts, such as the core bit, the core tube, the coal, and methane in the borehole. The parameters of various materials are shown in Table 2.

2.2.3. Numerical Calculation Results and Model Validation.

There are three stages that cause the temperature rise of the core tube wall during coring. They are as follows: (1) the friction heat generated between the side of the core bit and the coal body during the process of pushing the coring tube; (2) the cutting and friction heat of the core bit in the process of drilling CCS; and (3) heat transferring between gas and the core tube in the process of withdrawing the core tube. During the numerical simulation, the dichotomy method was adopted to adjust the heat flux of the drill in these three stages. The heat fluxes consistent with the experimental results were obtained by comparing the temperature variation of the measured points on the core tube wall in the field test. When the heat flux in the first stage is 42 kW/m\(^2\), the heat flux in the second stage is 80 kW/m\(^2\), and the convective heat-transfer heat flux in the third stage is −0.5 kW/m\(^2\). The numerical simulation results of the temperature at the measured point are basically consistent with the field test results.

The results of the field test and numerical simulation are shown in Figure 4. As can be seen from Figure 4, the variation trend and the quantitative results of temperature at the measuring point obtained by numerical simulation are consistent with the experimental results. When the core depth is between 10 and 30 m, the relative error between the field core wall temperature and the numerical simulation results is
between −5% and 15%, which meets the engineering requirements. The reason is that the numerical model simplifies the drilling coring process, resulting in a slight difference in the number. In short, when the above heat flux is used, the core depths are 10, 20, and 30 m, respectively, and the numerical simulation results are consistent with the measured results. This not only proves the feasibility of the established model and algorithm but also verifies the same coal seam coring, the same drilling parameters, the friction heat flux generated in the process of drilling pipe, and the cutting and friction heat flux generated in the mining process. Drilling CCS has nothing to do with the coring depth; that is, the heat flux of different coring depths is consistent in the same process.

The temperature cloud of the core bit—core tube at the end of the three stages of the coring process at a depth of 10, 20, and 30 m is shown in Figures 5–7, respectively. It can be seen from Figures 5–7 that the temperature of the core bit is the highest during coring at different core depths because the heat generation position during coring is at the position of the cutting edge and the friction surface of the core bit. At the end of the first stage, the heat generated by the core drill began to transfer to the core tube, and the wall temperature of the core near the core drill tended to increase. At the end of the second stage, the heat of the core drill has been transferred to the core tube. The closer to the core drill, the higher the temperature of the core tube wall. The temperature of the core tube wall is negatively correlated with the distance of the core bit. By the end of the third stage, heat has been transferred to the other end through the core tube near one end of the core bit. As can be seen from Figures 5–7, the maximum temperatures of the core

### Table 2. Parameters of the Model

| Parameters  | Values | Units   | Description of Parameters                        |
|-------------|--------|---------|--------------------------------------------------|
| rho_coal    | 1440   | kg/m³   | density of the coal sample                       |
| nu_coal     | 0.34   |         | Poisson ratio of the coal sample                 |
| E_coal      | 0.599  | Gpa     | elastic modulus of the coal sample               |
| k_coal      | 0.20   | W/(m·K) | thermal conductivity of the coal sample          |
| Cp_coal     | 1000   | J/kg°C  | specific heat capacity of the coal sample        |
| U           | 0.4    |         | friction coefficient between the coal sample and core bit |
| rho_steel   | 7850   | kg/m³   | density of the core bit and core tube            |
| nu_steel    | 0.3    |         | Poisson ratio of the core bit and core tube      |
| E_steel     | 206    | Gpa     | elastic modulus of the core bit and core tube    |
| k_steel     | 0.25   | W/(m·K) | thermal conductivity of the core bit and core tube |
| Cp_steel    | 460    | J/kg°C  | specific heat capacity of the core bit and core tube |
| rho_ch4     | 716    | kg/m³   | density of methane                               |
| k_ch4       | 0.002  | W/(m·K) | thermal conductivity of methane                   |
| Cp_ch4      | 460    | J/kg°C  | specific heat capacity of the coal sample        |
| mu_ch4      | 1.08 × 10⁻⁵ | m²/s | viscosity coefficient of methane                |
| h           | 10     | W/m²    | heat-transfer coefficient between steel and methane |

Figure 4. Numerical simulation and field test results.
bit during drilling CCS at a core depth of 10, 20, and 30 m are 74.3, 93.95, and 107.3 °C, respectively.

2.3. Factors Affecting the Rise of Temperature in the Core Tube during Coring. 2.3.1. Core Depth. When the same drilling rig and drilling parameters are used for coring in the same coal seam, the heat flux generated in the process of pushing the core tube, drilling the CCS, and withdrawing the core tube at different core depths is unchanged; that is, the heat flux in the first stage is 42 kW/m², the heat flux in the second stage is 80 kW/m², and the heat flux in the third stage is −0.5 kW/m².

When the core depth is different, the temperature change of the core wall measuring point is shown in Figure 8. It can be seen from Figure 8 that with the increase of core depth, the temperature of measuring points on the pipe wall gradually increases. At different core depths, the temperature of the measuring point has the same slope of change in the three stages. The time of pushing the core tube (the first stage) is different in different core depths. The time of the first stage and the temperature at the end of the first stage increase with the increase of core depth. This is because when only considering the effect of core depth during coring, the deeper the core depth is, the longer the core bit—core tube pushing in the hole, the longer the time of the friction heat transferring to the bit is, the higher the core bit temperature is, and the higher the temperature of the measuring point is. The core depth determines the length of the first stage and affects the temperature of the core tube wall by influencing the time

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Figure 5. Temperature nephogram of the core bit and core tube at a coring depth of 10 m: (a) end of first stage; (b) end of second stage; and (c) end of third stage.

Figure 6. Temperature nephogram of the core bit and core tube at a coring depth of 20 m: (a) end of first stage; (b) end of second stage; and (c) end of third stage.
dimension. It indicates that the deeper the core depth is, the higher the wall temperature of the core is.

The temperature at the end of drilling the CCS, that is, the temperature at the end of the second stage, and the highest temperature in the whole coring process show a linear increasing trend with the increase of core depth, which is shown in Figure 9. Among them, $T_2$ represents the temperature of measuring point at the end of the second stage; $T_{\text{max}}$ is the maximum temperature of measuring point during coring, and the following of this paper in Figures 11 and 13 are the same meaning.

2.3.2. Frictional Heat during the Process of Pushing the Core Tube. Taking a depth of 30 m as an example, considering the influence of friction while pushing the core tube process (namely, the first stage), the borehole deformation and the amount of coal falling from the borehole change the friction heat of the core, but the heat flux in other coring processes remains unchanged. Here, the heat fluxes in the first stage are 28, 42, and 56 kW/m². The heat flux in the second stage is 80 kW/m², and the heat flux in the third stage is $-0.5$ kW/m². In the process of pushing the core tube, the larger the friction heat generated in the core bit, the higher the temperature of the core tube wall temperature. That is, the larger the friction heat in the first stage, the higher the temperature of the core tube wall.

The influence of friction heat change on the temperature of measuring points on the core tube wall during the process of pushing the core tube is shown in Figure 10. As can be seen from Figure 10, the higher the friction heat generated by the rubbing between the side of the core bit and the coal wall, the more heat is transferred to the measuring point of the tube wall through the core bit and the core tube, resulting in a gradual rise in the temperature of the measuring point. The temperature variation trend of the measuring point is the same under different friction heat fluxes. The temperature variation trend of the measuring point is the same under different friction heat fluxes. However, due to the different friction heat fluxes during the propulsion of the core tube, the temperature of the measuring point changes.

Figure 7. Temperature nephogram of the core bit and core tube at a core depth of 30 m: (a) end of first stage; (b) end of second stage; and (c) end of third stage.

Figure 8. Temperature variations of temperature measuring points at different coring depths.

Figure 9. Maximum temperature of measuring points at different core depths.
greatly in the first stage. At the same core depth, the higher the friction heat flux is, the higher the measuring point temperature is.

As with the increase of friction heat flux, the temperature at the end of pushing the core tube and the maximum temperature increase linearly during coring, which are shown in Figure 11.

2.3.3. Coal Strength. Studies have shown that the higher the strength of coal, the greater the heat generated during drilling.27 Taking the core depth of 30 m as an example, considering the influence of coal strength, the cutting heat and the friction heat of the core bit change in the second stage (drilling the CCS process), while the heat flux in the process of pushing the core tube and the process of withdrawing the core tube remains unchanged. Here, the heat flux in the first stage is 42 kW/m²; the heat fluxes in the second stage are 60, 80, 100, and 400 kW/m²; and the convective heat flux in the third stage is −0.5 kW/m².

In the process of drilling the CCS (in the second stage), the higher the coal strength, the higher the cutting heat and friction heat of the core bit, the higher the temperature of the core bit, and the higher the temperature of the measuring point. The influence law of the core bit cutting and friction heat flux changes on the temperature of the measuring point during coring are shown in Figure 12. As can be seen from Figure 12, with the increase of coal strength, the cutting heat and friction heat increase during the coring process, and the temperature of the measuring point in the core tube wall rises gradually. The heat generated by the friction between the bit chip and the side face and the coal wall is transmitted to the temperature measuring point through the bit and the temperature measuring tube. The frictional heat generated during the process of pushing the core tube (the first stage) is the same, so the temperature of the test point is consistent. However, the heat flux generated by drilling the CCS with different coal strengths in the second stage is different, and the temperature variation trend at the test point is the same, but the temperature change is different. In the case of heat fluxes 60, 80, and 100 kW/m², the temperature change is small, which is due to the short time of drilling the CCS (3 min).

As with increase of the coal strength, the temperature at the end of drilling the CCS and the maximum temperature during coring increase linearly, which are shown in Figure 13.

3. CONCLUSIONS

In this paper, based on the self-designed temperature measuring device, the temperature of the core tube wall in the core-cutting stage and the withdrawing stage during coring at a core depth of 10, 20, and 30 m were measured. Thermodynamic models for the three stages of the core bit—core tube were established. The reliability of the model was verified by comparing the numerical simulation results with the field measurement results. The effects
of core depth, frictional heat generated while pushing the core tube, and coal strength on the temperature of the core tube wall during coring were studied by numerical analysis. The main results are as follows.

1. The temperature change of the core tube wall during coring can be divided into five stages: stability stage, slowly rising stage, fast rising stage, slowly rising stage, and slowly falling stage, which correspond to the process of installing the core tube, pushing the core tube, drilling the CCS, and early stage and later stage of withdrawing the core tube, respectively.

2. The maximum temperature of the core tube wall increases with the increase of the core depth. When the core depths are 10, 20, and 30 m, the maximum temperatures of the measuring point of the core tube wall are 63.13, 83.09, and 105.17 °C, respectively.

3. For the same core depth, the time required for pushing the core tube process is less than the time required for withdrawing the core tube, and the heating rate during drilling in the process is higher than the cooling rate during withdrawing out.

4. The temperature of the measuring point at the end of drilling CCS and the maximum temperature of the measuring point during coring are positively correlated with the core depth, friction heat generated during drilling, and coal strength.

4. EXPERIMENTAL SYSTEM AND EXPERIMENTAL METHOD

4.1. Temperature Measuring Device. The automatic temperature acquisition device of the core tube wall is mainly composed of four parts, including the core bit, the core tube (the temperature measuring tube), the thermocouple sensor, and the automatic temperature acquisition system, as shown in Figure 14. The core tube is a cylindrical hollow tube with open ends made of stainless steel, a diameter of 89 mm, and a length of 390 mm, which is used to install the automatic temperature acquisition system and temperature sensor inside. The diameter of the core bit is 108 mm and is connected to the core tube by thread. The position of the temperature sensor is arranged on the tube wall, as shown in Figure 14. The measurement range of the temperature sensor is between 0 and 300 °C, and the measurement error is a fluctuation of 0.5 °C. The automatic temperature acquisition system is mainly composed of a microcontrol unit module, a temperature signal conditioning module, a data storage module, a real-time clock module, a monitoring module, and a power module. The entire temperature acquisition device needs to be installed on the well, and each module can work continuously for 24 h after initialization.

4.2. Field Test Site and Test Procedure. The test place is the return air lane of the east fourth working face in the 15th mining area of level 1 of no. 2 coal seam in Jiulishan Coal Mine of Henan Jiaozuo Coal Mining Group. The original CSGC in the working face is 31 m³/t, the gas pressure is 1.74 MPa, the gas absorption constant \( a \) is 41.841 m³/t, \( b \) is 0.985 MPa⁻¹, the ash content of coal is 7.64%, the volatile content is 11.19%, and the moisture content is 1.87%. The permeability coefficient of coal is between 0.126 and 0.457 m²/(min·hm), and the attenuation coefficient is between 0.015 and 0.0389 d⁻¹. In brief, the permeability of the coal seam is poor, and the gas extraction is difficult.

The test drilling rig was a Tiefuli ZDY4500LXY crawler hydraulic drilling rig with a rated torque of 1000~4500 N·m and a rated speed of 60~215 rpm. The diameters of the core bit and the core tube were 113 and 89 mm, respectively. The core tube and the drill pipe were connected by a reducer joint. The core boreholes with an inclination angle of 12° were arranged at 163, 164, and 165 m of the return air lane of the east fourth working face. Considering that the depth of the borehole should exceed the depth of the heat regulating ring in the roadway and the endurance time of the temperature measuring device, the temperature of the measuring point on the core tube wall during coring was measured at depths of 10, 20, and 30 m, respectively. In order to minimize or eliminate the influence of workers’ operations and other factors on test data, the following measures were taken. First, complete coal was taken to avoid the influence...
of large cracks on sampling. Second, the drilling speed and rotational speed should be kept stable. Third, the vertical bedding plane was sampled. Fourth, we chose skilled and experienced workers when drilling and coring on site to minimize or eliminate the impact of workers’ operations on the test data.

The coring process includes five processes, such as drilling hole, withdrawing of the drill pipe, pushing the core tube, drilling the CCS, and withdrawing the core tube, which is shown in Figure 15. Combined with Figure 15, the test steps of the temperature of measuring points on the core tube during coring are as follows:

1. The coring hole was constructed at 163 m of the air return lane on the East Fourth working face, as shown in Figure 15a. When the drilling bit reached 10 m, the drilling was stopped and the drilling pipe was cleaned by high pressurized air, as shown in Figure 15b, and the shaped hole was obtained, as shown in Figure 15c.

2. The drilling bit was removed quickly, the core bit and the core tube were installed, namely, the temperature measuring the core tube, the core bit was pushed to the bottom of the hole, as shown in Figure 15d, then the CCS was drilled, as shown in Figure 15e, and the core tube and drill pipe were withdrawn when the CCS was filled with the core tube, as shown in Figure 15f.

3. After the completion of the coring process, the CCS was poured into the desorption tank for sealed preservation. The temperature test of the core tube wall during coring with a depth of 10 m was completed.

4. When the temperature of the core tube wall was restored to the ambient temperature, steps (1–3) were repeated with the same drilling rig and drilling parameters at 164 and 165 m of the return air lane of east fourth working face to measure the temperature of the core tube wall during coring with a depth of 20 and 30 m, respectively.

The three processes, such as pushing the core tube, drilling the CCS, and withdrawing the core tube, are the heat sources that cause the rise of temperature on the core tube wall and the CCS. Therefore, only these three processes need to be considered in the temperature measurement of the core tube wall during coring. In the process of pushing the core tube, the friction between the core bit and the coal wall increases the temperature of the air inside the core tube and the wall of the core tube. In the process of drilling the CCS, the elastic and plastic deformation of the coal body under the action of cutting and friction of the core bit will produce cutting heat and friction heat, which will be mostly transferred to the core bit and the core tube wall. When CCS enters the core tube, the temperature of the core tube wall is higher than that of CCS, and the heat is transmitted from the core tube wall to CCS. In the process of withdrawing the core tube, the air inside the core drill is convective heat transfer with the core wall and coal wall.

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Q.W. conceived the experiment, analyzed the results, and drafted the manuscript; Z.W., J.Y., F.A., J.D., and W.K. coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

Notes
The authors declare no competing financial interest.

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