Research on Factors and Influencing Correlation of Coal Core Temperature during Coring

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ABSTRACT: The core-tube method is a common method to measure the coal seam gas content (CSGC). However, cutting heat and friction heat will be generated in the core-tube coring process, which will increase the coal core temperature and the coal core gas loss, thus resulting in a large error in the determination of the gas content. The accuracy of the gas content determination is closely related to the temperature variation of coal core during core-taking. Based on this, the team developed the “thermal effect simulation device of coal core in the core-taking process” and carried out the temperature change test experiment of the coal core in the core-taking process under different conditions. The results show that the temperature variation of the coal core during the core-taking process shows four stages: constant temperature, rapid temperature rise, slow temperature rise, and temperature drop. The temperature rise rate, temperature rise duration, and temperature rise peak of the coal core increase with the increase in rotate speed, coal strength, friction area, and frictional load. In the axial direction, the closer to the upper end of the core pipe, the higher the core temperature. In the radial direction, the closer the core is to the wall of the core pipe, the higher the core temperature is. Under the influence of cutting heat and friction heat in the process of core-taking, the maximum heating rate of the core-taking tube wall within 8 min is 20 °C/min, the peak temperature is 158.4 °C, the average temperature of the wall is above 100 °C, and the average temperature rise of the coal core reaches 55.7 °C. Within 60 min, the average temperature of the coal core remained above 50 °C. The order of influence of coal core temperature from large to small is as follows: rotate speed, frictional load, friction area, and coal strength. It can provide a reference for accurately determining CSGC using the core-tube method or designing a coring device to eliminate or reduce the thermal effect during coring.

1. INTRODUCTION

The coal seam gas content (CSGC) is the main index for regional prediction of outburst risk, effect test of regional outburst prevention measures, and evaluation of coal mine gas risk degree, and it is also an indispensable basic parameter for CBM resource exploration and development.1−5 The CSGC determination method is divided into direct method and indirect method.6 Because the indirect method has some problems such as long determination cycle, low success rate, and large cumulative error, the direct method has become the main method for CSGC determination.7 The CSGC measured by the direct method is composed of underground gas desorption amount, residual gas amount, and gas loss amount.8 Underground gas desorption amount and residual gas amount can be measured in the laboratory, however, the gas loss amount is calculated by the law of gas desorption and gas loss time, so the error is large.8 The accuracy of direct method mainly depends on the accuracy of gas loss calculation.9

The sampling methods for the determination of CSGC by the direct method mainly include pressure air exhaust powder sampling, core tube sampling, and closed chamber sampling.10 The pressure air exhaust powder sampling cannot realize the fixed-point sampling, the sampling depth is small, and the coal particles taken out are small, then the gas loss amount is too large. The equipment required for the sealing coring device is expensive, and the testing technology is too complex. The core-tube method can realize fixed-point sampling, and the coal sample size is larger, which is more consistent with the original existence state of coal.11 Therefore, The Direct Method of Determining Coalbed Gas Content in the Mine12 stipulates that the determination of CSGC must adopt the core tube sampling or other effective verified fixed-point sampling method, and the use of the core tube sampling is recommended.

Received: September 17, 2022
Accepted: October 21, 2022
Published: November 21, 2022
However, the balanced environment of gas adsorption in coal seam is broken by drilling into coal body, resulting in gas desorption. In addition, cutting between the core bit and coal body and friction heat generation between core tube wall (CTW) and hole wall will increase the temperature of the CTW, which will then be transferred to the coal core and accelerate gas desorption in the coal core. Meanwhile, the coal body is exposed for long time during coring. In this case, the temperature field distribution of the coal core is not clear, and the law of gas desorption is unknown. At present, the gas desorption rule in the normal temperature environment is adopted in the calculation of gas loss, which leads to the gas loss amount in the calculated heating and temperature changing environment and is far less than the actual gas loss, resulting in the inaccurate measurement results of CSGC. Therefore, it becomes the key to obtain the variation law of coal core temperature during coring, in order to accurately determine the CSGC using the core tube method.

Many scholars have studied the heat generated during drilling. Okamura et al. measured experimentally the temperature near the cutting-edge by an embedded K-type thermocouple to determine the drilling temperature during the drilling and non-drilling periods of low-frequency vibration drilling. Heidari et al. found the cutting friction between the drill bit and the wall of hole in the process of drilling rock, which resulted in the temperature of the drill bit reaching about 500°C. Jiang et al. found that the cuttings temperature and temperature change rate increase with the increase in coal seam strength at the same drilling rate. A CWH425 INFRARED thermometer was used to measure the coal dust temperature variation during the sampling process, and the results show that the coal dust temperature increases linearly with the increase in drilling depth. Wang et al. studied the influence of different core-taking depths on CTW temperature by using the temperature measuring device of the core-taking tube wall and found that the maximum temperature of the core-taking tube wall increased with the increase in the sampling depth, and when the sampling depth was 30 m, the maximum temperature of the core-taking tube wall was 98.32°C. Sakurai 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 to cutting heat, causing the temperature of bit to rise rapidly. The heat generated during drilling rock was mainly affected by the geometrical shape of drilling tool, thermal properties, and drilling parameters, such as cutting force, cutting speed, and propulsion speed. 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. The above scholars have carried out a lot of research on the temperature variation of drill bit in the coring process and obtained many useful conclusions. However, there is lack of research on the temperature of coal core in the coring process under the influence of multiple factors.

It is difficult to directly measure the temperature of coal core during coring in the field test because the coal core entering the core tube is a dynamic process. To obtain the temperature variation characteristics of coal core during coring, the author team developed a simulation experimental device for the thermal effect of coal core during the core-taking process, which can realize real-time acquisition of the temperature of the CTW and the coal core in the whole process of core-taking, under different working conditions, so as to similarly simulate the temperature change process of coal core caused by core-taking. This device is used to carry out the core-taking process experiments under the conditions of different rotational speeds, coal seam strengths, friction areas, and frictional loads. Based on the average temperature rise data of coal core in the core-taking process, the correlation degree of influencing factors of coal core temperature rise in the core-taking process is calculated and analyzed by using the gray correlation theory. The research results play a fundamental role in quantitative evaluation of the thermal effect of the core-taking process and the reliability of CSGC measurements.

2. EXPERIMENTAL SYSTEM AND EXPERIMENTAL METHOD

2.1. Experimental System. In this paper, a set of coal core temperature test system in the core-taking process is
core tube connected to the bit. The friction heat can be simulated by squeezing the friction ring to form friction with the sample tank, and the heat generated by friction can be controlled by adjusting the amount of normal stress applied. A stepper motor is used to push raw coal or a similar material of coal toward the drill bit, and the two contact to generate cutting heat. The cutting heat is simulated by the method of coring tube rotation and front-end sample feeding.

The specific working method of the device is as follows: the three-phase geared motor drives the main shaft to rotate through the belt, and the main shaft sequentially connects the rotating conductive ring, the rotary sealing device, the core tube, and the core bit from left to right. The stepping motor is used to push raw coal or a similar material of coal sample tank (simulated core tube) rotation, friction belt rotation and into two parts, the horizontal motor drives the core sample tank (simulated core tube) rotation, friction belt rotation and into two parts, the horizontal motor drives the core sample tank and coal clamping seat through the ball screw. The core cutting heat is simulated by the method of cutting force of the core bit into the coal body. The heat generated by friction and shear is the combination of the propulsive force and shear deformation. The heat generated by friction and shear is related to the strength of coal body. When the coal seam is cored with different strength, the heat generated is different. In order to study the influence of coal strength on the temperature rise of coal core during coring, and to ensure the repeatability and reliability of the experiment, it is necessary to prepare materials with similar mechanical strength to coal. According to the Design Regulations of Ordinary Concrete Mixing Ratio (JGJS5-2011), the material cement, aggregate, and additive are selected and equipped. By constantly adjusting water consumption and sand rate, the mixing ratio meeting the requirements is determined, with the water-cement ratio 0.38 and sand rate 0.4. In order to change the compressive strength of the specimen, basalt fiber was added in the ratio of 0.05%, 0.1%, and 0.15%. All similar materials need to be preserved for 28 days before they can be used. The similar materials prepared were A, B, and C, and the corresponding compressive strengths are 28.1, 35.5, and 38.4 MPa, respectively. The size of the specimen was 100 × 100 × 100 mm. The preparation process of similar materials is shown in Figure 3.

2.2. Sample Preparation. 2.2.1. Coal Sample Preparation and Basic Parameter Test. The experimental coal sample is selected from Jiulishan Mine of Henan Nenghua Group, and the sampling location is the 14141 working face. The CSGC of this working face is 15.15~19.22 m³/t, the original gas pressure is 0.86 MPa, and the gas adsorption constant a is 41.841 m³/t, the b value is 0.985 MP⁻¹, the coal seam permeability coefficient is 0.35~0.457 m²/MPa⁻d, the initial borehole gas flow rate is 0.03~0.04 m³/(min·hm), and the borehole flow attenuation coefficient is 0.0218~0.0389 d⁻¹.

The coal core taken out of the coal body at the bottom of the hole cut by the core tube is powder, accompanied by a small amount of large particles. The fresh coal samples obtained from the sampling site were pulverized with the pulverizer, and the coal samples with a particle size of 60~80 mesh (0.17~0.25 mm) were screened out and used to carry out the coring simulation experiment. The industrial analysis of coal samples and the measurement of true/apparent relative density and porosity were carried out in accordance with Chinese standards, and the results are shown in Table 1.

![Figure 2. Physical picture of equipment.](image1)

![Figure 3. Schematic diagram of the temperature sensor layout.](image2)

Table 1. Physical Parameters of Coal Samples

| coal samples | Mₐd (%) | Aₐd (%) | Vₐ (%) | TRD (g/cm³) | ARD (g/cm³) | ϕ (%) |
|--------------|---------|---------|--------|-------------|-------------|-------|
| JLS          | 2.56    | 16.55   | 8.88   | 1.56        | 1.51        | 3.21  |

*Note: Mₐd (moisture), Aₐd (ash content), Vₐ (volatile matter), true relative density, apparent relative density, and porosity (ϕ).*
in Figure 4. The benchmark mix ratio of experimental groups are shown in Table 2.

### 2.3. Experimental Steps.

The specific experimental steps are as follows:

1. Before the start of the test, the coal sample is loaded into the core tube, and the temperature sensor is arranged. At the same time, the similar material cube of coal is loaded into the coal holder and clamped.

2. The integrity and reliability of the experimental device were checked and also checked whether the temperature sensor is normal, and the friction belt load was returned to zero.

3. The load sensor was opened, the three friction belts were calibrated, and the load at the set value (set as 0.4, 0.6, and 0.8 kN, respectively) was maintained.

4. The push button was turned on to gradually push the cube toward the bit at a steady speed of 0.5 mm/s.

5. The rotation button was turned on, the rotational speed was set (to 240, 360, and 480 rpm, respectively), the rotation for 8 min was maintained, and pushing the cube was stopped.

6. After collecting 1 h temperature data, this group of experiments was completed.

### 3. RESULTS AND DISCUSSION

#### 3.1. Analysis of the Temperature Field.

Figure 5 shows the three-dimensional temperature variation of the CTW and the coal core during the coring process at a rotate speed of 240 rpm. As can be seen from Figure 5, the temperature distribution of the CTW and the R/2 of coal core are basically consistent, showing a wave surface that first increases and then decreases, and the curvature decreases with the decrease in the radial distance. The initial temperature rise of the CTW is the fastest, and the temperature amplitude is the largest, reaching about 50 °C within 8 min. The highest temperature at R/2 of coal core reaches about 30 °C within 8 min, and the temperature of the axis of coal core (ACC) is stable within 5 min from the beginning of core-taking and then slowly increases, and the temperature of ACC reaches about 20 °C after 60 min. It can also be seen from Figure 1 that the cooling rate of the CTW is larger than that at the R/2 of coal core, and the temperature of ACC has been in an upward trend during the whole core-taking process. This is because the CTW heats up first, and there is a temperature difference between the core tube and the coal core, so the heat from the core tube is transmitted to the coal core. Due to the small thermal conductivity of the coal core, the temperature of the coal core rises slowly, and the heat is transmitted in the radial direction from outside to inside of the coal core. The heating rate at R/2 of the coal core is greater than that of ACC. The temperature between the CTW and the coal core will eventually reach equilibrium with time infinite increase.

#### 3.2. Influence of Rotation Speed.

During the coring process, the rotational speed of the drilling rig not only affects the frictional heat generation but also affects the cutting heat generation. Figure 6 shows the temperature of the coring tube wall and coal core when the rotational speed is 240, 360, and 480 rpm, respectively.

It can be seen from Figure 6 that under the same pressure, rotation time, and rotation speed, the temperatures in different axial directions are basically the same. The temperature variation of the CTW is roughly divided into three stages: rapid heating, slow heating, and cooling.

### Table 2. Standard Mix Proportion of Concrete

| category | aggregate (kg/m³) | cement (kg/m³) | water (kg/m³) | water reducing agent (kg/m³) | basalt fiber (kg/m³) | compressive strength (MPa) | coefficient of firmness |
|----------|------------------|----------------|---------------|----------------------------|---------------------|---------------------------|-------------------------|
| A        | 1638             | 494            | 188           | 2.47                       | 1.20                | 28.1                      | 0.96                    |
| B        | 1638             | 494            | 188           | 2.47                       | 2.50                | 35.5                      | 1.21                    |
| C        | 1638             | 494            | 188           | 2.47                       | 3.70                | 38.4                      | 1.31                    |
When the core tube starts to rotate, the temperature rises rapidly. After the rotation of the core tube stops, the temperature of the CTW will not decrease immediately, but the temperature will increase slowly and then gradually.

Figure 5. Three-dimensional temperature variation of CTW and coal core during coring. (a) CTW. (b) R/2 of coal core. (c) ACC.

Figure 6. Temperature variation of CTW and coal core during coring under different rotation speeds. (a) 240, (b) 360, and (c) 480 rpm.
rate and heating duration inside the coal core increase with the temperature of coal core enters in the rapid rising stage, with shorter the time for heat transferring to higher the heating rate, the faster the heat conduction, the coal core within 4 min. The higher the rotational speed, the difference, the faster the cooling.

It can be seen from Table 1 that the temperature of the CTW increases rapidly in the first 8 min. The temperature of CTW when the friction ends are 50.3, 68.7, and 81.3 °C, and the heating rates are 6, 7.8, and 9.6 °C/min at the rotational speed of 240, 360, and 480 rpm, respectively. When the rotation speed is higher, the heating rate is faster, and the temperature of the CTW is higher. With the stop of the rotation of the core tube, that is, the heat generation is stopped, the temperature of the CTW is in the stage of slow increase. After about 2 min, the temperature peaks are 52.4, 71.2, and 85.8 °C, respectively. This is because the temperature of the contact point between the friction belt and the core tube is higher, and the temperature of the CTW will also rise slightly. After that, it entered the cooling stage, and the cooling amplitudes were 29.2, 54.1, and 63.3 °C, respectively, within 40 min. Because the ambient temperature is lower than the temperature of CTW, the CTW exchanges heat with the air in the environment, which in turn causes the CTW to cool down, and the greater the temperature difference, the faster the cooling.

The temperature variation of R/2 of the coal core basically presents four stages: constant temperature, rapid temperature rise, slow temperature rise, and temperature drop. The specific value of R/2 of coal core at each stage is shown in Table 4.

It can be seen from Table 4 that at different rotation speeds the temperature of ACC increases gradually with the rise of ACC. At the rotational speed of 240, 360, and 480 rpm, the temperature peaks are 23.1, 24.9, and 29.5 °C, respectively. The ACC is in the heating state during the whole simulated core-taking process. The final peak temperature was 23.1, 24.9, and 29.5 °C, respectively.

It can be seen from Table 5 that at different rotation speeds of 240, 360, and 480 rpm, the temperature at ACC basically stays constant within 15, 12, and 9.5 min, and the temperature is 11.1, 11.5, and 11.2 °C, respectively. This is because the heat has not been conducted to the ACC in a short period of time due to the small thermal conductivity of coal, although the temperature of the CTW increases, showing that the temperature change of ACC is not obvious. The higher the rotational speed, the shorter the constant temperature time. After the core-taking tube stops rotating, the temperature at the ACC begins to rise slowly. At the rotational speed of 240, 360, and 480 rpm, the temperature rise rates are 0.6, 0.12, and 0.18 °C/min, respectively. The ACC is in the heating stage during the whole simulated core-taking process. The final peak temperature was 23.1, 24.9, and 29.5 °C, respectively.

Since the temperature of the CTW and the coal core is not constant and the temperature condition at the same time. The specific numerical values of the temperature at each stage of the CTW during coring are shown in Table 3.

| Table 3. Temperature of CTW at Different Rotation Speeds during Coring |
|----------------------------------------------------------|
| rotate speed (rpm) | time (min) | heating rate (°C/min) | temperature (°C) | time (min) | maximum temperature (°C) | time (min) | cooling amplitude (°C) |
|-------------------|------------|----------------------|-----------------|------------|-------------------------|------------|-----------------------|
| 240               | 8          | 6                    | 50.3            | 2          | 52.4                    | 40         | 29.2                  |
| 360               | 7.5        | 7.8                  | 68.7            | 2          | 71.2                    | 40         | 51.4                  |
| 480               | 7          | 9.6                  | 81.3            | 2          | 85.8                    | 40         | 63.3                  |

| Table 4. Temperature of R/2 of Coal Core at Different Rotation Speeds during Coring |
|-----------------------------------|
| rotation speed (rpm) | time (min) | heating rate (°C/min) | temperature (°C) | time (min) | heating rate (°C/min) | temperature (°C) | time (min) | cooling amplitude (°C) |
|----------------------|------------|----------------------|-----------------|------------|----------------------|-----------------|------------|-----------------------|
| 240                  | 3.8        | 0.3                  | 11.6            | 8.9        | 1.86                 | 28.3            | 9.4        | 29.9                  |
| 360                  | 2.9        | 0.42                 | 11.2            | 9.6        | 2.28                 | 32.7            | 9.8        | 35.3                  |
| 480                  | 2.1        | 0.72                 | 11.4            | 11.1       | 2.7                  | 41.3            | 10.2       | 43.7                  |

| Table 5. Temperature of ACC at Different Rotation Speeds during Coring |
|---------------------------------------------------------------------|
| rotation speed (rpm) | time (min) | temperature (°C) | time (min) | heating rate (°C/min) | temperature (°C) |
|----------------------|------------|-----------------|------------|----------------------|-----------------|
| 240                  | 15         | 11.1            | 56         | 0.6                  | 23.1            |
| 360                  | 12         | 11.5            | 50.5       | 0.12                 | 24.9            |
| 480                  | 9.5        | 11.2            | 50         | 0.18                 | 29.5            |
calculation method is incited from the article. Rotation speed affects the generation of cutting heat and friction heat and then affects the temperature of the CTW and the coal core, which can be shown as the effect on the equivalent average temperature. It can be seen from Figure 7 that the influence of rotation speed on the equivalent average temperature of the CTW, the R/2 of coal core, and the ACC is linear. The higher the rotation speed is, the higher the equivalent average temperature will be.

The average temperature of the CTW is higher than the average temperature of the coal core within 20 min, and heat is transferred from the CTW to the coal core. At different rotation speed, the average temperature peak of the CTW is 52.3, 71.4, and 87.2 °C, respectively, and the average temperature of the coal core reaches 26.1, 30.4, and 36.4 °C, respectively. After 20 min, the average temperature of the coal core is higher than that of the CTW, and the heat begins to conduct in the reverse direction. When the CTW is exposed to a relatively low external environment, the cooling rate and range are relatively large. The temperature inside the coal core decreases slowly and still maintains high temperature for a long time. The reasons are as follows: first, the thermal conductivity of the coal core is much smaller than that of the CTW; second, after the core tube stops rotating, the residual temperature of the CTW forms the insulation layer for the coal core. The higher the rotation speed, the shorter the holding time.

3.3. Influence of the Frictional Load. There is always friction contact between the CTW and the coal wall during coring, and the coal wall will have different degrees of cinder drop or even collapse the hole. The frictional load is the pressure exerted by the coal wall on the CTW, which is one of the main factors affecting the generation of friction heat. Figure 8 shows the temperature changes of the CTW and the coal core under the frictional loads of 0.4, 0.6, and 0.8 kN, respectively.

The temperature of the CTW increases rapidly in the first 6 min. When the frictional load is 0.4, 0.6, and 0.8 kN, the heating rate is 6, 7.8, and 9.6 °C/s, respectively. When the friction ends, the temperature of CTW is 40.1, 53.2, and 57.9 °C, respectively. The heating rate at R/2 of the coal core increases correspondingly, and the peak temperature is 28.4, 32.4, and 35.4 °C, respectively. It can be seen that when the frictional load is larger, the heating rate of the CTW and the coal core is faster, and the temperature is higher in the same time. Meanwhile, the influence of the frictional load on the equivalent average temperature is shown in Figure 9. It can be seen from Figure 9 that the influence of the frictional load on the equivalent average temperature of the CTW, the coal core at R/2, and the ACC is linear, and the larger the frictional load is, the higher the equivalent average temperature is.
Within 20 min, the average temperature of the CTW is higher than the average temperature inside the coal core, and heat is transferred from the CTW to the coal core. Under different frictional loads, the average temperature peak of the CTW is 52.3, 71.4, and 87.2 °C, respectively, and the average temperature of the coal core reaches 26.1, 28.3, and 30.2 °C, respectively. At 40 min, the CTW starts to cool, and the coal core temperature is basically unchanged. At 60 min, the coal core still maintains high temperature, and the temperature of CTW is significantly lower than the coal core.

3.4. Influence of Coal Seam Strength. Figure 10 represents the temperature variation of CTW and coal core during coring under different coal seam strengths. It can be seen from Figure 10 that under the conditions of different coal seam strengths, the temperature of core bit shows three stages: rapid temperature rise, slow temperature rise, and slow cooling. The temperature of coal core is affected by the change of core bit temperature, which can be roughly divided into four stages: delayed temperature rise, rapid temperature rise, slow temperature rise, and cooling down. When the coal seam strength is higher, the position closer to the core bit, the temperature rises faster, the temperature rise rate is higher, and the temperature peak is higher. This is consistent with the rule of the literature.13

The specific temperature values of core bit at different stages are shown in Table 6.

Table 6. Temperature of Core Bit at Different Coal Seam Strengths during Coring

| Coal strength (MPa) | Rapid heating stage | Slow heating stage | Cooling stage |
|---------------------|---------------------|--------------------|--------------|
|                     | Time (min) | Heating rate (°C/min) | Temperature (°C) | Time (min) | Maximum temperature (°C) | Time (min) | Cooling amplitude (°C) |
| 28.1                | 5         | 16.2                | 92.47         | 2          | 98.2              | 40        | 66.1 |
| 35.5                | 5         | 18.6                | 98.3          | 2          | 105.3             | 40        | 76.5 |
| 38.4                | 4.9       | 21                  | 104.8         | 2          | 110.4             | 40        | 30.2 |

Figure 11. Equivalent average temperature of CTW and coal core varies with different coal seam strengths.

Within 20 min, the average temperature of the CTW is higher than the average temperature inside the coal core, and heat is transferred from the CTW to the coal core. Under different frictional loads, the average temperature peak of the CTW is 52.3, 71.4, and 87.2 °C, respectively, and the average temperature of the coal core reaches 26.1, 28.3, and 30.2 °C, respectively. At 40 min, the CTW starts to cool, and the coal core temperature is basically unchanged. At 60 min, the coal core still maintains high temperature, and the temperature of CTW is significantly lower than the coal core.

3.4. Influence of Coal Seam Strength. Figure 10 represents the temperature variation of CTW and coal core under the influence of coal seam with different compressive strengths. It can be seen from Figure 10 that under the conditions of different coal seam strengths, the temperature of core bit shows three stages: rapid temperature rise, slow temperature rise, and slow cooling. The temperature of coal core is affected by the change of core bit temperature, which can be roughly divided into four stages: delayed temperature rise, rapid temperature rise, slow temperature rise, and cooling down. When the coal seam strength is higher, the position closer to the core bit, the temperature rises faster, the temperature rise rate is higher, and the temperature peak is higher. This is consistent with the rule of the literature.13

The specific temperature values of core bit at different stages are shown in Table 6.

In the first 6 min, the core bit and the cube with compressive strength of 28.1, 35.5, and 38.4 MPa generate heat during cutting, and the heating rate is 0.27, 0.31, and 0.35 °C/s, respectively. At the end of cutting, the core bit temperature reaches 98.2, 105.3, and 110.4 °C after residual temperature heating. When heat is transmitted to the coal core, the peak temperature in the coal core is 36.3, 42.7, and 44.5 °C, respectively. It can be seen that when the coal seam strength is higher, the heating rate of core bit is faster, and the temperature value reached in the same time is higher.

The influence of coal seam strength on the equivalent average temperature is shown in Figure 11. It can be seen from Table 6 that the influence of coal strength on the equivalent average temperature of CTW, the coal core at R/2, and the ACC is linear. The greater the coal seam strength, the higher the equivalent average temperature. Within 20 min, the heat conduction is gradually conducted from the CTW to the coal core, that is, the radial conduction is from the wall to inward, and the axial conduction is from the core bit to downward. The higher the temperature, the faster the temperature conduction in the coal core. After 20 min, the average temperature of the coal core is higher than the average temperature of the CTW, and the heat is transmitted from the coal core to the CTW. The temperature distribution at different radii of coal core is not uniform, and the cross-section of low-temperature area of coal core is trapezoidal. As time goes by, the bottom edges of the trapezoid decrease until the top and bottom edges are zero. The average temperature of coal core reaches 28.3, 35.6, and 36.5 °C at different coal seam strengths.

3.5. Influence of Friction Area. It can be seen from Figure 12 that when the core tube is rubbed at different
positions, the temperature changes of the measuring points corresponding to the friction positions are basically the same, and the temperature of the CTW is conducted faster; therefore, the temperature of the CTW is always higher than that of the coal core. When the friction position is at M1 of the core tube, the corresponding temperature measurement point \( T_4 \) at the coal core \( R/2 \) has the fastest heating rate and the highest temperature peak (37.4 °C). When the friction position is at M1M3, the temperature of the measurement point \( T_6 \) at the coal core \( R/2 \) is the highest. This is because the heat of the friction heat source M1M3 is superimposed, which makes \( T_6 \) the first to heat up, and the heating rate is the fastest, the temperature peak is 43.7 °C. It can be seen that under the same frictional load and rotational speed conditions, the larger the friction area, the faster the coal core heating rate and the higher the peak value. When the friction area is M1M2M3, the coal core forms isothermal surfaces at different radii in the axial direction, and the temperature changes are consistent. When the friction area of the CTW changes, the temperature changes of \( T_7, T_8 \), and \( T_9 \) at the center of the coal core are small. This is because the thermal conductivity of the CTW is large, the CTW forms an isothermal surface when the heat has not been transmitted to the ACC, which has little effect on the axial temperature distribution gradient in the center of the coal core.

The larger the friction area during coring, the faster the temperature rise rate of the coal core, and the higher the peak value. The effect of friction area on the equivalent average temperature is shown in Figure 13. It can be seen from Figure 13 that the effect of friction area on the equivalent average temperature of the CTW, the coal core at \( R/2 \) and the center of the coal core are positive linear relationship. The larger the friction area, the higher the equivalent average temperature. When the friction area is M1 or M2, the average temperature rate of the coal core is basically the same. The average temperature rate of the coal core is 0.9 °C/min within 20 min, and the temperature peak is 26.6 °C. When the friction area is M1M3, the average temperature rise rate of the coal core is 1.1 °C/min, and the temperature peak is 28.8 °C. When the friction region is M1M2M3, the average temperature rise rate of the coal core is 1.3 °C/min, and the temperature peak is 30.8 °C. It can be seen that when the friction area increases, the average temperature rise rate and the peak value of the coal core tend to increase. The temperature of CTW was lower than that of the coal core after 40 min, and at 60 min, the coal core maintained a higher temperature.

### 3.6. Significance of Factors Affecting Temperature Rise of the Coal Core during Coring

The average temperature of coal core showed an increasing trend with the increase in rotational speed, frictional load, coal seam strength, and friction area. However, due to the dimensional differences between the influencing factors, the influence strength of each influencing factor on the temperature rise of the coal core cannot be directly obtained. Therefore, the grey relational analysis theory which is a method of multivariate statistical analysis was introduced to discuss the significance of factors on the temperature rise of the coal core during coring. The basic steps of grey relational analysis as follows:

#### 3.6.1. Determine the Analysis Sequence

The average temperature rise of the coal core is set as the parent sequence \( Y \), and the rotational speed, frictional load, friction area, and coal seam strength are the influencing factors are set as sub-sequences \( X_i \). The data obtained under different experimental conditions are shown in Table 7.

#### 3.6.2. Data Series Dimensionless

The initial value matrix is obtained by means of formula 1, the result as shown in Table 8.

\[
\chi_i(k) = \frac{x_i(k)}{\bar{x}_i}, \quad k = 1, 2, ..., n
\]  

(1)

In the formula, \( k \) corresponds to the time period, and \( i \) corresponds to a row (i.e., a feature) in the comparison sequence.

---

**Figure 12.** Temperature variation of CTW and coal core during coring under different frictional areas: (a) M1, (b) M1M3, and (c) M1M2M3.

**Figure 13.** Maximum temperature of measuring points at different core depths.
### Table 7. Temperature of Core Bit at Different Coal Seam Strength During Coring

| average temperature rise (°C) | rotational speed (rpm) | frictional load (kN) | frictional area (m²) | coal seam strength (MPa) |
|-------------------------------|------------------------|----------------------|----------------------|-------------------------|
| Y                             | X₁                    | X₂                   | X₃                   | X₄                      |
| 28.3                          | 360.0                 | 0.6                  | 0.0942               | 0.0                     |
| 30.2                          | 360.0                 | 0.8                  | 0.0942               | 0.0                     |
| 26.1                          | 240.0                 | 0.4                  | 0.0942               | 0.0                     |
| 35.6                          | 240.0                 | 0.0                  | 0.0000               | 28.1                    |
| 36.5                          | 240.0                 | 0.0                  | 0.0000               | 35.5                    |
| 30.4                          | 240.0                 | 0.6                  | 0.0942               | 0.0                     |
| 26.6                          | 240.0                 | 0.6                  | 0.0314               | 0.0                     |
| 28.2                          | 240.0                 | 0.6                  | 0.0628               | 0.0                     |
| 26.4                          | 240.0                 | 0.4                  | 0.0942               | 0.0                     |
| 30.7                          | 360.0                 | 0.4                  | 0.0942               | 0.0                     |
| 36.9                          | 480.0                 | 0.4                  | 0.0942               | 0.0                     |

### Table 8. Mean Processing

| Y₀ | Y₁ | Y₂ | Y₃ | Y₄ | Y₅ |
|----|----|----|----|----|----|
| 0.932455 | 1.2 | 1.5 | 1.697313 | 0.000000 |
| 0.995058 | 1.2 | 2.0 | 1.697313 | 0.000000 |
| 0.859967 | 1.2 | 1.0 | 1.697313 | 0.000000 |
| 0.932455 | 0.8 | 0.0 | 0.000000 | 3.305882 |
| 1.172982 | 0.8 | 0.0 | 0.000000 | 4.176471 |
| 1.202636 | 0.8 | 0.0 | 0.000000 | 4.517647 |
| 1.001647 | 0.8 | 1.5 | 1.697313 | 0.000000 |
| 0.929160 | 0.8 | 1.5 | 0.113154 | 0.000000 |
| 0.876442 | 0.8 | 1.5 | 0.005658 | 0.000000 |
| 0.899852 | 0.8 | 1.0 | 1.697313 | 0.000000 |
| 1.011532 | 1.2 | 1.0 | 1.697313 | 0.000000 |
| 1.215815 | 1.6 | 1.0 | 1.697313 | 0.000000 |

### 3.6.3. Calculate the Correlation Coefficient

According to Formula 2, the correlation coefficient matrix is calculated for the initial value matrix, and the calculation results are shown in Table 9.

\[
\xi(k) = \frac{\min_{i} \min_{k} |y(k) - x_{i}(k)| + \rho \max_{i} \max_{k} |y(k) - x_{i}(k)|}{\Delta(k) + \rho \max_{i} \max_{k} \Delta(k)}
\]

(2)

Assume \(\Delta(k) = |y(k) - x_{i}(k)|\), then

### Table 9. Correlation Coefficient

| \(\xi_1\) | \(\xi_2\) | \(\xi_3\) | \(\xi_4\) |
|----------|----------|----------|----------|
| 0.867010 | 0.750112 | 0.689012 | 0.644426 |
| 0.896153 | 0.626881 | 0.707291 | 0.629217 |
| 0.835547 | 0.928513 | 0.668993 | 0.662981 |
| 0.932444 | 0.644426 | 0.644426 | 0.414057 |
| 0.821989 | 0.589664 | 0.589664 | 0.358086 |
| 0.810157 | 0.583551 | 0.583551 | 0.335653 |
| 0.897741 | 0.774187 | 0.709272 | 0.627658 |
| 0.934164 | 0.749003 | 0.674765 | 0.645247 |
| 0.962566 | 0.731693 | 0.660145 | 0.658671 |
| 0.966238 | 0.933647 | 0.671654 | 0.660388 |
| 0.904150 | 1.000000 | 0.712264 | 0.625333 |
| 0.817478 | 0.890951 | 0.780288 | 0.580874 |

Among them, \(\rho \in (0, \infty)\) called the resolution coefficient. The smaller the value, the greater the resolution, and the value range of \(\rho\) is \((0,1)\). When \(\rho \leq 0.5463\), the resolution is the best.

### 3.6.4. Relevance Calculation

The correlation coefficient is the value of the correlation degree between the comparison sequence and the reference sequence at each moment, and it has more than one number. After calculating the correlation coefficient between \(X_{i}(k)\) series and \(Y_{i}(k)\) series, calculate the average value of various correlation coefficients, then the average value \(r_{i}\) is called the degree of correlation between \(X_{i}(k)\) and \(Y_{i}(k)\). The larger the \(r_{i}\), the higher the correlation between them. The correlation degree \(r_{i}\) is calculated by Formula 4, and the result is shown in Figure 14.

\[
\gamma_{i} = \frac{1}{n} \sum_{k=1}^{n} \xi(k), \quad k = 1,2, ..., n
\]

(4)

It can be seen from Figure 14 that the correlation values corresponding to the rotational speed, frictional load, friction area, and coal seam strength are 0.8874, 0.76689, 0.67428, and 0.57022, respectively. It can be seen that the influences of these factors on the average temperature rise of coal cores are all positively correlated, and the order of the influences is: rotational speed > frictional load > friction area > coal seam strength.

### 3.7. Limitations and Future Work

The friction between the core bit and the core tube and the coal during coring produces heat, and the heat from the core bit and the core tube is transmitted to the coal core, resulting in the temperature increase in the coal core. To obtain the quantitative influence of heat in core-taking process on core temperature, we adopt a thermal effect system that can simulate the coring process to study the variation of coal core temperature under the influence of different factors in core-taking process, which is the basis of research on gas loss during coring process. In our future work, we will study the coal core temperature variation law during coring and its influence on the gas loss; finally calculate the gas loss amount in the process of coring.
4. CONCLUSIONS

In this paper, based on the self-developed coal core thermal effect simulation device during coring process, the temperature test experiment of CTW and coal core during coring under the influence of friction heat and cutting heat was carried out. The temperature variation characteristics of the coal core under different rotational speed, coal seam strength, frictional load and friction area are analyzed. Then based on the average temperature rise data of the coal core in the test, the significance of the factors affecting the temperature rise of the coal core during coring was discussed by using the grey relational theory. The specific research conclusions are as follows.

(1) Under a single change condition, the temperature change of coal core presents four stages: delayed heating stage, rapid heating stage, slow heating stage and slow cooling stage. The coal core temperature rise rate, temperature rise duration and temperature rise peak all tend to increase with the increase in rotational speed, coal strength, friction area, and friction pressure.

(2) In the simulation experiment of coring, under the influence of cutting and friction, the maximum heating rate of CTW within 8 min is 20.4 °C/s, the temperature peak is 158.4 °C, and the average temperature of CTW is above 100 °C. The average temperature rise of the coal core reached 55.7 °C, and within 60 min, the average temperature of the coal core remained above 50 °C.

(3) The influence of rotational speed, coal seam strength, friction area and frictional load on the temperature rise of the coal core is positively correlated, and the order of the influences is: rotational speed > frictional load > friction area > coal seam strength.

(4) According to the research in this paper, in the determination of CSGC by the coring method, on the one hand, the drilling parameters should be adjusted according to the actual coal seam conditions, and the factors that have a great influence on the temperature rise of the coal core should be avoided or reduced as much as possible. On the other hand, the core device should be improved, and the thermal insulation material or the double-layer core tube designed to carry the refrigerant should be used to eliminate or reduce the influence of the thermal effect on the coal core during coring, so that the coal sample can maintain low temperature environment as much as possible to reduce the amount of gas loss caused by the heat generated during coring.

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Author Contributions
Q.W. conceived the experiment, analyzed the results and draft the manuscript; Z.W., J.Y., S.M., S.X. and K.Z. coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was financially supported by the National Natural Science Foundation of China (nos. 52074107; no. 52104224; no. 52174172), the scientific research start-up fund for high-level talent introduction of Anhui University of Science and Technology (2021yjrc45), the key natural science research projects of colleges and universities in Anhui Province (KJ2021A0459).

■ ABBREVIATIONS

CSGS, coal seam gas content
CTW, core tube wall
ACC, axis of coal core
CBM, coalbed methane

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