Influencing factors and experimental study on electrothermal high temperature field of the outburst coal in China

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Abstract
In this study, we proposed a method to solve the problems of low permeability of the outburst coal seams and gas extraction in China. We used heating cables to heat outburst coal seams and increase the gas desorption capacity of coal seams to prevent outbursts. An experimental cement tank was constructed to investigate the influence of the heating temperature, cable layout and thermal insulation conditions in the cement tank on the electrothermal high-temperature field characteristics of the outburst coal sample. The following results were obtained: The effective heating radius of the heating cable was 800 mm ≤ R < 1,000 mm. As the heating time increased, the temperature of the coal sample in the cement tank first increased rapidly and then became stabilized. The same heating time, the coal sample temperature of the cement tank in the third experimental scheme is the highest When the heating temperature was 300°C, the maximum coal sample temperature was 107°C. The stable temperature of the coal sample in the cement tank was considerably higher under thermal insulation conditions than under no-thermal insulation conditions.

Keywords
Outburst coal sample, heating cable, cement tank, electrothermal high-temperature field, influencing factors

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Introduction

Coal and gas outburst is a severe dynamic disaster that causes considerable damages and threatens the safety of underground workers (Jinjia et al., 2017; Xionggang et al., 2019). Extracting gas from an outburst-prone coal seam effectively reduces the outburst risk by reducing the gas content in the coal seam (Fubao et al., 2014; Hong et al., 2019). Outburst coal seams in Guizhou have high gas content and low permeability, which increases the difficulty of gas drainage and seriously hinders the production efficiency of coal mines.

Temperature rise promotes coal seam gas desorption (Lei et al., 2017; Luo et al., 2013; Yuli et al., 2019). Xueqiu and Li (2000) demonstrated the influence of electromagnetic field on an outburst coal seam. Electric energy is converted into electromagnetic energy, which heats up the coal seam and promotes gas desorption, creating a new approach for gas drainage of low-permeability coal seam in China. Yang Xinle (2009) proposed a technique of injecting high-temperature steam into the coal seam to heat the coal seam for promoting coal seam gas desorption. This technique is economical and practicable. Yang Tao (2014) proposed a technique of placing a non-phase change heat storage material in a closed pipeline. The closed pipeline is inserted into a pre-drilled coal seam borehole to promote gas desorption by heating the coal seam. The technique is highly efficient and causes no pollution. SALMACHI and HAGHIGHI (2012) showed that the use of hot water for gas displacement in outburst coal seams increases the extraction capacity by approximately 60% and the extraction rate 6.8 times. YI Jun et al. (2005) made considerable advancements by using alternating electric and sound fields to promote gas desorption in outburst coal seam, transforming electric energy into heat energy. The heat energy is transmitted to the coal seam and heats up the coal seam to promote gas desorption.

Recently, mineral-insulated heating cable (hereinafter referred to as “heating cable”) has been widely used in the petrochemical industry, heating and thermal insulation, ice and snow melting, agricultural soil heating, and municipal engineering road construction (Feng, 2013; Nan et al., 2016; Xiaogang et al. 2016; Yanfeng et al., 2006). The effect of controlling material temperature was achieved by converting electric energy into heat energy and using heat exchange for heat transfer. Similarly, the electrothermal high-temperature field formed by the heating cable was reliable and stable.

To sum up, there are a lot of theoretical research (Haidong et al., 2020), experimental analysis (Tongqiang et al., 2021) and numerical simulation (Yinhua and Jiaomin, 2014) on the promotion of gas desorption by coal seam heating, but limited by conditions, the research on coal seam heating and gas desorption in the coal mine site is insufficient. The temperature field is established through medium heat conduction, and the heating cable has a good heating effect in ice and snow melting and soil insulation (Dongji et al., 2020; Nan et al., 2016). Coal and soil belong to medium and low heat conductivity media. The above soil engineering examples have successfully established the temperature field, and the required electrothermal high temperature field should also be established in the outburst coal seam of the mine. Therefore, it is of great engineering significance to explore the influencing factors of electrothermal high temperature field in outburst coal seam.

Therefore, in this study, the K5 outburst coal seam sample was selected in a mine in Guizhou, the cement tank experimental system was constructed, the mine outburst heading face was simulated, and the electric heating high-temperature field was generated by the heating cable for heating. The influencing factors and optimal parameter settings of the coal seam electrothermal high-temperature field were obtained from the experiments, which lays a foundation for the field application of the heating cable in mining outburst face in the subsequent step.
Effect of temperature on coal seam gas desorption

The gas in the coal seam exists adsorption and free states in dynamic equilibrium. When the external conditions change, the adsorption free equilibrium is broken, and the gas changes between the adsorption and free states to attain a new equilibrium. The adsorption free state of the gas in coal seam can be described using the improved Langmuir equation (Bo, 2019; Xiangguo et al., 2022) expressed as follows:

\[ V = \frac{V_L p}{P_L + p} \exp\left(-\frac{c_2(T - T_0)}{1 + c_1 p}\right) \]  

(1)

Where \( V \) is the adsorption amount, \( V_L \) is the adsorption volume constant, \( P_L \) is the adsorption pressure constant, \( P \) is the coal seam gas pressure, \( c_1 \) is the Langmuir pressure correction coefficient, \( c_2 \) is the Langmuir volume correction coefficient; \( T_0 \) is the initial temperature of coal; and \( T \) is the temperature of coal.

Equation 1 shows that the adsorption capacity of coal is related to the temperature of the coal body and gas desorption is an endothermic process. As the temperature of the coal body increases, the gas adsorption rate decreases, and more gas is released in the adsorption state as free state, which is suitable for extracting more gas from the mine.

Heating cable

After the heating cable (Figure 1) is powered on, the electric heating wire inside the cable slowly heats up, and the heat generated is transferred to the outer stainless steel sleeve through an MgO crystal. The heat is transferred to the outburst coal seam by conduction. The temperature of the heated body is regulated using a professional temperature regulator (Figure 2). At this time, the heated body gradually heats up. The required working temperature is attained within a certain time. In 2016, ZHAO Xiaogang et al. (2016) designed an isothermal mineral-insulated (Mi) electric heat tracing technique for the entire old hot spring electric heat tracing pipeline in the Tanggula mountain, Qinghai. The technique was used to regulate the heat tracing system, which limited

![Figure 1. Mineral-insulated heating cable.](image)
the oil temperature to 40–43°C. In 2016, ZHANG Nan et al. (2016) studied soil thermal conductivity and analyzed its various influencing factors. A rise in temperature can promote the gas desorption of coal seams; hence, the heating cable is introduced into the mine face. This process creates an electrothermal high-temperature field to heat the coal seams and promote gas desorption, which increases the extraction rate of outburst coal seams. According to relevant comparative experiments (Feng, 2013; Xiaogang et al., 2016) and the requirements for gas pre-drainage drilling in coal mines (Bo, 2019), a heating cable with a 1,500-W power and 160-mm diameter was selected in this experiment. On the basis of testing, the heating cable produced a uniformly distributed temperature field after the coal sample was heated.

**Experimental model**

The nature of the Guizhou coal mine heading face and the requirements of relevant coal mine laws and regulations in China necessitated the design and construction of an experimental reinforced concrete model. The effects of heating temperature, cable layout, and thermal insulation conditions on the electrothermal high-temperature field of the experimental coal samples were analyzed.

**Experimental platform**

The reinforced-concrete experimental platform comprised an experimental cavity and walls. The relevant dimensions of the device were determined according to the section size of the coal mine heading face and the space of the experimental site. The thickness of the wall and base was 100 mm, and the wall’s internal dimension was length × wide × height = 1,750 × 1,500 × 1,500 mm. Four symmetrical openings were drilled on the walls on both sides of the model (width × height = 100 × 100 mm) for placing two steel beams (length × wide × height = 1,800 × 70 × 70 mm. Other four reinforced concrete formworks (length × wide × height = 1,500 × 30 × 350 mm) were used as a baffle or cover plate. Wide grooves (50 mm) were placed at right angle to the front end of the walls in both sides of the cavity for placing the baffle. By applying vertical
pressure on the coal sample in the cavity, we simulated the compression state of the actual coal seam. The experimental model is shown in Figure 3.

**Pressure loading equipment**

Here, six hydraulic jacks and cement cover plates were evenly arranged in two groups. The maximum range of the hydraulic jack was 30 MPa. The load applied by the hydraulic jack was 20 MPa to ensure that the experimental coal seam was evenly subjected to normal stress from top to bottom (equivalent to the in-situ stress on the coal seam in the coal mine face with a buried depth of approximately 800 m).

**Thermal insulation of heated coal sample**

Considering the heat insulation effect of the quilt, the cement tank was wrapped with an old quilt to isolate the internal and external temperature conduction of the coal sample in the tank and prevent the influence of external temperature difference on the experiment. The experimental model is shown in Figure 4.

![Figure 3. Cement tank simulator experiment device.](image)
Analysis of electrothermal high-temperature field of coal samples

Three layout modes of coal sample heating cable in the cement tank (Figure 5) and three coal sample heating temperatures (100 °C, 200 °C, and 300 °C) were selected. The coal sample temperatures were directly obtained from the temperature sensor every 24 h, and the sensor temperatures were recorded under thermal insulation and no-thermal insulation conditions. The curve of the coal sample heating time under the thermal insulation condition is shown in Figure 6, and the curve of coal sample temperature heating time under the no-thermal insulation condition is illustrated in Figure 7. Table 1 illustrates the final coal sample temperature in the cement tank under the electrothermal high-temperature field of the three experimental schemes.

Coal sample temperature and heating cable layout

It can be seen from Figure 6, Figure 7 and Table 1:

1. Under the same heating temperature and thermal insulation conditions, the coal sample temperature of the three heating cable arrangement is the highest, and the coal sample temperature of the single heating cable arrangement is the lowest Among them, when the heating temperature of the three heating cables is 300°C, the corresponding coal sample temperature is up to 107°C.

2. In the same heating cable layout, the corresponding coal sample temperature increased with increasing heating temperature.

Coal sample temperature and heating time

Figures 6 and 7 show the following:
1. In the same heating cable arrangement, the coal sample temperature in the cement tank first increased rapidly with increasing heating time, and tended to be stable after heating for 7–10 days.

2. At the same heating time, the temperature of the coal sample in the cement tank was the highest in experimental scheme 3.

Figure 5. Three types of heating cable layout.
Coal sample temperature and thermal insulation

Figures 6 and Figures 7 show the following:

1. In the three experimental schemes, the coal sample temperature in the cement tank was high under the thermal insulation condition.
2. Under the two thermal insulation conditions, the temperature of coal samples in the cement tank exhibited the same variation law.

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Coal sample water injection and electric heating high-temperature field

Tangible results were obtained from analyzing the electric high-temperature field variations of the single-cable layout because the layout was not affected by the electric high-temperature field of other cables. Therefore, the conventional and water-injection coal samples of the single-cable layout were examined to characterize electrothermal high-temperature field.
Heating effect of water-bearing coal samples. The moisture content of the coal sample was set to 5.8–10%. The layout of temperature sensors and heating temperature are shown in Figure 5(a). The coal sample temperature–heating time diagram (Figure 8) and Table 2 summarize the 10-day coal sample temperature data.

Figure 8 shows that after heating the water-injection coal sample, the temperature rise rate of the coal sample first increased as indicated by the 1# temperature sensor, and then the temperature rise rate decreased before attaining stability on the 6th to 8th days. The coal sample temperature rise rate of the 2# temperature sensor also increased first before decreasing but attained stability on the 7th to 8th days. The coal sample temperature rise rate of the 3# temperature sensor remained constant for the first two days, increased afterward, and then decreased from the third day while attaining stability on the 7th to 8th days. The final temperature was 2–3 °C higher compared with the scheme without thermal insulation.
Analysis of electrothermal high-temperature field characteristics. We used EXCEL2019 to organize the experimental data and obtain the temperature fitting curve under the single-cable water injection condition, as shown in Figures 9, 10, and 11.

Figures 9–11 illustrate that the similarity coefficients of the temperature–heating time fitting equations of the coal samples were above 90%, and the fitting curves met the requirements. An increase in the heating temperature resulted in an increase in the water-injection coal sample temperature; the temperature and heating time of the coal sample corresponded with the logarithmic curve distribution. We compared the electrothermal high-temperature field data of the coal samples with and without water injection, and we found that the coal sample water injection had an obvious influence on the heating effect of the electrothermal high-temperature field.

Table 1. Temperature of coal sample under two kinds of heat preservation and insulation conditions.

| Experimental scheme | Heating temperature/°C | Cable layout | Sensor temperature/°C |
|---------------------|-------------------------|-------------|-----------------------|
|                     |                         |             | 1# | 2# | 3# |
| (a) Temperature of coal sample without thermal insulation |                         |             |     |     |     |
| 1                   | 100                     | Single cable| 35 | 28 | 20 |
|                    | 200                     |             | 48 | 40 | 30 |
|                    | 300                     |             | 60 | 52 | 41 |
| 2                   | 100                     | Double cable| 35 | 30 | 31 |
|                    | 200                     |             | 48 | 43 | 42 |
|                    | 300                     |             | 61 | 55 | 53 |
| 3                   | 100                     | Three cables| 39 | 36 | 40 |
|                    | 200                     |             | 53 | 49 | 53 |
|                    | 300                     |             | 66 | 59 | 68 |
| (b) Temperature of coal sample under thermal insulation condition |                         |             |     |     |     |
| 1                   | 100                     | Single cable| 50 | 42 | 32 |
|                    | 200                     |             | 78 | 71 | 60 |
|                    | 300                     |             | 99 | 91 | 79 |
| 2                   | 100                     | Double cable| 50 | 46 | 45 |
|                    | 200                     |             | 78 | 75 | 75 |
|                    | 300                     |             | 98 | 94 | 95 |
| 3                   | 100                     | Three cables| 54 | 50 | 55 |
|                    | 200                     |             | 83 | 79 | 86 |
|                    | 300                     |             | 105| 100| 107|

Table 2. Temperature and heating schedule of water-injection coal sample.

| Cable layout              | Heating temperature /°C | Final temperature of coal sample /°C |
|---------------------------|-------------------------|-------------------------------------|
|                           |                         | 1# | 2# | 3# |
| Single-cable mode         | 100                     | 37 | 31 | 23 |
|                           | 200                     | 51 | 44 | 32 |
|                           | 300                     | 63 | 54 | 44 |

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Effective heating radius

1. On the basis of the temperature changes of the coal samples recorded by the 1# to 3# temperature sensors in Table 1, we concluded that the effective heating radius of the heating cable under the experimental conditions was $800 \text{ mm} \leq R < 1000 \text{ mm}$.

2. Since the 2# and 3# temperature sensors were 600 mm and 800 mm away, respectively, from the No. 2 heating hole, the coal samples at both sensors were within the effective heating radius of the No. 2 heating hole. The 1# temperature sensor was 1000 mm away from the No. 2 heating hole.

**Figure 8.** Temperature–time curve of single-cable water-injection heating.

**Figure 9.** Fitting curve of 100 °C water-injection coal sample temperature change with time.
hole, which was not within the effective heating radius of No. 2 heating hole. Similarly, the distance from the 1#, 2#, and 3# temperature sensors to the No. 3 heating hole was 600, 630, and 720 mm, respectively, and the coal samples at 1# to 3# temperature sensors were within the effective heating radius of the No. 3 heating cable.

3. As the 2# and 3# temperature sensor of the coal samples were within the effective heating radius of No. 1 to No. 3 heating cables, the heating superposition effect led to a high, stable temperature of the coal samples. The coal sample at the 1# temperature sensor was closest to the No. 1 heating cable, resulting in high stable temperature.

Discussion

From the above experimental data, it can be obtained that the number and spacing of heating cables have a great influence on the electrothermal high temperature field. The closer the distance between heating cables, the higher the temperature of coal sample. The farther the distance is, the lower the temperature of the coal sample is, and the range of the electric heating high temperature field is
only limited around the heating cable. The heating effect and heating range of electrothermal high temperature field are obviously improved by water injection coal sample. Under the same heating temperature and cable layout, the temperature of injected coal sample rises rapidly, the maximum heating temperature increases, and the effective heating radius of electrothermal high temperature field increases. Therefore, by increasing the temperature of heating cable, increasing the moisture content of coal, increasing the number of rows of heating holes and reducing the spacing of heating holes, the required electrothermal high-temperature field can be established in the outburst coal seam of the mine.

However, due to the limited data available these observed correlations are merely proposed in this discussion part. More experimental and modeling studies are required to reveal these correlations.

**Conclusion**

1. In the three experimental schemes and under the two thermal insulation conditions, the temperature of coal samples in the cement tank first increased rapidly and then attained stability after 7–10 days.
2. Having the same heating temperature, the heating cable layouts obviously affected the electrothermal high-temperature field of the coal samples. With the same heating temperature and heating cable layout, the heating effect of the coal samples under thermal insulation is obviously better than that without thermal insulation.
3. Under the experimental conditions, the effective heating radius of the heating cable was 800mm≤R<1,000 mm. The heating temperature, cable layout, and thermal insulation conditions significantly affected the electrothermal high temperature field of the experimental coal samples.

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**Data availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Declaration of conflicting interests**

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