Research Article

Freezing Method for Rock Cross-Cut Coal Uncovering: Aging Characteristic of Effective Freezing Distance on Injecting Liquid Nitrogen into Coal Seam

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Based on artificial freezing engineering practice, the comprehensive technology is suggested to realize safe and fast rock cross-cut coal uncovering, which mainly includes four steps of drilling, water injection wetting coal, gas drainage, and injection liquid nitrogen into coal seam. Freezing test of liquid nitrogen injection into coal is carried out to obtain the cooling curves, and comparing the test results, the numerical inverse method is applied to determine the thermal conductivity of coal seam. Then, the model of injecting liquid nitrogen into coal seam is established to simulate and analyze the aging characteristic of effective freezing radius. The results show that the thermal conductivity of wetting coal increases linearly with temperature decreasing. The periodic method with 8h intervals can be adopted to inject liquid nitrogen into coal seam, and the freezing wall is formed around the injection hole. With the increase of freezing time, the effective freezing radius (below 273.15 K) increases by power exponent, and the freezing speed in coal seam decreases gradually. This result will provide a theoretical basis for layout optimization of injection holes in rock cross-cut coal uncovering.

1. Introduction

Coal and gas outburst is one of the serious disasters in the underground production process of coal mine, especially in rock cross-cut coal uncovering. Although there are relatively few outbursts in rock cross-cut coal uncovering, it has the greatest average strength of outburst, which is about 6 times than that of other outburst strength, and more than 80% of the super-huge outbursts occur in working face of rock cross-cut coal uncovering [1–3].

In order to eliminate and prevent coal and gas outburst in rock cross-cut coal uncovering, many scholars and technicians have carried out a lot of theoretical and experimental research studies and put forward many technical measures, such as predrainage gas [4, 5], hydraulic measures [6, 7], metal skeleton [8], deep-hole pre-splitting blasting [9, 10], and coal solidification [11, 12]. These measures have

achieved some results on eliminating outburst danger in rock cross-cut coal uncovering, but these technologies emphasize on safety and cause the process of uncovering coal which is very slow, and the time taken is usually over 6 months, even more than 12 month, which dramatically increases costs. Furthermore, with the increase of mining depth, in situ stress, ground temperature, gas pressure, and gas content in coal seam gradually increase, which enlarges outburst risk. The current measures find it difficult to achieve rapid and effective outburst elimination. Therefore, there is an urgent need to provide a new technology for safe and rapid rock cross-cut coal uncovering.

Based on artificial liquid nitrogen freezing engineering practice, this technology has many advantages, such as high freezing speed, low freezing temperature, high strength of frozen body, and absence of pollution [13, 14], which have been widely used in foundation reinforcement of urban

underground engineering, tunneling of railway and highway, and mine construction [2, 15–21].

So, the artificial liquid nitrogen freezing technology is suggested for rock cross-cut coal uncovering, which has four steps of drilling holes, water injection wetting coal, gas drainage, and injection liquid nitrogen into coal seam. The three main factors affecting coal and gas outburst are in situ stress, gas pressure, and coal mechanical properties. Compared with the current technology, this technology can solve two of the above factors, which are strength enhancement of frozen coal and gas pressure reduction. The strength of frozen coal body is indeed greatly improved, especially as coal body contains a certain amount of water [22, 23]. Yue et al. [24] tested the compressive strength, tensile strength, and shear strength of frozen coal specimens and obtained the mechanical parameters of the specimen. Then, the outburst prevention effects of rock cross-cut coal uncovering (RCCCU) are calculated and quantitatively analyzed with regard to three aspects, which are, respectively, the enhancement of coal the mechanical properties, the reduction in the coefficient of outburst hazard (COH) in the distressed zone, and the reduction in the interfacial elastic energy ratio (IEER) between the coal seam and the roof/floor. Gas adsorption capacity in coal increases with decrease in temperature, which results in lower gas pressure in the confined space [25, 26]. Both of these results are extremely beneficial to prevent outburst in uncovering coal. However, there two key problems about liquid nitrogen injection in coal seam, which is how to arrange the injection holes. In this paper, according to the temperature test of freezing coal, the thermal conductivity of coal seam is determined by the numerical inverse method. Then, the aging characteristic of effective freezing radius is obtained by calculating the model of periodically injecting liquid nitrogen into coal seam.

2. Temperature Test of Coal during Freezing Process

2.1. Test Process. For the temperature test of freezing coal seam, the main experimental equipment are as follows: ① steel drum (1.2 m × Φ 0.96 m) (as shown in Figure 1(a)), ② DTM-180A precision digital thermometer (as shown in Figure 1(e)), the temperature range is between -200°C and 200°C , the length of waterproof probe is 30 cm, and the resolution is 0.01°C , ③ the coal sample was taken from Second-1 coal seam in Dayugou coal mine, Gongyi, China (as shown in Figure 1(a)), ④ 5000 kN hydraulic pressure testing machine (as shown in Figure 1(b)), ⑤ thermal insulation pad, and ⑥ liquid nitrogen.

The thermometers are buried in the coal body with sector distribution (shown in Figure 1(f)), and the distances between thermometers and refrigeration hole are shown in Table 1. The main steps of the experiment are as follows:

- (1) Coal is pulverized into smaller particles, which can be compacted easily.
- (2) Water is fully mixed into the particle coal to make the coal uniform wetting.

- (3) The wetting coal is loaded into the steel drum, and after covering the steel plate, the force on the plate is slowly loaded to 15 MPa by 5000 kN hydraulic pressure testing machine (shown in Figure 1(b)).
- (4) The central hole in the coal body is drilled (diameter 9 cm and depth 80 cm) and the injection pipe is buried in about 20 cm depth (shown in Figure 1(c)). At the same time, the thermometer is buried in about 35 cm depth at different designed positions (shown in Figure 1(f)).
- (5) The steel drum exterior and the upper coal face are covered with thermal insulation pad to reduce the influence of external environment temperature.
- (6) After injecting a certain amount of liquid nitrogen into the freezing hole, the injection port is blocked (Figure 1(d)).
- (7) Record the datum of each thermometer every 10 minutes (Figure 1(e)).

2.2. Test Results and Analysis. Before freezing coal with liquid nitrogen injection, the moisture content of the compacted coal body should be tested with coring at different depths. The coal samples are taken by using Luoyang shovel (Figure 2(a)) at different depths in Figure 1(c)) and dried in the oven (Figure 2(b)) for 24 hours at 105°C ; then, the moisture contents are calculated and shown in Figure 2(c). It can be seen that the moisture content of compacted coal in the barrel is between 11.6% and 12.4% and the mean value is about 12%. Although the moisture content of the bottom coal body is a little larger than that of the upper coal body, the difference is small and relatively uniform.

In order to freeze coal quickly and reduce the frequency of liquid nitrogen injection, liquid nitrogen about 4 L was injected every 8 hours during the freezing process according to the consumption of liquid nitrogen. The experiment lasted 70 hours, and the test results of temperature at different positions are shown in Figure 3.

It can be seen from Figure 3 that, as the distances between the thermometer and the freezing hole are the same, the temperatures are basically consistent. However, the closer to the freezing hole, the more obvious the change of coal temperature. Figure 3(a) shows that the temperatures of No. 1 and No. 2 are particularly affected by injecting liquid nitrogen. The temperatures rapidly drop off while injecting liquid nitrogen, and then, the temperatures increase gradually with the consumption of liquid nitrogen, which shows periodic change with injecting liquid nitrogen. From Figure 3(b), it can be seen that, as the temperature of coal decreases, the closer the distance to the injection hole, the larger the cooling rate, which will form frozen coal pillars centered on the freezing hole. And, with the freezing time increasing, the freezing wall (temperature front of 273.15 K) expands outwards, but the expansion rate of the freezing wall is getting slower and slower, for example, the temperature front of 273.15 K moves from 0.1 m to 0.2 m and it takes about 6 h, the temperature front of 273.15 K moves from

FIGURE 1: Test design process. (a) Steel drum and wetting coal. (b) Pressurized coal sample. (c) Coal body after embedding thermometers and injecting tube. (d) Liquid nitrogen injection. (e) Temperature display and recording. (f) Layout of thermometers.

TABLE 1: The layout of thermometers.

Serial number of thermometer	Distance (cm)
No. 1 and No. 2	1
No. 3 and No. 4	10
No. 5 and No. 6	20
No. 7 and No. 8	30
No. 9 and No. 10	40

0.2 m to 0.3 m and it takes about 11 h, and the temperature front of 273.15 K moves from 0.3 m to 0.4 m and it takes about 18 h.

3. Numerical Inversion of Thermal Conductivity of Freezing Coal

Thermal conductivity of coal are affected by many factors, especially temperature and moisture content, so obtaining thermal conductivity is a key to predict the freezing distance in coal seam.

3.1. Physical Model. Based on the experiment of freezing coal, a physical model, which is consistent with the experiment, is established to numerically inverse the thermal conductivity of wetting coal, as shown in Figure 4. Because of the consumption and supplement of liquid nitrogen in the freezing hole, the temperature fluctuation is large, but the temperature test results of No. 1 and No. 2 thermometers at 1 cm away from the freezing hole have obvious periodic trends, so the mean temperature value of No. 1 and No. 2 thermometers is used as the variable cold source for simulation.

With the freezing hole as the center, the transient heat conduction equation of liquid nitrogen in the coal body is as follows:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right), \quad (1)$$

where ρ is density of coal, kg/cm^3 , t is the time, s, C_p is specific heat capacity, $\text{kJ}/(\text{kg}\cdot\text{K})$, T is the temperature, K, and k is thermal conductivity, $\text{W}/(\text{m}\cdot\text{K})$.

Initial conditions of the coal body:

$$T(r, t)|_{t=0} = T_0. \quad (2)$$

According to the test results of No. 1 and No. 2 thermometers, the temperature of cold source is set as follows:

$$T|_{r=r_0} = T_D(t), \quad (3)$$

where r_0 is the radius of the freezing hole, cm, R is the radius of the coal body, cm, T_0 is initial temperature of the coal body (ambient temperature), K, and $T_D(t)$ is the temperature in the freezing hole, K.

3.2. Determination of Thermal Conductivity. The research results show that thermal conductivity of rock and soil is linearly correlated with temperature [1, 12]. So, it is supposed that thermal conductivity of wetting coal also has linear relation with temperature, and the equation can be expressed as equation (4), and other parameters of the model are shown in Table 2:

$$k = AT + B. \quad (4)$$

FIGURE 2: Moisture content test of the coal sample. (a) Luoyang shovel. (b) Oven. (c) Moisture content.

FIGURE 3: Temperature change in different positions in coal. (a) Test temperatures of No. 1 and No. 2 thermometers. (b) Test temperatures of No. 3~No. 10 thermometers.

FIGURE 4: Calculation model and dissecting grid.

TABLE 2: Model parameters.

Parameters	Symbol	Value	Unit
Coal density (not frozen)	ρ	1430	kg/cm ³
Coal density (frozen)	ρ	1350	kg/cm ³
Specific heat capacity (not frozen)	C_p	1360	kJ/(kg·K)
Specific heat capacity (frozen)	C_p	1180	kJ/(kg·K)
Thermal conductivity	k	$AT + B$	W/(m·K)
Coal radius	R	0.45	m
Radius of cold source	r_0	0.055	m
Coal height	H	0.9	m
Initial temperature	T_0	300.3	K

According to equation (4), two group values of parameter A and B are set, in which one group is bigger and other is smaller. Then, these parameters are used to numerically calculate the physical model, and the calculation result is compared with the temperature of No. 3 thermometer (taking temperature test of No. 3 thermometer as an example), which is shown in Figure 5. If the calculation result is bigger or smaller, the parameter A and B are revalued based on dichotomy, and the model is recalculated until the result is consistent with the test results, so the values of parameter A and B are determined.

As the A and B are -0.0035 and 1.274 , not only trend but also quantity of calculation result are in good agreement with the test results (temperature test of No. 3 thermometer), as shown in Figure 5, and the absolute error of temperature is not exceeding 3 K. Therefore, as the moisture content of coal is about 12%, the relationship between thermal conductivity and temperature can be determined as $k = -0.0035T + 1.274$. With the decrease of temperature, the thermal conductivity of coal increases.

FIGURE 5: Comparison the calculation results with test results.

4. Aging Characteristics of Freezing Radius in Coal Seam

The effective freezing radius of liquid nitrogen in wetting coal seam is an important parameter for the layout of injection holes. Based on the obtained thermal conductivity of moisture content 12%, the aging characteristics of freezing radius in the coal seam are analyzed numerically. According to the consumption process after injecting liquid nitrogen in the freezing hole, the same period of temperature change (in Figure 3(a)), which is set in Figure 6, is adopted in freezing coal seam D-model (shown in Figure 7), and initial temperature of coal seam is 300.3 K.

FIGURE 6: Periodic temperature variation in the freezing hole.

FIGURE 7: Calculation model.

The temperature distribution in coal seam with different freezing times is shown in Figure 8. It can be seen from Figure 8 that, with the increase of freezing time, the refrigerating capacity transfers from the freezing hole to the surrounding area, and the temperature contour is circular, which centers on the freezing hole. Here, the effective freezing radius of coal seam refers to the radius of freezing wall, where the temperature is at 273.15 K. With the increase of freezing time, the freezing front slowly moves outward.

Figure 9 shows the coal temperature variation in x direction at different freezing times. Near the freezing hole, the temperature gradient of coal is much larger, which is because liquid nitrogen injected into the freezing hole causes the coal temperature decrease sharply. However, beyond a certain

distance, the temperature gradient becomes smaller. And, with the same freezing time, the freezing speed decreases gradually, for example, the freezing distance increases by 0.19 m from 5 d to 10 d of freezing time, the freezing distance increases by 0.11 m from 10 d to 15 d of freezing time, and the freezing distance only increases by 0.09 m from 15 d to 20 d of freezing time. The effective freezing radii at different freezing times are shown in Figure 10. It can be seen from Figure 10 that the effective freezing radius increases by the power exponent with the freezing time. That is to say, the effective freezing radius increases rapidly in the initial stage and then increases slowly. At the same time, the calculated results are consistent with the measured results (the maximum distance is only 0.4 m due to the size limitation of the test device), which indicates that the calculation model is reasonable.

FIGURE 8: Temperature contour of coal seam around the injection hole at different freezing times: (a) 5 d, (b) 10 d, (c) 15 d, and (d) 20 d.

FIGURE 9: Temperature curves of coal seam in (x) direction at different freezing times.

FIGURE 10: Variation of effective freezing radius with freezing time.

5. Conclusions

For the practical engineering problems of coal and gas outburst in rock cross-cut coal uncovering, the freezing method of injecting liquid nitrogen into coal seam is suggested to prevent coal and gas outburst. The temperature is tested during the freezing wetting coal process, and comparing with the test temperature, thermal conductivity is obtained by numerical inversion. Finally, aging characteristics of effective freezing radius in coal seam are simulated and analyzed numerically. The main conclusions are as follows:

- (1) The thermal conductivity increases linearly with the decrease of temperature at moisture content 12% of the coal body.
- (2) The closer to the freezing hole, the larger the temperature gradient of coal, but the temperature gradient becomes smaller sharply at a certain distance.
- (3) With increase of the freezing time, the freezing front expands outwards, but the expansion rate of freezing front is getting slower and slower.
- (4) With the increase of freezing time, the effective freezing distance in the coal body decreases. The effective freezing radius of coal body increases by power exponent with the freezing time.

This study will provide a theoretical basis for the rational layout of injection holes in rock cross-cut coal uncovering and will point out a new way to realize safe and fast uncovering coal and develop new technologies to prevent coal and gas outburst.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Heyi Ma curated the data and wrote and prepared the original draft. Chuanqu Zhu investigated the study. Pengtao Zhao reviewed and edited the article. Binbin Wang conceptualized the study and developed the methodology.

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