Using seasonal temperature difference in underground surrounding rocks to cooling ventilation airflow: A conceptual model and simulation study

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Abstract
With the gradual development of deep mining, heat hazard has become an increasingly prominent problem, which poses a great threat to the coal mine production. In order to reduce the heat hazard effectively, it is necessary to investigate the temperature distribution characteristics and regulation of the surrounding rock of the mine tunnels. Based on field measurement data from a Chinese coal mine, the present study probes into the dynamic law of periodic variation of the heat regulation circle (HRC) in surrounding rocks, which is featured by the serious heat hazard, and further reveals the evolution characteristics of the physical range of HRC and the temperature field distribution. By analyzing field data, it can be concluded that a total of five typical distribution models of HRC of surrounding rocks are summarized. Influencing factors concerning thermophysical properties, thermal environment conditions of the stratum, and boundary conditions play important roles and affect the formation of such five models. A mathematical model of heat regulation and energy storage of surrounding rocks in a mine tunnel is proposed. Calculations of air temperature–regulating capability of HRC and evaluating its cooling storage capacity are
also demonstrated. Using the HRC in rocks for cooling underground ventilation may be a good and green engineering practice for coal mines.

**KEYWORDS**
coal mine tunnel cooling effect, HRC (HRC) of surrounding rocks, numerical simulation, temperature field

## 1 | INTRODUCTION

With the continuous exploitation of coal mineral resources, the mining depth increases accordingly and now it is over 500 m in China. In the eastern regions, a large number of coal mines are entering the stage of deep mining since the shallow coal resources are almost consumed.\(^1\)\(^-\)\(^5\) Statistics show that, at present, the depth of coal mining in China extends at the depth of 8–12 m per year. For example, only 8 Chinese coal mines were reported with a mining depth over 1000 m in 2004. However, as of the year of 2012, 47 coal mines are reported with the average mining depth of 1086 m. Deep mining can bring many safety problems. For example, the original temperature of the underground rock layer increases with the rising of depth, which will result in the serious deterioration of working conditions.\(^4\)\(^-\)\(^6\) According to statistics, the temperature of the stratum below normal temperature zone increases at a scale of 3°C/100 m. The high-temperature and humidity environment exerts great influence on the physical health of underground operators and production efficiency.\(^7\)\(^-\)\(^9\)

Scholars carry out in-depth studies from the perspective of the temperature of surrounding rocks and ground temperature measurement. Jiang maintains that the ground temperature field is the main factor that affects the thermal environment of deep mines.\(^10\) Liu\(^11\) investigates the thermal environment in a deep underground mine and analyzes the main heat source and formation mechanism of mining areas and further measures the air temperature, humidity, and velocity under different mining depths. Wang\(^12\) summarizes the characteristics and causes of heat hazard in deep coal mines from the viewpoints of mining depth, regional geological structural characteristics, and physical properties of rocks and provides the basic idea for the cooling work in mines. According to the principle of mass conservation and law of conservation of energy, Li\(^13\) proposes the heat conduction control equation, the heat coupling model of surrounding rocks in mine tunnels, and the stress-seepage-temperature coupling model. In addition, he conducts the numerical simulation of the temperature field in the tunnel surrounding rock using finite element software. Pang and Yang illustrate the basic concept and grade classification of heat hazard and its related safety regulations.\(^14\)

The heat regulation circle (HRC) of surrounding rocks in the mine tunnel is the outcome of the interaction between geothermal energy and airflow in the tunnel, the process of which does not require large-scale investment in specialized mechanical equipment. In fact, the potential and natural energy utilization of preheating and precooling effect has attracted increasing attention. In engineering practices, the heat exchange between the surrounding rock and mine tunnel is employed to regulate the temperature in the tunnel. Tang specially sets up an experimental platform and investigates the heat conduction coefficient of surrounding rocks.\(^15\) Besides, she also takes the deep rock mass as a sample to deal with the coefficient under the solid and liquid coupling condition. According to similar theories, Zhao puts up a simulation experiment platform of heat and moisture exchange of airflow and employs a concrete sample,\(^16\) which has similar thermal performances to the surrounding rock in the mine, to substitute the actual tunnel and simulate the exchange process of heat and moisture. By changing the temperature, humidity, and velocity of air inlet, the change of the air condition at the exit and the temperature inside the surrounding rock can be effectively monitored. Liu\(^17\) verifies the formula concerning the coefficient of unsteady heat transmission. Furthermore, through the assumption of the constant inlet air temperature and relative humidity, he analyzes the feasibility of temperature scale at zero on the theoretical basis of the special form of Sturm-Liouville equation. Furthermore, he also employs the method of separation of variables to derive the distribution function of temperature field in surrounding rocks and theoretical solution of unsteady heat transmission coefficient. Loredo conducts the correlation analysis and numerical model calculation and summarizes the main parameters in the process of flow and heat exchange.\(^18\) It can be found that the ground source (geothermal) heat pump (geothermal system of low enthalpy) can be used to heat or cool the space. Since the heat capacity for this stored water is limited, its flow must be controlled within a sustainable range. In addition, Loredo et. al inquire into the geothermal energy by pumping water from an abandoned mine, located in Asturias in the northwest of Spain.\(^19\) The result shows that the steady temperature of water increases with the rising of depth and the long use of geothermal resource exploitation can be achieved by excavating mine reservoirs.

This paper conducts the measurement of the temperature distribution of surrounding rocks in the tunnel mine and reveals the physical range characteristics of HRC and the
evolution characteristics of temperature distribution in the tunnel. Moreover, this paper summarizes five change patterns of temperature curves of surrounding rocks and establishes the two-dimensional and three-dimensional mathematical description models for the heat storage. In addition, the numerical simulation method is used to simulate the natural heat and cold regulation of the airflow, which is realized by the HRC, and initial discussion on the feasibility and economy is concluded in this paper. It has been found that the HRC, as a more economical self-heat transfer mode, would have a strong positive outlook in the selection of the cooling engineering of mine tunnels.

2 | TEMPERATURE DISTRIBUTION CHARACTERISTICS OF HRC OF TUNNEL SURROUNDING ROCKS

2.1 | HRC of surrounding rocks

Before the excavation of a mine tunnel, the temperature of rock mass at every point is in equilibrium with the original rock temperature. Owing to the temperature difference between surrounding rocks and airflow, the thermal movement in rock mass occurs from the deep to the wall and the temperature of rocks at every point will decrease with the airflow at the time of excavation. However, the deep surrounding rock, at a certain distance from center of the tunnel, will remain the original temperature, without the effect of airflow temperature. The boundary, not affected by the ventilation temperature (the range within the isotherm of original rock temperature), is defined as the HRC of surrounding rocks in the mine tunnel. The temperature distribution in this circle is called the temperature field. The isotherms of the temperature field are a group of approximately concentric circles, and the distance between isotherms varies with the shape of tunnels and heat exchange conditions. Influenced by the direction of terrestrial heat flow, generally, the isotherms at the bottom of the tunnel are denser than those above the tunnel, as is shown in Figure 1.

The distance from the center of the tunnel to the limit boundary of the circle (the isotherm of original rock temperature) is called the radius of HRC. In addition to the rock temperature, airflow temperature, rock thermal physical properties, airflow quantity, and the size of radius also depend on the ventilation period. Therefore, the size of the circle varies continuously. The radius is relatively small with short ventilation time in new excavated tunnels, while it will become larger and larger over the ventilation time since the range of the circle will be enlarged with the cooling effect. Given enough ventilation time (about 2 years), it can be considered that the heat exchange between the surrounding rock and the airflow has been fully completed, and the radius of the circle, with relative stability, is close to the maximum value. At the same level of the tunnel with the same original temperature of surrounding rocks, the radius of the circle becomes smaller along the downward direction of airflow. In practices, the heat exchange between surrounding rocks and tunnels can be used to regulate the temperature in the mine. With cold air in winter, surrounding rocks are constantly cooled down with more heat taken away, while the cooled rocks will absorb plenty of heat in summer and further achieve the control of the tunnel temperature.

2.2 | Temperature measurement of HRC

Ground temperature measurement, one of the methods of geophysics, has been widely applied in the studies of geothermal geology, hydrogeology, structural geology, earthquake geology, and mineral geology. As an important physical parameter, ground temperature is also an essential parameter in the design of mine cooling. In order to obtain the data of ground temperature, the mine temperature can be measured by means of ground hole-drilling exploration or mining tunnel.

From the systematic study on geothermal field characteristics, it is necessary to construct some special boreholes for temperature measurement. However, existing thermometric holes must be taken into consideration in the arrangement of special boreholes, and a geothermal profile is preferred in combination with the underground tunnel system. In general, the ground temperature profile should be arranged in the upward (downward) tunnel along the air inlet. According to the size of the mine, two or three profiles are required. Besides, the selection of drilling location should be kept from the influence of underground water drainage, and the number of holes depends on the ground temperature at different depths. Normally, the larger the formation dip is, the denser the boreholes are, and the distance between boreholes can be longer when the formation dip is slower. In the meanwhile, in order to measure the original temperature of rocks, the depths of holes must exceed the thickness of HRC which needs to be measured.
2.2.1 | The observation position of borehole temperature

Taking a Chinese Mine as an example, three sets of boreholes are arranged in the south mining area with an aim to control the whole mine when measuring the temperature and to obtain the temperature data at different horizontal levels. The first set of holes are arranged in −740-m horizontal track tunnel, the second set are laid in −700-m west track tunnel, and the third set are located in the 4th eastern mining section of south mining area. The details are as follows.

1. There are 5 five holes in the first set, which are located in −740-m horizontal track tunnel. Among these holes, hole#1 is drilled in −700-m bypass contacting tunnel, hole#2 is arranged in −980 m downward side of the return air of South Wing, and hole#3 is fixed in −980 m downward side of track tunnel. The drilling interval is 50 m.

2. The second set includes 3 holes, which are arranged in −700-m west track tunnel. All these holes are placed in the track tunnel, with an upward vertical angle and the depth of 11 m. The drilling interval is 50 m.

3. There are five holes in the third set which is located in the fourth eastern mining area of South Wing. The specific location of the boreholes is shown in Figure 2.

2.2.2 | Measuring equipment and temperature measurement of boreholes

The temperature of horizontal holes is measured point by point by thermistor probe, with the distance ranging from 1~3 m. Inwards from the orifice, the stability time of each temperature measurement point is 10 minutes. When the borehole is finished, the orifice should be closed first, and after the temperature becomes stable inside the hole, the probe should be carried into the borehole along with the long wire and then the temperature can be observed point by point to the deep. Specific equipment installation for the temperature measurement of boreholes is shown in Figures 3 and 4.

2.2.3 | Observation scheme

In order to investigate the variation of the HRC of tunnel surrounding rocks during different seasons, the measurement work took place throughout the year of 2015 with the selected typical time in spring, summer, autumn, and winter. Four rounds of measurements were required for the above 13 temperature measuring points. After the measurement, we got the basic grasp of the temperature distribution law of HRC of tunnel surrounding rocks in different horizontal levels, different working areas, and different mine environments in the mining area of South Wing. Besides, in the process of temperature measurement, the complete control of the whole mine was achieved and the temperature data on different levels were obtained at the worksite. Altogether, a total of 52 temperature measurement curves and hundreds of temperature measurement data were acquired.

2.3 | Distribution characteristics of the temperature field of HRC

2.3.1 | Temperature distribution mode of HRC

With the change of four seasons, based on the repeated measurement of 13 observation points under different mine environment conditions, five distribution modes of the HRC of surrounding rocks in the tunnel are summarized through the comprehensive analysis of 52 temperature distribution curves of the circle.
1. The range of the circle of surrounding rocks becomes larger during the alternate periods between summer and winter. The ineffective dissipation of stored cooling capacity is relatively small in winter, while the dissipation of heat storage is large in summer (Figures 5-7).

Curves of this mode include the temperature measurement of hole 1-1# in −700-m bypass tunnel of South Wing, hole 1-5# in −700-m bypass tunnel of South Wing, and hole 3-4# in the fourth eastern track tunnel. The common feature of such curves is that the radius of HRC achieves a relatively greater expansion, going deep into the rock, at the turn of the summer and winter. In addition, it can be found, by comparing the curves in summer with those in winter, that the wide range of temperature variation will lead to the drastic change of the temperature near the tunnel wall and a considerable amount of cooling (heat) capacity theoretically. From winter to summer, the curves of temperature measurement show an “upward” trend, with an increase in temperature with varying degrees at every point. However, at the alternate periods, there is not a sharp increase in temperature. With regard to the effect of HRC, it is hoped that the stored cooling capacity in winter can be preserved and “totally” released in summer.

**Figure 3** Long borehole temperature measurement layout drawing

**Figure 4** Schematic diagram of the distribution of underground cable temperature measurement holes

**Figure 5** 1-1# long borehole temperature curve of the four seasons in −700-m bypass of South Wing

**Figure 6** 1-5# long borehole temperature curve of the four seasons in −700-m bypass tunnel of South Wing
Nevertheless, it is often the case that a portion of cooling capacity will be lost before summer owing to the erosion of original rock temperature, but little upward trend is shown in the curves of this kind, which indicates that the cooling capacity is perfectly preserved with slight loss during the alternate period and the function of HRC is fully realized. Generally speaking, the airflow can be effectively cooled down in summer in the tunnel of this mode.

In summer and autumn, there is a drastic “decrease” in temperature. The temperature difference between summer and autumn is much greater than that in winter and spring, which reflects that it is difficult to store heat in the tunnel and the rocks are easily cooled down.

2. At the turn of winter and summer, the range of HRC varies greatly and the ineffective dissipation of stored cooling (heat) capacity is large in winter (summer) (Figures 8-10).

Curves of this mode include the temperature measurement of hole 1-4# in −740-m track tunnel, hole 3-1# in the fourth eastern track tunnel, and hole 3-5# in the fourth eastern track tunnel. The common feature of curves of this kind is that there is a great expansion of the radius of the circle at the turn of summer and winter, deep into the rock. Moreover, the temperature varies greatly by comparing the curves in winter with those in summer, especially the temperature near the tunnel wall. This mode, similar to the first mode, also suggests a considerable amount of stored cooling (heat) capacity in theory. From winter to summer, the curves of temperature measurement show an “upward” trend, despite the large increase in temperature at every observation point. Still, it can be found that almost half
of the temperature rise occurs during the transition from winter to spring. As is mentioned earlier, in the aspect of the effect of HRC, it is more hoped that the stored cooling capacity in winter can be preserved and totally released in summer, but actually 50% of cooling capacity in the rock mass will dissipate ineffectively before summer comes. Therefore, it is unlikely to have a good cooling effect in such tunnels and the effective time is extremely limited for cooling the airflow. It can be believed that the retained cooling capacity cannot serve as an ideal HRC for the temperature regulation of airflow. In summer and autumn, the curves present a “drastic” decrease in temperature and almost half of the temperature “decrease” occurs within this period. The result shows that the overall effect is limited, although the storage of heat capacity is better than that in the first mode, which also accounts for the limitation of heating the cold air in winter. Furthermore, the curves of spring and autumn are similar, with a great difference near the tunnel surface and slight difference deep inside the rock.

3. The range change of HRC of surrounding rocks is extremely limited at the turn of winter and summer. The ineffective dissipation of stored cooling (heat) capacity is large in winter (summer) (Figures 11 and 12).

Curves of this mode include the temperature measurement of hole 1-2# in the excavation tunnel of uphill drift in the second South Track and hole 1-3# in frontal uphill of return air of South Wing. The common feature of curves of this kind is that the expansion of the circle radius is restricted during the alternate period of winter and summer with limited depth into rocks at the same time. The range of the radius fluctuates from 1 to 2 m. Through the comparison of curves of summer and winter, we can conclude that the radius expansion is usually within the distance of 1.5 m despite the wide temperature difference. On this basis, it is believed that the tunnel is theoretically stored with very limited amounts of cooling (heat) capacity. From winter to summer, the curves of temperature measurement show an “upward” trend, with a sharp increase in temperature at every observation point, while from summer to autumn, there is a “downward” tendency in temperature. The changes in these two periods are similar to those in the second mode, and basically, half of the temperature rise (or fall) occurs during the transition from winter (summer) to spring (fall). The curves of spring and autumn are similar, with a great difference near the tunnel surface and slight difference deep inside the rock. With regard to the HRC of this kind, 50% of cooling capacity in the rock mass will dissipate ineffectively before summer comes and the amount of stored cooling capacity in the rock itself is very limited. Therefore, it can be concluded that this kind of tunnel should not be regarded as an ideal HRC for the temperature regulation of airflow.

4. At the turn of winter and summer, the range of HRC of surrounding rocks varies sharply and there is a steady change presented in the curves of four seasons. In winter, the ineffective dissipation of stored cooling capacity is relatively small, while the dissipation is large in summer Figures 13-15.

Curves of this mode include the temperature measurement of hole 2-1#, hole 2-2#, and hole 2-3# in -700-m west track tunnel. The common feature of curves of this kind is that significant change of the circle radius occurs during the alternate periods of summer and winter (about 6 m in summer and about 15 m in winter with the maximum expansion of 18 m). Through the comparison of curves of summer and winter, there is a huge difference in temperature at every point in winter and summer. In other words, the adjustable range of

**FIGURE 11** 1-2# long borehole temperature curve of the four seasons in the excavation tunnel of uphill drift in the second South Track

**FIGURE 12** 1-3# long borehole temperature curve of the four seasons in frontal uphill of return air of South Wing
the radius is large and the temperature changes greatly. The temperature measurement curves of the four seasons are basically evenly distributed. Different from the first three modes, every curve of this mode presents a slight change in temperature with a minor rising speed, which indicates a considerable amount of stored cooling (heat) capacity in theory. From winter to summer, the curves of temperature measurement show an “upward” trend, with an increase in temperature with varying degrees at every observation point. By way of contrast, there is a slight change in temperature during the transition from winter to spring. However, the temperature increase becomes more obvious in spring and summer, but the temperature drops greatly in summer and autumn. With regard to the effect of HRC, a portion of cooling (heat) capacity will be dissipated, and this part of energy cannot be used to cool (heat) the airflow in summer. But fortunately, the circle of this mode has a larger radius, which will help to store more cooling (heat) capacity. Therefore, the lost energy will not exert great influence on the effect of cooling or heating the airflow. Besides, the long-lasting effect can fully realize the function of the HRC of surrounding rocks. The tunnel of this mode can effectively cool the airflow in summer.

5. At the turn of winter and summer, the range of HRC varies greatly and the ineffective dissipation of stored cooling (heat) capacity is small in winter but large in summer with a high proportion of water inside surrounding rocks (Figures 16 and 17).

Curves of this mode include the temperature measurement of hole 3-2# in 7407 track tunnel and hole 3-3# in the fourth eastern excavation tunnel. The common feature of curves of this kind is that, given the short ventilation time (mostly <2 years), the radius of the circle varies greatly
with more depth into the rock mass. For example, in terms of hole 3-3# with the ventilation time of 1 year, the radius extends to 5 m or so in winter, while the radius lies between 1 and 2 m. It can be found through the comparison of curves of summer and winter that there is a great change in temperature, especially at the distance of 2 m from the tunnel surface. The fact above suggests a considerable amount of stored cooling (heat) capacity in theory. From winter to summer, the curves of temperature measurement show an “upward” trend, with an increase in temperature with varying degrees at every observation point, while there is a slight temperature increase at the turn of winter to spring. From the perspective of the effect of HRC, which is put forward in the first mode, we can conclude that curves of this mode present a minor “increase” in temperature, which contributes to the preservation of cooling capacity and less loss of energy during the transition period. On the other hand, from summer to autumn, the curves show a slight decrease in temperature and the decline is almost the same as that from winter to spring, which indicates the ideal effect of the tunnel in the storage of heat capacity. Generally speaking, the curves are similar of spring and autumn with a small temperature difference.

2.3.2 | The formation mechanism of temperature distribution modes of HRC

Both heat transfer in rock mass and heat exchange between rock mass and airflow are complicated processes. In fact, the temperature change inside the rock indicates the comprehensive effect of the thermal physical properties of rocks, the thermal environment conditions of stratum, air conditions in the tunnel (such as airflow velocity, temperature, and humidity), tunnel sizes, etc.

The following is the interpretation of the formation mechanism concerning the first mode of HRC of tunnels. From the lithological perspective, tunnels of this type mainly consist of medium sand, among which quartz, the main component, accounts for more than 65%. The thermal conductivity coefficient of quartz can reach 6.12 kJ/(m·h·°C) and the coefficient presents an increasing trend with the increase in quartz content, which contributes to the heat transmission. Besides, in the aspect of time (the general ventilation time in this kind of tunnel is over 5 years), the longer the cooling time for surrounding rocks is, the easier the circle will penetrate into the deep of rocks with large expansion. Moreover, in the process of heat and moisture exchange between surrounding rocks and airflow, most energy is transferred from the tunnel wall to airflow, which is usually defined as the heat release coefficient. Heat release coefficient is not a physical property value, but a complex function related to airflow velocity temperature, thermal conductivity of surrounding rocks, specific heat of air, air density, dynamic viscosity coefficient, and the geometry and shape of the tunnel wall. Among these factors, airflow velocity exerts greater influence on the coefficient. Owing to the three small tunnel sections and large airflow, the calculated airflow velocity, about 7 m/s, leads to a large heat release coefficient of tunnel wall to airflow, a rapid loss of heat at the turn of summer and autumn, and a great decline in temperature. On this basis, it can be concluded that tunnels of this kind are ideal ones for the regulation of temperature.

The following is the interpretation of the formation mechanism concerning the second mode of HRC of rocks. From the lithological perspective, tunnels of this kind are mainly composed of sandstone and medium sand. The content of quartz, the main mineral component, is relatively low (<25%). As for calcareous rock, syenite, and granite, their thermal conductivity is 2/3 lower than that of quartz. Given the universal ventilation time of over 5 years, the radius of HRC is shorter than that of the first mode owing to the low thermal conductivity which is not conducive to heat transfer. In addition, most tunnels of this mode are underground ones. The large tunnel sections and small airflow velocity (usually <3 m/s) result in the small heat release coefficient of tunnel wall to airflow, which is not helpful in heat transfer and dissipation. Technically speaking, tunnels of this kind show an obvious deficiency in regulating the tunnel temperature.

The following is the interpretation of the formation mechanism concerning the third mode of HRC of rocks. From the lithological perspective, the surrounding rocks are mainly made up of sandy mudstone with a quite low thermal conductivity coefficient (lower than the first two modes). Furthermore, the altitude distribution of the coal seam and tunnel is about...
On the basis of geological data, the original ground temperature is about 45.8°C, which accounts for the fact that the high-temperature environment around the tunnel seriously erodes the HRC. The radius of the circle in the tunnel is only about 1 m with a small contraction distance in winter and summer. In addition, the short ventilation time, about 1 year, results in the short cooling time of surrounding rocks to airflow. Therefore, tunnels of this kind are not ideal enough for the temperature regulation whether in terms of economics or technology.

The following is the interpretation of the formation mechanism concerning the fourth mode of HRC of rocks such as hole 2-1#, hole 2-2#, and hole 2-3# in −700-m west track tunnel, with the most remarkable characteristic of longer ventilation time. The ventilation time of these observation points, mainly arranged in the main tunnel, is up to 18 years. At the beginning of ventilation, there is a drastic change in the gradient of the circle but with small range of change in the radius. With the increase in ventilation time, surrounding rocks are totally cooled down by the airflow, which leads to the extension of the radius to the deep of rock mass. However, the radius expands at a low speed and the variation of rock properties tends to be stable. The radius of HRC can extend to 18 m in winter. Additionally, from the lithological perspective, the tunnels of this type are mainly composed of medium sand. Quartz, with the strongest thermal conductivity, accounts for more than 50% among main mineral components. As a result of long ventilation time and no water drenching in the tunnel, the inside of rocks is relatively dry, which can help to store the heat. Moreover, since these three are main tunnels in the coal mine, the larger section and airflow can contribute to store the heat. The curves of the four seasons are relatively smooth, and the curves of spring and autumn are evenly located between summer and winter. In spite of the loss of cooling and heat capacity at the turn of winter and summer and the turn of summer to autumn, the lost energy can be omitted owing to the wide range of the circle and strong ability of heat transfer. Generally speaking, tunnels of this kind are ideal ones for the regulation of temperature.

The following is the interpretation of the formation mechanism concerning the fourth mode of HRC of rocks, such as hole 3-2# in 7407 track tunnel and hole 3-3# in the fourth eastern excavation tunnel, with a wide range of HRC. In winter, the radius can reach 5 m and there is a huge difference between winter and summer in the radius. Furthermore, the changing trend of curves in this mode is similar to that in the first mode. The short ventilation time indicates the good capability of heat transfer of tunnels. However, in combination with other actual site conditions, this “false appearance” can be further interpreted as follows. From the perspective of lithology, the tunnels of this kind are mainly made up of medium sand and coal, and the quartz in sandstone, based on measurement, accounts for a small proportion (<25%), and the thermal conductivity of coal is small. Therefore, the wide range of heat regulation sphere mainly depends on the effect of “water” in the coal. For the same kind of rocks, the decrease in density will lead to the increase in porosity. Owing to the small thermal conductivity coefficient of air, the coefficient of rocks also decreases, among which sandstone and limestone are most easily influenced. The pores in rocks are often saturated by water, which exerts great influence on the thermal conductivity coefficient although water evaporation will absorb heat. Field tests show that the moisture content of coal and rock mass is very high, reaching more than 8%. Meanwhile, the phenomenon of water drenching in the tunnel is serious. Under the influence of high-temperature airflow, the water, whether on the tunnel wall or in the pores of rock mass, will evaporate with a lot of heat taken away, which manifests the wide extended cooling range of rock mass. However, in essence, the heat storage capacity of the rock mass is not ideal.

Based on the in-depth analysis above, the test results, concerning the temperature distribution of tunnel surrounding rocks in coal mine, show that the HRC of tunnel surrounding rocks, affected by many factors, is mainly determined by the following ones: (a) the heat release coefficient of tunnel wall to airflow, which determines the heat exchange rate between the tunnel wall and airflow. It should be noted that this coefficient is by no means an absolute thermophysical parameter but a comprehensive variable value influenced by the thermal environment of tunnel, in which the ventilation speed exerts greater influence; (b) the thermal conductivity coefficient of rocks, which determines the thermal conductivity of geothermal energy in stratum and further restricts the range of the circle to a large extent; and (c) the water content of rock mass. The water content in rocks has an important influence on its thermal conductivity, which can change the range of HRC. However, the water in rocks is easy to evaporate, which leads to the change of thermal conductivity coefficient. Therefore, with the increase in ventilation time, the temperature distribution of tunnel surrounding rocks changes constantly.

In the meanwhile, it can be concluded that tunnels, which are suitable for the regulation of temperature in the coal mine with high temperature, should have the following characteristics: (a) Surrounding rocks should have good thermal conductivity properties with high conductivity coefficient. Rocks of this kind can contribute to both the heat transfer and cooling capacity storage with a high efficiency. (b) Tunnels with large sections should be selected, which can help to keep a moderate ventilation speed on the one hand, and expand the physical range of HRC for more energy storage on the other hand. (c) The ventilation time should be longer. The longer the ventilation time, the better the cooling effect of rocks and more stable the thermal property parameters. (d) The water content in surrounding rocks should be as low as possible.
Besides, the dry rock mass is preferred, with an aim to eliminate the influence of water. (e) Tunnels, with the elevation near the ground surface, should be selected. The smaller elevation means the lower temperature of original rocks and less erosion by the high temperature. Moreover, a tunnel in a zone with constant ground temperature to avoid the influence of the surface air temperature may be the ideal one.

3 THE CALCULATION MODEL OF HEAT TRANSFER AND ENERGY STORAGE OF HRC OF SURROUNDING ROCKS

Before the excavation of the tunnel, the rock mass is in a balanced state at every point, keeping the original rock temperature. Starting from the ventilation of the tunnel, the heat transfer occurs from the deep to the wall of the tunnel, and the temperature of each point in the surrounding rock decreases with the airflow, as a result of the temperature difference between the rock and airflow. Based on the observation data shown in Chapter Three, it can be found that the longer the distance from the tunnel wall, the smaller the temperature difference in the rock between summer and winter (as is shown in Figure 18). In other words, the temperature curve of the rock mass changes from winter (blue line) to summer (red line) by heating gradually. In this physical process, heat is gradually stored in the rock mass. During the alternate period between summer and winter, the heat is gradually released, while the cooling capacity is gradually stored. On the contrary, at the turn of winter to summer, the cooling capacity is released, while the heat is stored.

The method of thermal analysis is employed to derive the mathematical model of heat storage for tunnel surrounding rocks. Suppose the distance between the surrounding rock and the tunnel wall is \( x \), and then, the temperature curves of rocks are expressed as \( t_w = f_w(x) \) in winter and \( t_s = f_s(x) \) in summer. The bounded enclosed area of these two curves is \( Q \), and the stored heat in the unit longitudinal length can be expressed as Formula 1:

\[
Q = c \cdot \rho \cdot \int_{D} f(x, t) \, dx \, dt = \int_{x=0}^{x=L} \int_{t=0}^{t=ts} f(x, t) \, dx \, dt
\]  

(1)

In the formula above, \( c \) is specific heat capacity and \( \rho \) refers to the density of rocks.

Of course, the formula above can also be generalized in three dimensions. Assuming that the tunnel length is \( L \) and the rock mass increases with the longitudinal length along \( z \) direction, then the heat storage in the longitudinal tunnel length can be expressed as follows:

\[
Q = c \cdot m \cdot \iiint_{V} f(x, z, t) \, dV = \int_{z=0}^{z=zs} \int_{x=xw(z)}^{x=xs(z)} \int_{t=ts(z)}^{t=tw(z)} f(x, z, t) \, dx \, dz \, dt
\]  

(2)

In the formula above, \( m \) denotes the quality of rock mass in length \( L \) within a variable temperature range, \( xs(z), xw(z) \) are the spatial functions of HRC in summer and winter along \( z \) direction, and \( ts(z), tw(z) \) refers to the temperature curves of summer and winter on \( X \) and \( Z \) planes.

It should be noted here that the above two formulae only provide the theoretical calculation method of heat (cooling) storage capacity in winter and summer, but, in reality, the thermal energy is not possible to be fully employed to cool or heat the airflow. The reasons are as follows.

1. In view of spring between winter and summer and autumn between summer and winter, the stored heat (cooling) capacity cannot be fully used for heating or cooling the airflow. Generally speaking, the energy is partially consumed in spring and autumn.

2. In fact, with regard to the cooling or heating of airflow, it is necessary to take into account whether the temperature difference between the tunnel wall and airflow is positive or negative. The positive difference means the heating process for the airflow, while the air temperature increases while the rock mass is cooled down. On the contrary, the negative difference denotes the heating process for the rock mass, where the rock temperature increases with the decreasing temperature of airflow. On this basis, it can be concluded that the two formulae only denote the maximum capability of surrounding rocks to heat or cool the airflow. The airflow temperature should also be taken into consideration in terms of how much energy can really be used (in other words, the question of “efficiency”). The process calculations are complicated, and it can be conducted with the help of computer numerical simulations.
4 NUMERICAL SIMULATION AND ECONOMIC EVALUATION OF TEMPERATURE-REGULATING PROCESS OF TUNNEL SURROUNDING ROCKS

4.1 Numerical simulation of temperature-regulating process of tunnel surrounding rocks

Against the background of the project case of coal mine, a tunnel in the mine, with the length of 3 km, is selected in the present study, and its thermophysical parameters are all taken from the actual tunnel. In addition, on the basis of software Abaqus, a numerical model is established to carry out the numerical calculation of temperature-regulating process of tunnel surrounding rocks, which will contribute to the effective evaluation of the economy of the designed temperature regulation scheme.38,40

Suppose that the material follows Fourier heat conduction law, and then, the transient heat transfer control equation is expressed as41,42:

\[
\rho c \frac{\partial T(x,y,z,t)}{\partial t} = \left( k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} \right) + Q(x,y,z,t)
\]

In this formula, \(Q(x, y, z, t)\) refers to internal heat source, \(\rho\) denotes the density of material, \(c\) denotes the specific heat capacity, and \(k_x, k_y, k_z\) represent the thermal conductivity in three directions: \(x, y,\) and \(z,\) respectively.

Generally speaking, the transient heat conduction (also called the transient temperature field) depends on time. We can obtain the first-order ordinary differential equations, which cannot be solved directly, after the discretization of the Galerkin method of equivalent integral form of differential equation by finite element. From the perspectives of practical application and convenience, the solution principle is usually the direct integration method. In order to balance the accuracy and efficiency effectively, the variable time-step method is adopted to analyze and solve the problem. Furthermore, the backward differential method is used to solve the heat conduction equation of the discretized system with an aim to guarantee the stability of solution.

4.2 The establishment of numerical model

In the calculation, the length \((L)\) of tunnel is 3km, and its 3D model, cross-sectional size, and boundary conditions are shown in Figure 19.

As is displayed in Figure 19B, based on the conditions of about 700-m west track tunnel in the coal mine, the set height is \(h = 3.5\) m, the radius at the top of tunnel mine is \(r = 2.5\) m, and the radius of surrounding rocks, in the calculation model, is originally selected as \(R = 14.5\) m. Convective heat transfer is mainly taken into account for the internal surface, and other heat sources in the tunnel are neglected for simplified calculation.

Some of the material parameters used in the calculations are as follows: the density of surrounding rocks in the tunnel mine is \(\rho = 1709\) kg/m\(^3\), specific heat capacity is \(c = 837\) J/kg·°C, heat conductivity is \(k = 2.68\) W/m·°C, and the original temperature of surrounding rocks is \(T_0 = 40\) °C.

Owing to the total length of 3 km and the difficulty in expressing all meshes, the finite element meshes in the tunnel mine with the length of about 100 m are presented as an example. The DC3D20 element in Abaqus, namely, 20-node three-dimensional heat conduction hexahedral element, is employed for calculation. This type of element is used to construct the element shape function by means of the interpolation method of higher order, which can guarantee the calculation accuracy (Figure 20).

The determination of the convection heat transfer coefficient of the tunnel surrounding rock is complicated, since the coefficient is mainly affected by the airflow velocity, the shape of the cross section, and the roughness of tunnel wall. Moreover, the average convective heat transfer coefficient will increase with the rising of average ventilation velocity. According to the experimental results and data from some Chinese coal mines, the following empirical formula for heat transfer coefficient of tunnel surrounding rocks is used:
In the formula above, $v$ refers to the ventilation airflow velocity in the tunnel and $\alpha$ denotes the convection heat transfer coefficient of the surrounding rock to airflow.

### 4.3 The results and analysis of the numerical simulation

To start the numerical simulation of the temperature regulation of the surrounding rock, three stages should be taken into consideration. In the first stage, the surrounding rock keeps absorbing and storing cold air of $-20^\circ C$ that is introduced into the mine tunnel so that the surrounding rock temperature is decreasing. The numerical simulation is carried out by using finite element method. The results of the temperature field distribution of surrounding rocks at the exit of the tunnel are given as shown in Figure 21.

In Figure 21, the temperature of surrounding rocks is basically stable after 9 months or so when the radius of the HRC is about 13.8 m. The temperature changes rapidly in the first 3 months and relatively slowly in the latter months until the balance has reached. With cold air adding into the tunnel, the air temperature is increasing and the temperature in the tunnel is reducing, which gradually weakens the absorption of cooling capacity. Air temperature changes at the outlet of the 3 km tunnel are given as shown in Figure 22.

According to the Figure 22, it can be concluded that with the heat exchanges between cold air and the surrounding rock, the temperature of the surrounding rock is declining due to the increase in cooling capacity and the same as the air temperature at the outlet of the tunnel. When cold air is introduced for about 2 months, the air temperature at the outlet of the tunnel remains above $10^\circ C$ that is beneficial for maintaining normal operation down the mine. When cold air is introduced for about 9 months, the air temperature at the outlet of the tunnel reaches $-15^\circ C$ more or less, out of the normal working temperature down the mine. When cold air is introduced for about 2 months, the length and the size of the tunnel are larger than those of the section, so only the temperature distribution of the surrounding rock at 100 m away from the inlet and the outlet of the tunnel is given as shown in Figures 23 and 24.
In Figures 23 and 24, there is a large temperature gradient at the inlet and outlet of the mine tunnel. Surrounding rocks at the inlet cool faster due to the lower temperature of cold air at the inlet. With the continuous flow of cold air in the tunnel to absorb the heat of surrounding rocks, the rising temperature leads to the decline of the heat transfer rate with the surrounding rock and to the high temperature of the outlet surrounding rock. With the continuous ventilation, the surrounding rock will keep absorbing cold air and storing, until balance is reached.

In general, when cold air is introduced for 3 months, the rising temperature of cold air at the outlet is acceptable. Continued ventilation requires some measures to heat cold air; otherwise, the needs of safe operation cannot be satisfied.

In the second stage, hot air of about 37°C is introduced into after the previous balance, when surrounding rocks exchange heat with hot air. The finite element method is used to carry out the numerical simulation of the temperature field in surrounding rocks, and Figure 25 provides the results of the temporal temperature distribution of surrounding rocks at the outlet of the tunnel.

In Figure 25, about 8 months later, the temperature of surrounding rocks reaches stable. The temperature changes rapidly in the first 3 months and relatively slowly in the latter months until the balance has reached. With hot air adding into the tunnel, the air temperature is reducing owing to the absorption of heat capacity by the cooling surrounding rocks. As the temperature in the tunnel goes up, the absorption of heat capacity is weakening. The air temperature changes at the outlet of the 3 km tunnel are given as shown in Figure 26.

Figure 26 shows that surrounding rocks with lower temperature keep absorbing the heat capacity in hot air that continues to be introduced, which cools the air in return. However, with the heat exchange going on, the capacity of absorption of surrounding rocks is weakening, leading the rising temperature in the outlet. About 3 months later, the temperature at the outlet could reach 27°C and will keep going up without stopping hot air so that the normal operation temperature cannot be guaranteed. When hot air is introduced for nearly 3 months, the temperature distributions of the surrounding rock at 100 m away from the inlet and the outlet of the tunnel are given as shown in Figures 27 and 28.

In Figures 27 and 28, there is a large temperature gradient at the inlet and outlet of the mine tunnel. The temperature of surrounding rocks at the inlet goes up faster due to the higher temperature of hot air there. With the continuous flow of hot air in the tunnel to absorb the cooling capacity of surrounding rocks, the declining temperature leads to the decline of the heat

**FIGURE 22** Variation curve of air temperature with time at exit of roadway

**FIGURE 23** Temperature field distribution of surrounding rock at the inlet of roadway

**FIGURE 24** Temperature field distribution of surrounding rock at the exit of roadway
transfer rate between hot air and the surrounding rock, and to the low temperature of the outlet surrounding rock. With the continuous ventilation, the surrounding rock will keep absorbing heat capacity in hot air and storing, until balance is reached.

To conclude, given the ventilation time of 3 months, the temperature of hot air at the outlet is acceptable. Continued ventilation requires some measures to cool hot air; otherwise, the needs of safe operation cannot be satisfied.

In the third stage, based on the previous stable state in the second stage, cold air at −20°C is introduced and heat exchange goes on between cold air and surrounding rocks which keep absorbing cooling capacity in cold air. Abaqus is used to carry out the numerical simulation of temperature field in surrounding rocks, and Figure 29 shows the results of the temporal temperature distribution of surrounding rocks at the outlet of the tunnel.

As shown in Figure 29, about 8 months later the temperature of surrounding rocks reaches stable again. The temperature also changes rapidly in the first 3 months and relatively slowly in the latter months, until the balance has reached. Similar with the first stage, with the cold air adding into the tunnel, the air temperature is rising owing to the absorption of cooling capacity by the surrounding rocks with higher temperature. As the temperature in the tunnel goes down, the absorption of cooling capacity is weakening. The air temperature changes at the outlet of the 3 km tunnel are given as shown in Figure 30.

Figure 30 shows that surrounding rocks keep absorbing cooling capacity in cold air that continues to be introduced, which heats the air in return. However, as it continues, the capacity of absorption is weakening and the temperature at the outlet is declining, which is similar to the first stage. When hot air is introduced for nearly 2 months, the temperature distributions of the surrounding rock at 100m away from the inlet and outlet of the tunnel are given as shown in Figures 31 and 32.

Figures 31 and 32 prove that the third stage is almost same as the first stage when the air warming effect is better in the beginning because of all surrounding rocks of 40°C, and there is little difference in latter periods. With a second introduction of hot air and cold air, the temperature of the air and surrounding rocks will change in circular between the second and the third stage.
4.4 Economic analysis and evaluation of temperature regulation scheme of surrounding rocks

With the increase in mining depth, heat harm is becoming more and more serious. In many high-temperature mines, the artificial refrigeration cooling must be adopted. By consulting relevant literatures, it has been found that many deep wells have installed refrigeration equipment for artificial refrigeration, and the air conditioning system has been applied in more and more high-temperature mines. When evaluating the proposed scheme, the refrigeration data of Pingdingshan No. 8 Mine are calculated, and the capacity of air conditioning refrigeration is about 2300 kW. In order to calculate the feasibility and economy of the proposed technical scheme, the 3-km-long heat-regulating tunnel is evaluated by examining the regulating effect of the surrounding rock on the air temperature in the tunnel. Cooling capacity stored by surrounding rocks can be calculated by the Formula (5).
It is necessary to consider whether the difference between the temperature of the rock wall surface and the air temperature is positive or negative. If positive, it means the heating of the airflow; the air temperature rises and the rock cools; if negative, it means the heating of the rock; the rock temperature increases and the air temperature drops. Therefore, the above formula only theoretically deals with the maximum capacity of heating (cooling) airflow for the surrounding rock. The absorption of heat capacity or cooling capacity in the process of temperature change is up to the temperature difference between air and the surrounding rock surface, so the comparison is needed between the wall surface and the real-time air temperature. The relevant temperature correction is introduced to determine the integral interval and to ensure that the calculated cooling capacity storage (ie, "effective cooling capacity storage\(^{43-47}\)) by surrounding rocks is correct in the Formula (5).

Comparing the energy value with the value of air conditioning required to produce the same temperature change in air, it is possible to verify whether the proposed scheme is feasible and economical.

In consideration of the introduction of cold air in winter and hot air in summer for 3 months, respectively, the formula is programmed into Abaqus software and after numerical calculation we can see: Different seasonal airflows have different cooling and heating effects on the surrounding rock, and the surrounding rocks accumulate a total of about \(12.87 \times 10^{13}\) J of cooling capacity from cold air during the first phase of the simulation process; in the second stage, the surrounding rocks have absorbed in total of \(3.31 \times 10^{13}\) J of cooling capacity from hot air; and in the third stage of recooling, total effective cooling capacity is about \(8.53 \times 10^{13}\) J absorbed from surrounding rocks by the air. For the 2300 kW mine refrigeration and air conditioning system, to achieve the goal of the cooling capacity storage in the third stage requires working hours of:

\[
t = \frac{t}{(2300000 \times 3600 \times 24 \times 30)} = 14.31 \text{ months}
\]

It can be seen that even if the 2300 kW mine refrigeration system keeps working for 24 hours a day, it will take 14.31 months to achieve the temperature regulation effect of the surrounding rocks on air (but usually breakdown happens so that the mine refrigeration system cannot work continuously).

\[
N = \frac{8.53 \times 10^{13}}{(3600 \times 1000)} = 2.37 \times 10^7 \text{ kilowatt}
\]

At present, commercial electricity price roughly ranges from 0.8 Chinese yuan to 1 Chinese yuan. For the 3-km-long...
tunnel used in numerical simulation, the corresponding mine refrigeration system will cost about:

\[ M = 2.37 \times 10^7 \times 0.8 = 18.94 \text{ million Chinese Yuan} \]

This scheme requires ventilation equipment to introduce cold air and hot air, which will consume some electricity. But the power of ventilation equipment is smaller than mine refrigeration system and the tunnel is supposed to need ventilation, so economically the proposed scheme is superior to that of the air conditioning scheme. Mine refrigeration system is prone to failure; once failure occurs, it will directly affect production and bring about significant economic losses. Therefore, its reliability is not as good as mine surrounding rock temperature regulation program. In addition, the air conditioning equipment in large mines is more complex and less economical due to the higher cost of underground installation and debugging as well as the cost of maintenance.

In summary, after the comparison of the advantages and disadvantages of the two programs, it can be seen that, as for the mine surrounding rock temperature adjustment program, the regulation effect is good when cold air or hot air is introduced for about 3 months, and too poor in the rest of the time to meet the safety requirements underground. It is suggested that the final scheme should be mainly based on the temperature regulation scheme of the surrounding rock assisting with the low-power air conditioning refrigeration program, so as to ensure a more precise control of the tunnel temperature and as much as possible to reduce costs, and to achieve the purposes of mine energy conservation and green mining.

5 | CONCLUSIONS

The high-temperature working environment in deep mining has a great influence on the health and work efficiency of underground workers. It is of great significance to study the distribution characteristics and control of heat hazards in tunnels to ensure the normal mining of deep wells and improve the safety production in mines. The main conclusions are as follows:

1. Through on-site drilling and 1-year continuous observation of the surrounding rock temperature field, five typical heat-regulation-circle distribution modes in mine are concluded. Key thermal physical parameters, affecting the heat transfer zone of the surrounding rock in mine, are also summarized as follows: the heat release coefficient of the wall to airflow, the thermal conductivity of the surrounding rock, and the water content of the rock. At the same time, it puts forward the principal characteristics suitable for the high-temperature heat-regulating tunnels.
2. 2D and 3D mathematical description models of heat capacity storage of surrounding rocks are established. Due to the difference between winter temperature and summer temperature curves, the surrounding rocks are able to regulate temperature. In this process, heat capacity is gradually stored in the rock mass. At the turn from summer to winter, heat capacity is gradually released and cooling capacity is gradually stored. At the turn from winter to summer, cooling capacity is released and heat capacity is stored, but the effective heat (cooling) release is closely related to the air temperature.
3. Based on the theory of transient heat conduction, a numerical model for the unsteady temperature transfer between airflow and surrounding rocks is established, and the finite element method is used to deal with it. According to the practical background of mine, a tunnel of 3 km length is simulated, and a study of numerical simulation is carried out of temperature field distribution of the HRC in the course of the seasonal and physical cycle, “introduction of cold air in winter → introduction of hot air in summer → introduction of cold air in winter.” Finally, economic evaluation of the utilization of cold (heat) capacity for the HRC is accomplished. The results show that the HRC, as an economical heat-self-regulating technology, has a good application prospect.

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