Influence and sensitivity analysis of thermal parameters on temperature field distribution of active thermal insulated roadway in high temperature mine

Weijing Yao[1,2,3] · Jianyong Pang[1,2,3] · Qinyong Ma[1,2,3] · Happiness Lyimo[1]

Abstract To study active heat insulation roadway in high temperature mines, the typical high temperature roadway of − 965 m in Zhujidong Coal Mine of Anhui, China, is selected as prototype. The ANSYS numerical simulation method is used for sensitivity analysis of heat insulation layer with different thermal conductivity and thickness, as well as surrounding rock with different thermal conductivity and temperature on a heat-adjusting zone radius, surrounding rock temperature field and wall temperature. The results show that the heat-adjusting zone radius will entirely be in the right power index relationship to the ventilation time. Decrease in thermal conductivity and increase in thickness of insulation layer can effectively reduce the disturbance of airflow on the surrounding rock temperature, hence, beneficial for decreasing wall temperature. This favourable trend significantly decreases with ventilation time, increase in thermal conductivity and temperature of surrounding rock, heat-adjusting zone radius, surrounding rock temperature field, and wall temperature. Sensitivity analysis shows that the thermal physical properties of surrounding rock determine the temperature distribution of the roadway, hence, temperature of surrounding rock is considered as the most sensitive factor of all influencing factors. For the spray layer, thermal conductivity is more sensitive, compared to thickness. It is concluded that increase in the spray layer thickness is not as beneficial as using low thermal conductivity insulation material. Therefore, roadway preferential consideration should be given to the rocks with low temperature and thermal conductivity. The application of the insulation layer has positive significance for the thermal environment control in mine roadway, however, increase in the layer thickness without restriction has a limited effect on the thermal insulation.

Keywords High temperature mine · Active thermal insulation · Temperature field of surrounding rock · Numerical simulation · Sensitivity analysis

✉ Weijing Yao
  yaoweijing0713@163.com

1 School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan 232001, Anhui, China

2 Engineering Research Centre of Underground Mine Construction, Ministry of Education, Anhui University of Science and Technology, Huainan 232001, Anhui, China

3 State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines, Anhui University of Science and Technology, Huainan 232001, Anhui, China

1 Introduction

Deep mining of underground engineering is normalised and the thermal environment of mine, caused by high ground temperature, restricts further excavation (Yi et al. 2019; Xie et al. 2012). During recent years, many mines in China have gradually entered the deep mining stage. So far, the main mining depth has reached up to 800 m, with an excavating downward at the speed of 8–12 m, every year. Most of the mines have entered the First and Second Grade Heat Damage Area (In China, according to the original rock temperature of the mine field, the heat damage can be divided into two grades, including the First Grade, which is

between 31 and 37 °C, and the Second Grade, which is higher than or equal to 37 °C). He and Guo (2013), especially in the old mining area of east, north, and north-east of China. Wu et al. (2019) and Xu (2014) explored the geothermal geological characteristics of the Huainan Mining Area in Anhui, China. In this area, the geothermal gradient is between 1.00 and 4.00 °C/hm, the average is 2.80 °C/hm. Moreover, the average geothermal temperature is 29.96 °C for the burial depth of − 500 m, 41.84 °C for − 1000 m, and 69.62 °C for − 2000 m. It can be seen that the geothermal temperature gradually increases with the increase of burial depth. Focusing on the Pansan Coal Mine in Huainan, Yuan (2007) enumerated the proportion of various heat sources in the heat release and concluded that the heat of surrounding rock accounted for more than 40% of the total heat sources. Therefore, the control of heat, released from roadway surrounding rock, was considered as a sensitive matter to be solved and discussed urgently in the future.

Scholars have successively proposed an active thermal insulation method that covers the surrounding rock surface to prevent spreading of the surrounding rock heat into the roadway. A considerable amount of laboratory work and research on engineering applications in this field have been completed, so far. For instance, boiler slag concrete spray layer was used to insulate heat in high-temperature roadways in Russia. The chemical polyurethane materials were used for roadway heat insulation in South Africa, Russia, and other countries (Du Plessis et al. 2013a, b). In China, Yao and Zhang (2002) and Guo et al. (2003) developed thermal insulation materials, with thermal conductivity of 0.17 W/(m K), using cement, silica lime, perlite, fly ash, and various supplementing additives. Li (2010b) developed a new type of insulating material made of "slurry injecting" and "sprayed concrete" for the roadway, using glazed hollow bead-based material, which was applied to the heat insulation structure of the high temperature roadway. The release mode of heat from surrounding rock to the roadway and the change of heat-adjusting zone were discussed in his study. Li (2010a) developed a polyurethane heat insulation and waterproof material which could effectively reduce the thermal radiation and latent heat exchange between the airflow and the roadway, when coated on the inner wall of the roadway. Zhang and Wan (2016) investigated the idea of combining the thermal insulation material of spraying and injecting into the roadway to form a thermal insulation structure between the thermal insulation material and the loose broken rock of the roadway, in order to prevent heat release of the surrounding rock and the flow of hot water in the fissures. Focusing on the development of thermal insulation materials and application technology, Yao (2019) used ceramsite and glazed hollow bead as lightweight coarse and fine aggregate, respectively. The optimum proportion of thermal insulation shotcrete was obtained by the orthogonal test and the engineering application was completed in Zhujidong Coal Mine, Anhui, China.

Currently, the numerical methods have been used to calculate the temperature field of surrounding rocks. For instance, Sun (2005) used numerical models to simulate the temperature and heat dissipation characteristics of the surrounding rock of roadway. Qin et al. (2017) calculated the roadway surrounding rock temperature field, using finite volume calculation method. Furthermore, some scholars have discussed the influence of thermal physical parameters of a thermal insulation layer on the thermal insulation effect and airflow temperature of mine roadway (Zhou and Song 2018; Zhou et al. 2019; Zhang et al. 2019; Song et al. 2017; Zhu et al. 2017). Based on these studies, the thermal insulated layer could slow down the heat dissipation of the surrounding rock to the air flow, with the internal temperature gradient change in the surrounding rock. However, the existing research fail to clarify the influence of thermal parameters of thermal insulation layer on the thermal insulation effect of roadway, in strata with different thermal parameters. Indeed, in these studies, the temperature field distribution spatiotemporal evolution law of surrounding rock in the active thermal insulated roadway has not been discussed. Hence, the mechanism behind the insulation has not been fully understood, causing failure in providing effective guideline field application.

Combining thermal insulation and support, this study aims to investigate the active thermal insulation roadway. Indeed, the shotcrete layer has certain heat insulation ability, while, satisfying the support strength. The software ANSYS is used to analyse the influence of the thermal insulation layer and surrounding rock with different thermal physical parameters on the roadway temperature field and the sensitivity analysis of the influence factor.

2 Numerical model of active insulation roadway

2.1 Mathematical model of temperature field of roadway surrounding rock

According to the energy conservation law and Fourier's law, a cylindrical coordinate system is used to express the heat conduction control equation of a roadway surrounding rock with thermal insulation (Zhang et al. 2007), as follows:

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \lambda \left(\frac{1}{r} \frac{\partial T_i}{\partial r} + \frac{\partial^2 T_i}{\partial r^2} \right) \quad (i = 1, 2, 3) \tag{1}$$

The boundary conditions:

$$\lambda_1 \frac{\partial T_1}{\partial r} = h(t_b - t_f) \quad (r = r_0) \tag{2}$$

$$\begin{cases} T_1(t, r) = T_2(t, r) \\ \lambda_1 \frac{\partial T_1}{\partial r} = \lambda_2 \frac{\partial T_2}{\partial r} \end{cases} \quad (r = a) \tag{3}$$

$$\begin{cases} T_3(t, r) = T_2(t, r) \\ \lambda_3 \frac{\partial T_3}{\partial r} = \lambda_2 \frac{\partial T_2}{\partial r} \end{cases} \quad (r = b) \tag{4}$$

The initial conditions:

$$\begin{cases} T_3(t, \infty) = T_0 \\ T_i(0, r) = T_0 \end{cases} \tag{5}$$

where T_i is the temperature of the No. i layer medium, °C. A total of three layers are existed, including thermal insulation layer, surrounding rock layer 1, and surrounding rock layer 2. ρ_i, c_i, and λ_i are density, specific heat, and thermal conductivity, respectively in kg/m^3, J/(kg °C) and W/(m K). t is the ventilation time, s. r is the distance from the centre of the roadway, m. r_0 is the distance from the roadway wall to the roadway centre, m. h is the heat transfer coefficient of the wall and wind, W/(m^2 °C). t_b is the wall temperature, °C. t_f is the wind temperature, °C. a is the distance from the boundary between the thermal insulation layer and the surrounding rock layer 1 to the roadway centre, m. b is the distance from the interface between the surrounding rock 1 and the surrounding rock 2 to the roadway centre, m. Finally, T_0 is the rock temperature, °C.

Based on Eqs. (1)–(5), the temperature field distribution of the roadway surrounding rock depends on the thermal parameters of thermal insulation layer and surrounding rock, including the thickness and the thermal conductivity of the thermal insulation layer, as well as the temperature and the thermal conductivity of surrounding rock. Subsequently, the ANSYS numerical simulation of the above parameters is carried out in the next sections.

2.2 Numerical model and assumptions

In this study, the − 965 m return air roadway of Zhujidong Coal Mine of Anhui, in China, is selected as the typical high temperature prototype. After the roadway surrounding rock excavation, the active thermal insulation model is constructed in the roadway full-face spraying thermal insulation spray layer. It is assumed that the original rock integrity has remained good after excavation. Moreover, the structure of the pray layer and the original rock layer are stable and the coupling effect is good. Figure 1 represents the active thermal insulation roadway, with a thermal insulation layer, formed after ventilation. It has a
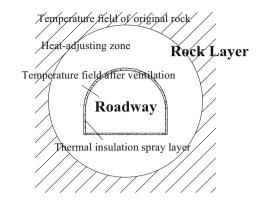

Fig. 1 Schematic diagram of active insulated roadway

dimension of height × width = 4110 mm × 5400 mm, with a cross-section area of about 19.06 m^2.

The ANSYS software and the transient algorithm are used to carry out the heat transfer analysis, with the simplifications and assumptions, as follows:

(1) According to the test, the heat-adjusting zone thickness in the surrounding rock tends to be stable after 3 years of ventilation with a radius of 15–40 m (Gao and Yang 2005). Therefore, the length and width of the modelling range are both 100 m and the roadway is located at the centre of the model.

(2) The far-field boundary condition of surrounding rock are the upper and lower boundaries of the model, which are set as constant temperature boundaries and the inner boundary spray layer as convective heat transfer boundary. According to Yao et al. (2018), initially after the excavation, the wall temperature of the newly excavated roadway was relatively high. However, after long-term ventilation, the wall temperature has been maintained in the range of 24–28 °C. Therefore, the average airflow temperature of the roadway is assumed to be 26 °C.

(3) Assuming that the material isotropy, homogeneity, and thermal physical parameters of each layer are constant, a good thermal contact is existed between each layer. Furthermore, the air temperature and the heat conduction coefficient of the airflow in the roadway wall are both constant.

2.3 Parameter selection

Following the specifications in the current literature and the laboratory test results from previous studies, as well as construction design specification, field testing in Anhui Mining Area, the parameters of each group of the driving factors and the basic conditions are selected, as follows:

(1)   Thermal conductivity of spray layer: Based on data in Yao and Zhang (2002), Guo et al. (2003), Li (2010a, b) and Yao and Pang (2017a, b), the thermal conductivity of spray layer is considered between 0.10 and 1.80 W/(m K), the interval as 0.20 W/(m K), and the basic parameter as 0.80 W/(m K).

(2)   Thickness of spray layer: Based on field construction design specification (Cheng et al. 2019), the optimum thickness of spray layer ranges from 80 to 240 mm, with intervals of 20 mm, and a basic parameter of 120 mm.

(3)   Thermal conductivity of surrounding rock: following Wu et al. (2019) and Xu et al. (2014), the thermal conductivity of surrounding rock in the study area is considered between 0.37 and 4.36 W/(m K), with an average value of 2.54 W/(m K), after removal of coal, sand, and other special rock masses. The thermal conductivity of surrounding rock is considered between 0.50 and 4.50 W/(m K), with an interval of 0.50 W/(m K) and the basic parameter of 2.50 W/(m K), when the rock is homogeneous.

(4)   Temperature of surrounding rock: According to the Safety Regulations in Coal Mine in China, the original rock temperature exceeding 31 °C is termed as the First Grade Heat Damage Area and the exceeding 37 °C is termed as the Second Grade Heat Damage Area. Based on our field observations, the rock temperature in the newly excavated roadway and the transient temperature of the original rock at − 965 m fluctuates between 37 and 40 °C. Hence, the rock temperature is considered in a range of 31–40 °C, with 1.0 °C interval, and the basic parameter of 37 °C.

The determination of each working condition is presented in Table 1. The thermal physical parameters of thermal insulation spray layer and surrounding rock are demonstrated in Table 2.

2.4 Numerical model calibration and validation

In this study, the software ANSYS is used to calculate the temperature field of roadway surrounding rock, under the basic conditions. To verify the reference of the calculation results, the calculation results are compared and verified with the actual field measurement data, obtained during the field observations (Fig. 2). As can be seen from Fig. 2, the numerical simulation has high accuracy, hence, they can be used to calculate the temperature field of the roadway surrounding rock, with thermal insulation layer.

3 Temperature field distribution of roadway surrounding rock

The stabilities of grid sizes and times steps are tested, before simulation calculation. Taking the basic working condition as an example, the thermal conductivity of spray layer is 0.80 W/(m K), the thickness of spray layer is 120 mm, the thermal conductivity of surrounding rock is 2.50 W/(m K), and the temperature of surrounding rock is 37 °C. In calculation analysis, the model is assumed in the original rock temperature conductions, then is restricted to the boundary lines around the model and the adiabatic conduction is considered. The convective heat transfer boundary is taken from the inner spray layer. Moreover, the corresponding convective heat transfer coefficient and temperature values are set to analyse the temperature field distribution of the roadway, under different ventilation times.

3.1 Distribution of the surrounding rock heat-adjusting zone

The temperature fields of the roadway after 1 day, 30 days, 90 days, 365 days, 1095 days, and 3650 days are obtained, as presented in Fig. 3. With the prolongation of ventilation time, the surrounding rock temperature around the roadway gradually decreases, thus, forming the heat-adjusting zone,

Table 1 The basic parameter and range variation of working condition

Working condition	Thermal conductivity of spray layer (W/(m K))	Thickness of spray layer (mm)	Thermal conductivity of surrounding rock (W/(m K))	Temperature of surrounding rock (°C)
1	0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8	120	2.5	37
2	0.8	80, 100, 120, 140, 160, 180, 200, 220, 240	2.5	37
3	0.8	120	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5	37
4	0.8	120	2.5	31, 32, 33, 34, 35, 36, 37, 38, 39, 40

Table 2 Thermal physical parameter of materials

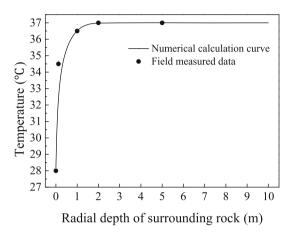| Materials	Density (kg/m^3)	Specific heat capacity (J/(kg °C))	Heat transfer coefficient (W/(m^2 °C))
Surrounding rock	2500	896	20
Concrete spray layer	1705	970	20

Fig. 2 Comparison of calculation results and measured results

gradually. The wall temperature of the roadway lining after 30 days, 1 year, and 3 years of ventilation are 26.470, 26.218, and 26.218 °C, respectively. Eventually, after 10 years of long-term ventilation, the wall temperature is maintained at a value of 26.138 °C (Fig. 3).

An area, in which the temperature reduction value of surrounding rock exceeds 1% of the original rock temperature, is defined as the heat-adjusting zone. Subsequently, the distance between the interface of the heat-adjusting zone, original rock, and the centre of the roadway is defined as the radius of the surrounding rock heat-adjusting zone (Qin et al. 2017). As seen in Fig. 3, the surrounding rock is continuously cooled and the heat-adjusting zone expands with the airflow. Figure 4 shows the formation law of the heat-adjusting zone, in 10 years under the basic working condition. The heat-adjusting zone radius in 30 days, 180 days, 365 days, 3 years, and 10 years after ventilation are 6.163, 13.049, 17.048, 26.708, and 41.973 m, respectively. According to the fitting data, the heat-adjusting zone radius is in the right power index relationship to the ventilation time.

$$R = 0.864\sqrt{t} + r_0 \quad R^2 = 0.994 \tag{6}$$

where, R is the radius of the heat-adjusting zone, m; t is ventilation time of roadway, d; r_0 is the distance from the centre of the roadway to surrounding rock, which is 2.82 m in this case.

3.2 Distribution of surrounding rock temperature field

Generally, the temperature field of the surrounding rock of roadway tends to be stable after 3 years. According to the above calculation, the heat-adjusting zone radius is about 30 m. Taking 3 years as the research period, the 1.41 m high lining wall point on the left side of the roadway is selected and a ray is drawn from the point to the boundary of the roadway surrounding rock, in the model. Figure 5 demonstrates the temperature changes of the lining wall, the interface of the spray layer and rock layer, and the measuring points range of 1–30 m in the surrounding rock layer, during the research period.

As presented in Fig. 5, spatially the roadway lining wall temperature is the lowest because of the influence of ventilation. The temperature of other rock layers increases with the radial depth and gradually tend to be consistent with the original rock temperature, in other words, it gradually reaches the edge of the heat-adjusting zone.

With respect to time, the temperatures of each measuring point decrease gradually with time. The temperature of the roadway lining wall decreases sharply and tends to be flat, after 30 days. After 90 days, the temperature still decreases slowly and tends to be stable.

4 Analysis of influencing factors of surrounding rock temperature field
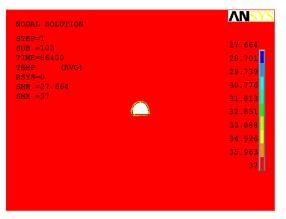
4.1 Influence of spray layer thermal conductivity

4.1.1 Influence of spray layer thermal conductivity on heat-adjusting zone radius

Taking 3 years ventilation time of roadway as the research period, the change of heat-adjusting zone under different spray layer thermal conductivity is calculated, as shown in Fig. 6, for working conduction 1 in Table 1. It can be seen from Fig. 6 that the heat-adjusting zone radius decreases, as the spray layer thermal conductivity decreases. After 30 days of ventilation and cooling, the heat-adjusting zone of spray layer with 0.1 W/(m K) thermal conductivity is less by 19.44%, compared to the spray layer with thermal conductivity of 1.8 W/(m K). After 1095 days, the
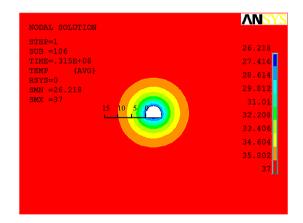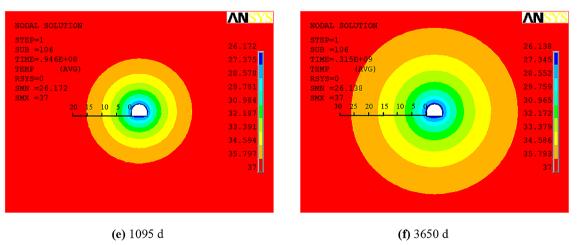
(a) 1 d

(b) 30 d

(c) 90 d

(d) 365 d

(e) 1095 d

(f) 3650 d

Fig. 3 Temperature field of roadway surrounding rock under basic working condition

decrement rate is 13.33%. This suggests that the enhanced thermal insulation ability of the spray layer can effectively reduce the airflow disturbance to the temperature field of the deep surrounding rock.

4.1.2 Influence of spray layer thermal conductivity on surrounding rock temperature field

The disturbance of ventilation cooling on the surrounding rock temperature field gradually weakens, with the prolongation of ventilation time and the increase in radial depth. Hence, considering ventilation for 30 days and

Fig. 4 Change and fitting of heat-adjusting zone radius of basic working condition

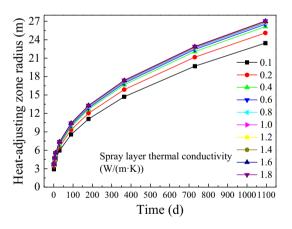**Fig. 5** Temperature distribution of roadway surrounding rock of basic working condition

Fig. 6 Influence of spray layer thermal conductivity on heat-adjusting zone radius

1095 days as examples for the initial and long-term excavation of roadway, the variation of surrounding rock temperature field under different spray layer thermal conductivity is demonstrated in Fig. 7.

Based on the results, the temperature of the rock layers gradually increases with an increase in rock layer radial depth, during the research time. The temperature of each point increases with a decrease in spray layer thermal

conductivity, at different rates. The smaller the radial depth is, the higher the increase rate is, which is due to greater degree of cooling through ventilation. The greater the radial depth along the roadway is, the weaker the degree of improvement is, because the original rock temperature is cooled through ventilation and it increases with time, thus, causing the heat-adjusting zone to increase.

The reason for the above phenomena is that when the thermal insulation ability of the spray layer is stronger, the cooling effect of the roadway airflow on the rock layer temperature field is blocked, thus, the influence on the original temperature of the rock layer is gradually weakened. This results to an increase in temperature, at all spray layer points and temperature gradient of the spray layer. The temperature difference between the shotcrete and rock layer is very large, hence, it indicates that shotcrete plays a significant role in reducing heat dissipation of the surrounding rock, through airflow.

However, the heat dissipation of surrounding rock through airflow is inevitable. The main purpose of the thermal insulation spray layer is to slow down the heat transfer in the surrounding rock, in order to achieve the purpose of reducing airflow temperature. Therefore, the temperature distribution of the surrounding rock is the same, under each thermal conductivity, but with a different increasing rate at each point. The thermal insulation capacity of the spray layer increases and the disturbance of temperature field of roadway surrounding rock decreases, as the thermal conductivity increases. In contrast, when the thermal conductivity decreases, the thermal insulation capacity tends to be saturated. After 30 days and 1095 days, the temperature of the interface between the spray layer and the original rock with thermal conductivity of 0.1 W/(m K) is 21.44% and 13.60% higher than that of 1.8 W/(m K), respectively.

4.1.3 Influence of spray layer thermal conductivity on roadway wall temperature

Since, the wall temperature of the roadway lining has an important reference for mine thermal environment, the influence of spray layer thermal conductivity on wall temperature with time is evaluated in this study and the results are presented in Fig. 8.

Based on Fig. 8a, in the initial stage of ventilation, the wall temperature of the roadway decreases sharply with ventilation time and then gradually stabilizes. As presented in Fig. 8b, at each typical point, the lower the spray layer thermal conductivity is, the lower the wall temperature is. It also indicates that heat insulation capability is stronger in the first 30 days of excavation, compared to the later days. In 30 days, the wall temperature for the spray layer with thermal conductivity of 0.1 W/(m K) is 1.27% lower, in
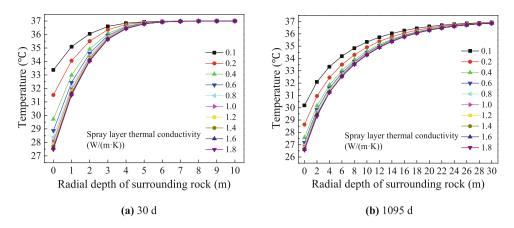
Fig. 7 Influence of spray layer thermal conductivity of surrounding rock temperature field
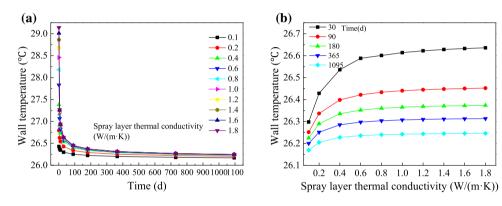

Fig. 8 Influence of spray layer thermal conductivity on wall temperature

comparison with the spray layer with thermal conductivity of 1.8 W/(m K). This indicates that improving the thermal insulation capacity of the material increases the thermal insulation effect of the spray layer. However, the cooling effect is not obvious in the later stage of the ventilation. As the ventilation time is prolonged, the heat-adjusting zone of the surrounding rock is gradually formed, followed by stabilisation, resulting the same temperature of airflow, in the roadway. After 1095 days of ventilation, the wall temperature of spray layer with thermal conductivity of 0.1 W/(m K) is about 0.29% lower than that of 1.8 W/(m K). This indicates after a certain ventilation time, the effect of spray layer thermal conductivity is gradually weakened on wall temperature.

The above analysis shows that the small spray layer thermal conductivity can effectively reduce the disturbance of airflow to the surrounding rock temperature field and reduce the heat dissipation of the surrounding rock to airflow, which is beneficial for the reduction of the roadway wall temperature. When the thermal conductivity of spray layer decreases, the favourable range increases and when the ventilation time is prolonged, the favourable trend decreases.
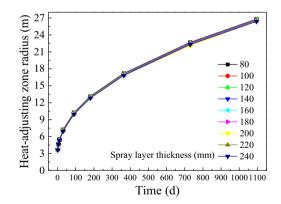

Fig. 9 Influence of spray layer thickness on heat-adjusting zone radius

4.2 Influence of spray layer thickness

4.2.1 Influence of spray layer thickness on heat-adjusting zone radius

Figure 9 represents the change of heat-adjusting zone under the different spray layer thickness results, based on the working condition 2, presented in Table 1. As

presented in the figure, the influence of spray layer thickness on the heat-adjusting zone is not as significant as that of the spray layer thermal conductivity. From the data analysis, it can be concluded that the heat-adjusting zone radius decreases with the increase of spray layer thickness and decreases with the ventilation time. After 30 days, the heat-adjusting zone radius of the spray layer with thickness of 240 mm is 4.54% less than that of the 80 mm. After 1095 days, the heat-adjusting zone radius decreases by 1.61%.

This suggests that increase in the spray layer thickness can prevent the disturbance of roadway airflow to the temperature field of the deep surrounding rock, however, it is not as significant as reducing the spray layer thermal conductivity. This can be explained by the thermal conductivity of the concrete spray layer, which is 0.8 W/(m K) in this working condition, which is improved from the ordinary concrete of thermal conductivity of 1.2–1.8 W/(m K), although, there is still a difference between the general thermal insulation material and the foam concrete with thermal conductivity below 0.05 W/(m K). It is also closely related to decrease of the spray layer thermal conductivity, which can effectively reduce the disturbance to the surrounding rock temperature field.

4.2.2 Influence of spray layer thickness on surrounding rock temperature field

Considering 2 examples of 30 days after excavation and 1095 days of long-term ventilation, the temperature variation of surrounding rock under the different spray layer thickness is demonstrated in Fig. 10, based on the working condition 2, in Table 1. The rock layer temperature increases as the rock layer radial depth increases and approaches the original rock temperature, hence the

smaller the radial depth of surrounding rock, the greater the increment in temperature (Fig. 10). Indeed, as the spray layer thickness increases, the temperature of each point in the surrounding rock also increases. After 30 days, the temperature between the interface of the spray layer with thickness of 240 mm and the rock layer increases by 6.79%, compared to the spray layer with thickness of 80 mm and increases 3.15% after 1095 days. This is due to the fact that when spray layer thickness increases, it hinders the heat transfer from the air to the surrounding rock, thus, weakening the disturbance of the surrounding rock temperature field.

4.2.3 Influence of spray layer thickness on roadway wall temperature

Figure 11 represents the influence of spray layer thickness on roadway wall temperature. As presented in Fig. 11a, the temperature roadway lining wall decreases rapidly in the initial stage of ventilation and then tends to be stable, which is similar to the effect of the spray layer thermal conductivity on the roadway wall temperature. Based on Fig. 11b, in each period as the spray layer thickness increases, the temperature of the roadway wall decreases with a limited decrement value. In 30 days, the influence of the spray layer thickness of 240 mm on the wall temperature is weaker than that of the 80 mm, because of the following reasons. Firstly, when the spray layer thickness exceeds 160 mm, the change of wall temperature tends to stabilised at each time, indicating that increases in the spray layer thickness without restriction cannot significantly improve the thermal insulation. Secondly, as the ventilation time is prolonged, the roadway wall is gradually cooled by the airflow, hence, the influence of the spray layer on the roadway wall temperature is almost negligible.
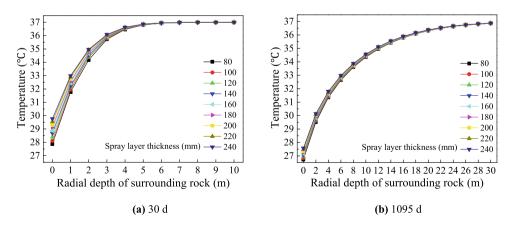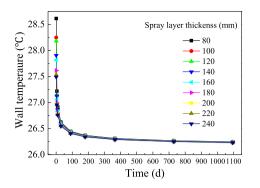

(a) 30 d   **(b)** 1095 d

Fig. 10 Influence of spray layer thickness on surrounding rock temperature field

(a) The change of wall temperature with time

(b) The change of wall temperature with thickness

Fig. 11 Influence of spray layer thickness on wall temperature

The above analysis suggests that at the initial stage of ventilation, any increase in the spray layer thickness can reduce the heat dissipation of surrounding rock to airflow and the disturbance of surrounding rock temperature field. However, increasing in the spray layer thickness cannot significantly improve the thermal insulation, because it causes the temperature gradient in the spray layer to increase, hence, it increases the thermal insulation capacity, due to saturation impact.

4.3 Influence of surrounding rock thermal conductivity

4.3.1 Influence of surrounding rock thermal conductivity on heat-adjusting zone radius

Based on the working condition 3, presented in Table 1, the changes of the heat-adjusting zone under different surrounding rock thermal conductivity is demonstrated in Fig. 12. As the surrounding rock thermal conductivity increases, the heat-adjusting zone expands, remarkably.
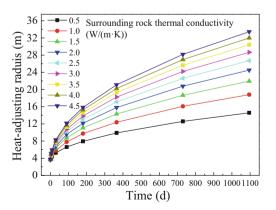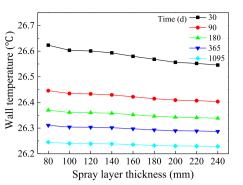

Fig. 12 Influence of surrounding rock thermal conductivity on heat-adjusting zone radius

After 30 days, the heat-adjusting zone radius of the surrounding rock with thermal conductivity of 4.5 W/(m K) is 57.62% larger than that of the 0.5 W/(m K) and after 1095 days, the enlargement is 129.48%. This shows that the influence of the heat conduction property of the surrounding rock is a very important factor.

4.3.2 Influence of surrounding rock thermal conductivity on surrounding rock temperature field

The temperature changes of surrounding rock under different thermal conductivity is shown in Fig. 13, based on the working condition 3 of Table 1.

After 30 days, at the interface of the spray layer and surrounding rock, as the surrounding rock thermal conductivity increases, the temperature also increases. However, the temperature of large surrounding rock thermal conductivity decreases, with the increase of the surrounding rock radial depth. The temperature of the surrounding rock with the thermal conductivity of 4.5 W/(m K) is 8.52% higher than that of the 0.5 W/(m K), meanwhile, the temperature decreases by 7.26% at the radial depth of 2 m.

After 1095 days, at the interface of spray layer and surrounding rock, the temperature of the surrounding rock with the thermal conductivity of 4.5 W/(m K) is 4.44% higher than that of the 0.5 W/(m K). At the radial depth of 8 m, the temperature decreases by 7.05%, then as the radial depth increases, it becomes consistent with the original rock temperature.

Indeed, the temperature inside the original rock transfers to the roadway airflow, which results in the zoning of surrounding rock near the roadway. The rock temperature decreases, in varying degrees, with the increase of the surrounding rock thermal conductivity. The decreasing extent is related to the location of the rock and the variation interval of the thermal conductivity. This is consistent with
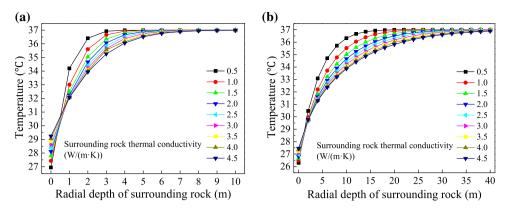
Fig. 13 Influence of surrounding rock thermal conductivity on temperature field
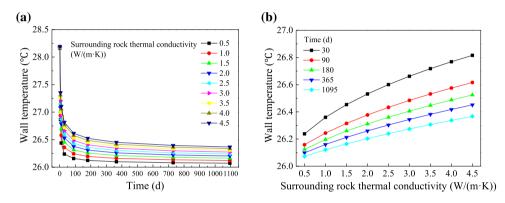

Fig. 14 Influence of surrounding rock thermal conductivity on wall temperature

the research conclusions of the tunnel temperature field, in a cold region (Li et al. 2017; Zhao et al. 2019).

4.3.3 Influence of surrounding rock thermal conductivity on roadway wall temperature

The change of wall temperature under different surrounding rock thermal conductivity is concluded in Fig. 14. Based on Fig. 14a, at each point in time, the wall temperature decreases, as the surrounding rock thermal conductivity decreases. As shown in Fig. 14b, the reduction rate is different, at different times. As the ventilation time is prolonged, the rate of decline increases rapidly, followed by a decrease. Compared to the thermal conductivity of 4.5 W/(m K), the wall temperature of surrounding rock with thermal conductivity of 0.5 W/(m K) decreases by 2.15%, 1.72%, 1.51%, 1.33%, and 1.12%, after 30, 90, 180, 365, and 1095 days, respectively. This is because the heat preservation and the insulation abilities of surrounding rock are good, hence, hindering the heat transmission from the original rock to inside the roadway. Therefore, the smaller the thermal conductivity of the surrounding rock is, the more favourable it is for cooling the roadway and controlling the thermal hazards, in the initial stage of ventilation.

Based on the above analysis, for the thermal environment control of the mine with an objective of reducing the wall temperature and initial cooling of the roadway, lowering the surrounding rock thermal conductivity is favourable, as it reduces the airflow temperature in the roadway. If the objective is to reduce the temperature of the surrounding rock and enlarge the heat-adjusting zone, increasing the surrounding rock thermal conductivity is
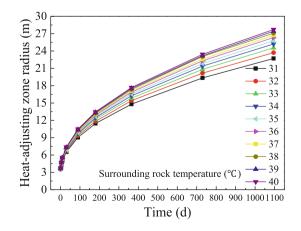

Fig. 15 Influence of surrounding rock temperature on heat-adjusting zone radius

more favourable, because it enlarges the heat-adjusting zone.

4.4 Influence of surrounding rock temperature

4.4.1 Influence of surrounding rock temperature on heat-adjusting zone radius

Based on the working condition 4, presented in Table 1, the change of the heat-adjusting zone under different surrounding rock temperatures is presented in Fig. 15. As seen in the figure, the heat-adjusting zone radius enlarges with the increase of the surrounding rock temperature. This influence is similar to that of the surrounding rock thermal conductivity on the heat-adjusting zone radius. The rock temperature at 40 °C increases by 12.95%, compared to that of 31 °C after 30 days, also further increases by 22.09%, after 1095 days.

4.4.2 Influence of surrounding rock temperature on surrounding rock temperature field

The temperature changes of the surrounding rock at different temperatures is demonstrated in Fig. 16, based on the working condition 4, presented in Table 1. The law of temperature development is the same at all points, in the surrounding rock. The temperature of each location at the surrounding rock increases, as the rock temperature increases, however, at different rates. Indeed, the greater the radial depth along the surrounding rock is, the lower the increase rate is. The increment continues until the surrounding rock temperature is the same as the original rock temperature. This is because the higher the rock temperature is, the weaker the cooling effect of the roadway, through ventilation and the weak cooling effect is enhanced as the surrounding rock radial depth increases.

4.4.3 Influence of surrounding rock temperature on roadway wall temperature
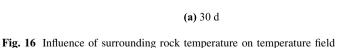
The influence of the surrounding rock temperature on the wall temperature with time is shown in Fig. 17. Based on Fig. 17a, the wall temperature increases linearly, with the increase of rock temperature at each time. This influence is similar to the effect of the surrounding rock thermal conductivity on the roadway wall temperature. From Fig. 17b, in comparison with 31 °C, the rock temperature of 40 °C, for 30, 90, 180, 365, and 1095 days is 1.87%, 1.35%, 1.13%, 0.95%, and 0.75% higher, respectively, and this influence is gradually weakened. This suggests that the rock temperature has a significant impact on the temperature of the internal surrounding rock and the lining wall. The lower the surrounding rock temperature is, the more conducive it becomes to the treat thermal hazards.

Based on different working conditions, we attempted to analyse the single-factor influences of the thermal conductivity, thickness of spray layer, thermal conductivity, and the temperature of surrounding rock on the heat-adjusting zone radius, the rock temperature, and the wall temperature. However, it was difficult to distinguish the significant and sensitivity influence of each factor on the temperature field, hence, a sensitivity analysis was carried out for this purpose.

5 Sensitivity analysis of surrounding rock temperature field

5.1 Method of sensitivity analysis

Sensitivity analysis is a method used to analyse the system stability. The model is assumed $y = f(x_1, x_2,..., x_k,...)$, where, x_k is the No. k influence factor of the model and each factor is a change in the range of possible values. The

(a) 30 d   **(b)** 1095 d

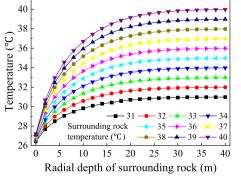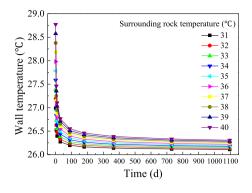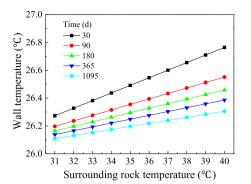**Fig. 16** Influence of surrounding rock temperature on temperature field

(a) The change of wall temperature with time

(b) The change of wall temperature with temperature

Fig. 17 Influence of surrounding rock temperature on wall temperature

influence of factors change on the model output is already studied (Li et al. 2017; Fu et al. 2017).

Firstly, the system model should be established and then the benchmark parameter set should be given. When analysing the influence of parameter x_k on characteristic y, the signal-factor analysis method can be used. That is, the other parameters are fixed to the benchmark parameter, and the x_k is changed within its possible range, the system characteristic y is shown, as follows:

$$y = f(x_{k1}, x_{k2}, \ldots, x_{kn}) \tag{7}$$

If a small change in x_k causes a large change in y, then y is more sensitive to x_k. Alternatively, if a large change in x_k causes a small change in y, then y is less sensitive to x_k. To facilitate the comparative analysis of different dimensional parameters, the dimensionless form sensitivity factor is defined, as follows:

$$s_k = \left| \frac{x_k^*}{y^*} \times \frac{\Delta y}{\Delta x_k} \right| \tag{8}$$

where s_k is the sensitivity of parameter x_k, x_k^* is the benchmark parameter of parameter x_k, y^* is the system characteristic value, corresponding to the benchmark parameter set, and $\Delta y / \Delta x$ is the change rate of characteristic y to parameter x_k in the range of parameter x_k.

When multiple systems need to be analysed at the same time, sensitivity factors are normalised for comprehensive analysis. If the sum of the sensitivity factors of all the influencing parameter for the same system is 1, then the sensitivity factors of the normalised parameters are, as follows:

$$s_k' = \frac{s_k}{\sum_{i=1}^{n} s_i} \tag{9}$$

Therefore, the thermal conductivity of spray layer, thickness of spray layer, as well as the thermal conductivity of surrounding rock and temperature of the surrounding rock are taken as the influencing parameters x_1, x_2, x_3, x_4, respectively. Meanwhile, the heat-adjusting zone radius, the

rock layer temperature, and wall temperature are taken as the characteristics y. The sensitivity of each parameter to the characteristic is calculated under each working condition, presented in Table 1.

5.2 Sensitivity analysis of different factors to the heat-adjusting zone radius

The normalised sensitivity of each factor to the heat-adjusting zone radius is obtained according to Eq. (9). Finally, the sensitivity of each factor to the heat-adjusting zone radius is further visually expressed as shown in Fig. 18.

Based on Fig. 18, the sensitivity of the thermal physical properties of the surrounding rock to the heat-adjusting zone radius always take up a large proportion, while the sensitivity of structural factors of the spray layer is small. For the surrounding rock, the temperature sensitivity is higher, while, for the spray layer, the thermal conductivity is higher. The thermal conductivity sensitivity of the spray layer is at a high level within 90 days of ventilation, especially in the first 10 days, followed by a gradual decrease with time. Therefore, the thermal physical properties of the surrounding rock determine the range of the heat-adjusting zone.

5.3 Sensitivity analysis of different factors to the surrounding rock temperature

The sensitivity analysis of the surrounding rock temperature field, affected by different factors in the early ventilation (30 days) and the long-term ventilation (1095 days), is presented in Fig. 19. As the radial depth increases, the thermal physical properties of the surrounding rock gradually dominate, hence, the influence of the surrounding rock temperature is much more significant, in comparison with the thermal conductivity. However, the thermal conductivity and thickness of the spray layer still affect the
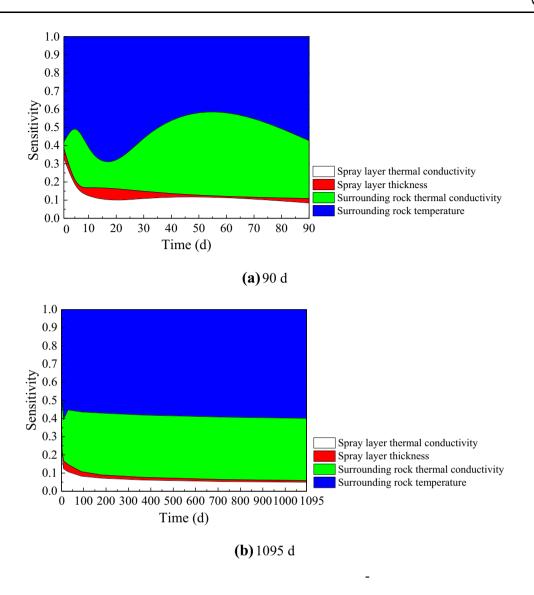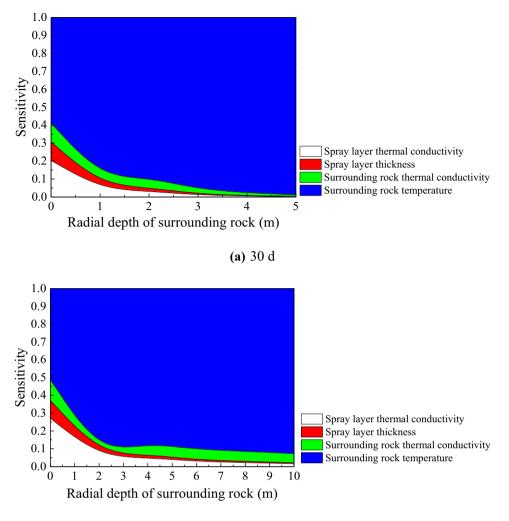
(a) 90 d

(b) 1095 d

-

Fig. 18 Sensitivity of different influencing factors to heat-adjusting zone radius

surrounding rock temperature field in the radial depth of 3 m and the thermal conductivity is more significant than thickness. The latter suggests the limited capacity of increasing in the thickness of the thermal insulation spray layer to improve the thermal insulation capacity of the roadway. Therefore, it is better to use low thermal conductivity thermal insulation material.

5.4 Sensitivity analysis of different factors to the roadway wall temperature

The sensitivity analysis of the roadway wall temperature, affected by different factors, is demonstrated in Fig. 20. Based on the figure, the surrounding rock temperature is considered as the most influential factor and its sensitivity accounts for the largest proportion, at each time. The

surrounding rock thermal conductivity is the second important influential factor and its sensitivity gradually increases with time. The sensitivity of the thickness of the spray layer is the smallest and it decreases gradually with time. The spray layer thermal conductivity is more sensitive in the initial stage of ventilation, followed by a gradually decrease in its sensitivity. This suggests that the changes of the thermal conductivity and the thickness of the spray layer can reduce the wall temperature and the disturbance of surrounding rock temperature field to the airflow, at the initial stage. However, with a prolongation of ventilation time, the heat-adjusting zone gradually stabilises, resulting in a gradual weakening of the influence.

In the entire test, the thermal conductivity sensitivity of the spray layer is larger than that of its thickness, which indicates the remarkable decreasing effect of the spray

(a) 30 d

(b) 1095 d

Fig. 19 Sensitivity of different influencing factors to temperature field distribution of surrounding rock
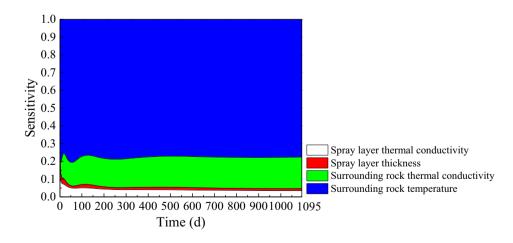

Fig. 20 Sensitivity of different influencing factors to wall temperature

layer thermal conductivity on the wall temperature, compared to the increasing effect of the spray layer thickness, under this working condition.

In conclusion, the thermal physical properties of the surrounding rock determine the temperature distribution of surrounding rock. The method of using the spray layer with low thermal conductivity and increased thickness can prevent the heat dissipation of the surrounding rock and reduce the influence of the airflow to the surrounding rock, however, it gradually weakens with the time. Therefore, when arranging roadways, the low temperature and thermal conductivity of the surrounding rock should be prioritised. The use of low thermal conductivity thermal insulation spray layer has a positive significant impact on controlling the thermal environments of the mine roadway, although, the unlimited increase of the spray layer thickness has a limited effect on the improvement of the thermal insulation.

6 Conclusions

In this study, the temperature field of the active thermal insulation roadway is analysed in detail, using the numerical test method. The influence of the thermal conductivity of the spray layer, the thickness of the spray layer, the thermal conductivity of the surrounding rock, and the temperature of the surrounding rock on the temperature field are discussed. The main findings of our study are, as follows:

(1) The heat-adjusting zone radius increases exponentially with ventilation time. With the increase of the radial depth, the surrounding rock temperature increases gradually and tends to be consistent with the original rock temperature. The wall temperature decreases sharply in the initial stage of ventilation, then tends to be flat after 30 days, followed by a gradual decrease, and finally stabilises after 90 days.

(2) With the decrease in the thermal conductivity and an increase in the spray layer thickness, the thermal insulation layer can be constructed, which can effectively reduce the disturbance of airflow to the surrounding rock temperature and is beneficial to decrease the wall temperature. With the decrease of the thermal conductivity and the increase of the spray layer thickness, the advantageous range increases, while, the ventilation time advantageous trend decreases. The temperature gradient in the spray layer increases with the increase of spray layer thickness, resulting in the increase of the thermal insulation capacity, due to saturation. The thermal conductivity and temperature of the surrounding rock have significant effects on the heat-adjusting zone radius, rock temperature, and wall temperature. As the thermal conductivity and rock temperature increase, the heat-adjusting zone radius, rock temperature, and wall temperature increase, significantly.

(3) The thermal physical properties of the surrounding rock determine the temperature distribution of the roadway. Rock temperature is the most sensitive factor and the thermal conductivity of the spray layer structure is more sensitive than that of the thickness. It is concluded that increase in the thickness of the spray layer is not as beneficial as using low thermal conductivity insulation material. Therefore, when arranging roadways, the low temperature and the thermal conductivity of the surrounding rock should be prioritised. The use of low thermal conductivity thermal insulation spray layer has positive significant impact on controlling the thermal environment of the mine roadways, however, the unlimited increase of the spray layer thickness has a limited effect on the improvement of thermal insulation.

References

Cheng LK, Fan JL, Li CJ, Kang HP, Zhang XS (2019) Engineering design and construction of geotechnical anchoring and shotcrete support. China Architecture & Building Press, Beijing

Du Plessis GE, Liebenberg L, Mathews EH (2013a) The use of variable speed drives for cost-effective energy savings in South African mine cooling systems. Appl Energy 111:16–27

Du Plessis GE, Liebenberg L, Mathews EH (2013b) Case study: the effects of a variable flow energy saving strategy on a deep-mine cooling system. Appl Energy 102:700–709

Fu JX, Song WD, Tan YY (2017) Influence degree analysis of rock mass' mechanical parameters on roadway's deformation characteristics. J Zejiang Univ (Eng Sci) 51(12):2365–2372

Gao JL, Yang M (2005) Analysis of the factors influencing temperature distribution of surrounding rock and cooled zone radius. China Saf Sci J 15(2):73–76

Guo WB, Tu XZ, Yao R, Li WC (2003) Research on isolation material for deep mine roadway. Coal Sci Technol 31(12):23–27

He MC, Guo PY (2013) Deep rock mass thermodynamic effect and temperature control measures. Chin J Rock Mech Eng 32(12):2377–2392

Li CY (2010a) Experimental research on energy-saving of new mine insulated and waterproof material applied on mine. Dissertation, Tianjin University

Li GF (2010b) Research on technology of active cooling supporting structure in high temperature road way. Dissertation, Taiyuan University of Technology

Li S, Sun KG, Qiu WG, Xu WP, Li LP (2017) Influence and sensitivity analysis of surrounding rock thermal parameters on temperature field of cold region tunnel. China Civ Eng J 50(S1):117–122

Qin YP, Wang H, Guo KY, Xue PF, Wang JW, Wu JS (2017) Simulation of finite volume method and experimental analysis for temperature field of roadway surrounding rock. J China Coal Soc 42(12):3166–3175

Song DP, Zhou XH, Bai G, Li A (2017) Study on temperature field distribution law of surrounding rock in active thermal insulated roadway of high temperature mine. Coal Sci Technol 45(12):107–113

Sun PD (2005) Visualization simulation of temperature distributions in geothermal field of surrounding rock of deep mine tunnels. Rock Soil Mech 26(S2):222–226

Wu JW, Wang GT, Zhai XR, Zhang WY, Peng T, Bi YS (2019) Geothermal geological characteristics and geothermal resources evaluation of Huainan mining area. J China Soc 44(8):2566–2578

Xie HP, Zhou HW, Xue DJ, Zhang HW, Zhang R, Gao F (2012) Research and consideration on deep coal mining and critical mining depth. J China Coal Soc 37(4):535–542

Xu SP (2014) Study on the distribution law and control mode of geothermal field in Huainan-Huaibei Coalfield. Dissertation, Anhui University of Science and Technology

Xu SP, Peng T, Wu JW, Zhang HC, Ren ZQ (2014) The characteristics of rock thermal conductivity of coal measure strata and their influence on geothermal field in Huainan-Huaibei coalfield. Coal Geol Explor 42(6):76–81

Yao WJ (2019) Research and application of thermal insulation concrete spray layer support technology for deep and high temperature rock roadways. Dissertation, Anhui University of Science and Technology

Yao WJ, Pang JY (2017a) The orthogonal experimental study on the thermal insulation injection concrete of high temperature mine roadway. Non-Met Mines 40(5):48–52

Yao WJ, Pang JY (2017b) Research and application of a shotcrete support technique using thermal insulating concrete. J Yangtze River Sci Res Inst 34(1):124–128

Yao R, Zhang YB (2002) Research of adiabatic material used in the deep mine lanewall. Mater Sci Eng 20(4):572–575

Yao WJ, Zhang R, Pang JY (2018) A multi-point thermocouple installation device for measuring rock temperature of tunnel surrounding rock. China patent

Yi X, Ren LF, Ma L, Wei GM, Yu WC, Deng J, Shu CM (2019) Effects of seasonal air temperature variation on airflow and surrounding rock temperature of mines. Int J Coal Sci Technol 6(3):388–398

Yuan L (2007) Theoretical analysis and practical application of coal mine cooling in Huainan Mining Area. J Min Saf Eng 24(3):298–301

Zhang Y, Wan ZJ (2016) Temperature field of surrounding rock roadway and its experimental method. China University of Mining and Technology Press, Xuzhou

Zhang XM, Ren ZP, Mei FM (2007) Heat transfer. China Architecture & Building Press, Beijing

Zhang SG, Chang J, Wang HW (2019) Characteristics of heat-adjusting ring and the influence of thermal insulation support structure in high-temperature roadway. Coal Geol Explor 47(5):179–185

Zhao PY, Chen JX, Luo YB, Chen LJ, Wang CW (2019) Investigation of the effect of thermal insulation layer in the seasonally frozen region tunnel: a case study in the Zoumutai tunnel. Adv Civ Eng, China. https://doi.org/10.1155/2019/4978359

Zhou XH, Song DP (2018) Airflow temperature change of active thermal insulation tunnel in high temperature coal mine. J Liaoning Tech Univ (Natl Sci) 37(4):680–685

Zhou XH, Tang XY, Song DP (2019) Thermal insulation performance affected by thermal physical parameters of thermal insulation layer in active thermal insulation tunnel. Min Saf Environ Protect 46(1):14–18

Zhu S, Wu SY, Zhu SX (2017) Temperature field distribution model and analysis of the influencing factors of heat adjustment circle of wall rock in roadway. Ind Saf Environ Protect 43(2):21–24