Research Article

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Evolution regularity of temperature field of active heat insulation roadway considering thermal insulation spraying and grouting: A case study of Zhujidong Coal Mine, China<https://doi.org/10.1515/htmp-2021-0023>

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Abstract: To study the active heat insulation roadways of high-temperature mines considering thermal insulation and injection, a high-temperature –965 m return air roadway of Zhujidong Coal Mine (Anhui Province, China) is selected as a prototype. The ANSYS numerical simulation method is used for the sensitivity analysis of heat insulation grouting layers with different thermal conductivities and zone ranges and heat insulation spray layers with different thermal conductivities and thicknesses; thus, their effects on the heat-adjusting zone radius, surrounding rock temperature field, and wall temperature are studied. The results show that the tunneling head temperature of the Zhujidong Mine is $>27^{\circ}\text{C}$ all year round, consequently causing serious heat damage. The heat insulation circle formed by thermal insulation spraying and grouting can effectively alleviate the disturbance of roadway airflow to the surrounding rock temperature field, thereby significantly reducing the heat-adjusting zone radius and wall temperature. The decrease in the thermal conductivities of the grouting and spray layers, expansion of the grouting layer zone, and increase in the spray layer thickness help effectively reduce the heat-adjusting zone radius and wall temperature. This trend decreases significantly with the ventilation time. A sensitivity analysis shows that the use of spraying and grouting materials of low thermal conductivity for thermal insulation is a primary factor in determining

the temperature field distribution, while the range of the grouting layer zone and the spray layer thickness are secondary factors. The influence of the increased surrounding rock radial depth and ventilation time is negligible. Thus, the application of thermal insulation spraying and grouting is essential for the thermal environment control of mine roadways. Furthermore, the research and development of new spraying and grouting materials with good thermal insulation capabilities should be considered.

Keywords: high-temperature mine, thermal insulation spraying and grouting materials, temperature field of roadway, field measurement, numerical simulation, sensitivity analysis

1 Introduction

With increasing mining depth, high-temperature heat damage has become more evident. This affects mine workers in terms of their physical and mental health and also their work efficiency, necessitating thermal environment control of mines. Mine thermal environment refers to the natural and production environment where miners perform underground engineering activities [1]. For deep mines, a high ground temperature plays a decisive role in mine thermal damage. It not only directly affects the heat transfer of the airflow, which increases the air temperature in the roadway, but also causes thermal pollution of the cold air generated by air conditioning, thereby reducing the effect of artificial cooling. Therefore, studying the temperature field of roadways has significance for improving the heat transfer characteristics of the surrounding rock of high-ground-temperature roadways and carrying out prevention and control measures against heat damage in high-temperature mines [2].

Relevant scholars have put forward a thermal insulation method combining spraying and grouting in high-ground-temperature rocks to construct a large-scale thermal insulation circle that prevents the ground temperature from spreading into the roadway; this method is

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called active cooling. The idea here is to use insulation spraying and grouting materials to construct an insulation structure that prevents geothermal heat from spreading into the roadway and then supplementing it with ventilation to remove heat in time [2–4]. Many scholars have committed to the research and development of thermal insulation injection materials. For instance, a boiler slag concrete spray layer has been used to insulate heat in a high-temperature roadway in Russia. Polyurethane products have been used for roadway heat insulation in South Africa, Russia, and other countries [5,6]. In China, Li *et al.* tested the heat insulation effect of glazed hollow bead thermal insulation mortar for a high-ground-temperature roadway [7]. Yao *et al.* developed thermal insulation materials with a thermal conductivity of $0.17 \text{ W m}^{-1} \text{ K}^{-1}$ using cement, silica lime, perlite, fly ash, and various supplementary additives [8,9]. Li tested the thermal insulation and waterproof properties of polyurethane materials [10]. Yao and Pang used ceramic and glazed hollow bead as lightweight coarse and fine aggregates, respectively. The optimum proportion of thermal insulation shotcrete was determined by conducting an orthogonal test, and an engineering application was implemented in Zhujidong Coal Mine, Anhui, China [11]. In some of the mining areas in Shanxi and Henan Provinces, China, spray thermal insulation materials have been applied on the surface of high-ground-temperature roadways [12,13].

The above-mentioned thermal insulation materials were mostly applied on roadway wall surfaces, and their durability was low. The research and development of thermal insulation grouting materials are still at a theoretical level [14]. Most scholars discussed an active thermal insulation structure formed by a thermal insulation spray material and its influence on the roadway temperature field using numerical simulation methods. For instance, Zhang *et al.* established a surrounding rock insulation thermal support system under high-temperature roadways and discussed the influences of the thermal properties of the thermal insulation structure on the temperature field of the surrounding rock. The results showed that a sensible heat insulation structure affects the temperature field of the rocks surrounding the roadway [15–17]. However, because of the lack of research and development into thermal insulation grouting materials, there is no relevant research on the influence of thermal insulation spraying and grouting structures that form a large-scale thermal insulation circle on the space–time evolution regularity of the surrounding rock temperature field.

The new insights gained in this study are expected to help effectively implement insulation structures for the control of roadway thermal environment. The ANSYS numerical simulation method was used to discuss the distribution regularity of the temperature field of the roadway surrounding rock under different thermal physical parameters of the grouting and spray insulation layers. ANSYS complements the analysis of the active thermal insulation mechanism of the thermal insulation layer with spraying and grouting materials and hence provides a theoretical basis for the research and development of such materials.

2 Engineering background

In this study, the –965 m return air roadway of Zhujidong Coal Mine in Huainan, Anhui, China, was selected as a typical high-temperature prototype. It is a straight wall with a circular arch. Its dimensions are $5,400 \text{ mm} \times 4,300 \text{ mm}$ (height $\times$ width) and has a cross-sectional area of approximately 19.06 m^2 . The support scheme is an anchor spray support. A high-strength prestressed resin bolt was used with a diameter of 22 mm and a length of 2,500 mm, installed at an interval of 800 mm along the roadway axis, with an anchoring force $\geq 50 \text{ kN}$. An anchor cable was used with a diameter of 22 mm and a length of 6,300 mm, at intervals of 1,600 mm along the roadway axis. The grade of the shotcrete was C20 with a thickness of 120 mm. In the case of broken rocks, the grouting was used for reinforcing the surrounding rock, with a water–cement slurry.

The measuring points of the air and wall temperature were arranged in the roadway, as shown in Figure 1. Figure 1 also includes one tunneling head point and five temperature measurement points in the roadway. An air temperature test was conducted for a year to compare the ground indoor and outdoor temperatures with those at the tunneling head and five measurement points. The MS6508 digital thermometer was used for testing the air temperature in the roadway, with a test accuracy of 0.1°C , and a non-contact infrared thermometer was used for roadway lining wall temperature, with a test accuracy of 0.1°C . Moreover, the GFW15 wind speed sensor was used for the wind speed test. The wind speed in the test roadway is in the range of $3.0\text{--}3.5 \text{ m s}^{-1}$ all year round. Figure 2 shows the test results.

As shown in Figure 2(a), the ground indoor and outdoor temperatures are lower than that in the mine

Figure 1: Arrangement of temperature measurement points in the roadway.

underground environment. Huainan City has four distinct seasons but two extreme ones: a cold and dry winter with a temperature range of 1–13°C and a hot and humid summer with an outdoor temperature of approximately 30°C. The external temperature changes do not affect the mine roadway temperature because the air temperature, wall temperature, and tunneling head air temperature of the roadway are between 25 and 30, 24 and 28, and above 27°C, respectively. The wall temperature mostly exceeds 27.5°C, and the relative humidity mostly exceeds 70%. In China, the “Coal Mine Safety Regulations” stipulate that the working surface air temperature should not exceed 26°C. The above results show that the mine thermal damage is severe and seriously affects the physical and mental health and work efficiency of miners [18].

3 Model establishment and parameter selection

3.1 Numerical model of thermal insulation spray and grouting layers

The –965 m return air roadway of Zhujidong Coal Mine of Anhui, China, was selected as the prototype. After the excavation of the roadway surrounding rock, an active thermal insulation model of the thermal insulation spray and grouting layers was constructed in the roadway. The original rock integrity was assumed to remain intact after excavation. Furthermore, it was assumed that the structures of the grouting layer, the original rock layer, and the spray layer are all stable and that the coupling effect

Figure 2: Temperature test results of roadway: (a) air temperature; (b) wall temperature.

Figure 3: Active thermal insulation roadway constructed by thermal insulation spray and grouting.

is good [19]. Figure 3 represents the active thermal insulation roadway with spray and grouting thermal insulation layers.

3.2 Model assumption

The ANSYS software and transient method were used to carry out a heat transfer analysis, and the PLANE 55 2D four-node solid element model was used, with the following simplifications and assumptions:

- (1) Based on the test, the heat-adjusting zone radius in the surrounding rock tends to be stable after 3 years of ventilation with a radius ranging from 15 to 40 m [20]. Therefore, the length and width of the modeling range are both 100 m, and the roadway is located at the center of the model.
- (2) The far-field boundary condition of the surrounding rock is the upper and lower boundaries of the model. The upper and lower boundaries were set as constant temperature (37°C) boundaries, and the inner boundary spray layer was set as a convective heat transfer boundary. Based on the engineering background of this study and the results obtained by Yao *et al.* [21], initially, after excavation, the wall temperature of the

newly excavated roadway is relatively high. After long-term ventilation, the wall temperature is maintained between 24 and 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 exists between the layers. Furthermore, the air temperature and heat conduction coefficient of the airflow in the roadway wall are both constant.

3.3 Parameter selection

A numerical model was established considering the influences of thermally insulated grouting layers with different thermal conductivities and grouting range and thermally insulated spray layers with different thermal conductivities and spray thicknesses on the temperature field of the roadway surrounding rock. Each working condition was compared with the parameters of each group of the influencing factors. The following basic conditions were selected:

- (1) Thermal conductivity of grouting layer: With reference to Wu et al. [22], the thermal conductivity of the surrounding rock in this study area is set between 0.37 and 4.36 W m⁻¹ K⁻¹. The average value of 2.54 W m⁻¹ K⁻¹ is considered after the removal of coal, sand, and other special rock masses. There is little related literature on the research and development of insulation grouting layer materials. While the thermal conductivity of the insulation layer in the ground structure is controlled below 0.35 W m⁻¹ K⁻¹ [23], the thermal conductivity of the thermal insulation grouting layer is considered to range from 0.3 to 2.4 W m⁻¹ K⁻¹, with a 0.3 W m⁻¹ K⁻¹ interval and a basic parameter value of 1.2 W m⁻¹ K⁻¹.
- (2) Range of grouting layer zone: Based on the “Construction Code of Coal Mine Roadway Engineering” [24], the optimum range of the grouting layer zone should be 1–8 m, with an interval of 1 m and a basic parameter value of 4 m.
- (3) Thermal conductivity of spray layer: Based on the data provided in related literature [7–11,25,26] and the measured thermal conductivity of on-site injection molding sampling, the thermal conductivity of the insulated spray concrete ranges from 0.15 to 0.85 W m⁻¹ K⁻¹, whereas the thermal conductivity of ordinary concrete ranges from 1.20 to 1.75 W m⁻¹ K⁻¹. Therefore, the thermal conductivity of the spray layer is considered to range from 0.20 to 1.60 W m⁻¹ K⁻¹, with an interval of 0.20 W m⁻¹ K⁻¹ and a basic parameter value of 0.80 W m⁻¹ K⁻¹.
- (4) Spray layer thickness: According to the “Construction Code of Coal Mine Roadway Engineering” [24], the optimum thickness of the spray layer should range from 80 to 220 mm, with an interval of 20 mm and a basic parameter value of 140 mm.

Table 1 presents the determination of each working condition. Table 2 lists the thermal physical parameters of the thermal insulation grouting and spray layers and the surrounding rock.

In this study, ANSYS is used to calculate the temperature field of the roadway surrounding rock based on the actual conditions in Zhujidong Coal Mine, with a spray layer thickness of 120 mm, spray layer thermal conductivity of 0.8 W m⁻¹ K⁻¹, surrounding rock temperature of 37°C, and surrounding rock thermal conductivity of 2.5 W m⁻¹ K⁻¹. To verify the reference of the calculation results, the calculation results are compared and verified with the actual field measurement data obtained during field observations (Figure 4).

Table 1: Basic parameters and range variation of the working condition in the numerical test

Working condition	Thermal conductivity of grouting layer (W m ⁻¹ K ⁻¹)	Range of grouting layer zone (m)	Thermal conductivity of spray layer (W m ⁻¹ K ⁻¹)	Thickness of spray layer (mm)
1	0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.1, 2.4	4	0.8	140
2	1.2	1, 2, 3, 4, 5, 6, 7, 8	0.8	140
3	1.2	4	0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6	140
4	1.2	4	0.8	80, 100, 120, 140, 160, 180, 200, 220

Table 2: Thermal physical parameters of the materials used in the numerical test

Materials	Density (kg m^{-3})	Specific heat capacity ($\text{J kg}^{-1} \text{°C}^{-1}$)	Heat transfer coefficient ($\text{W m}^{-2} \text{°C}^{-1}$)
Surrounding rock	2,500	896	20
Insulated grouting layer	2,103	933	20
Insulated concrete spray layer	1,705	970	20

Figure 4: Comparison between calculation and measured results.

As shown in Figure 4, the numerical simulation has a high accuracy; hence, they can be used to calculate the temperature field of the roadway surrounding rock, with thermal insulation and grouting.

4 Distribution regularity of roadway surrounding rock temperature field

The distribution of the roadway temperature field is discussed under two working conditions: normal working condition and thermal insulation working condition. Under the normal working condition, the thermal conductivity of the spray layer was $1.70 \text{ W m}^{-1} \text{K}^{-1}$, the spray layer thickness was 140 mm, and the thermal conductivity of the surrounding rock was $2.50 \text{ W m}^{-1} \text{K}^{-1}$. Under the thermal insulation working condition, the thermal conductivity of the spray layer was $0.80 \text{ W m}^{-1} \text{K}^{-1}$, the spray layer thickness was 140 mm, the thermal conductivity of the grouting layer was $1.20 \text{ W m}^{-1} \text{K}^{-1}$, the range of the grouting layer zone was 4 m, and the thermal conductivity of the surrounding rock was $2.50 \text{ W m}^{-1} \text{K}^{-1}$.

During the calculation analysis, quadrilateral nodes were used for model meshing, and the stabilities of the grid sizes and times steps were tested, before simulation.

The model was assumed in the original rock temperature condition and then restricted to the boundary lines around the model. An adiabatic conduction was considered. The convective heat transfer boundary was taken from the inner spray layer. Moreover, the corresponding convective heat transfer coefficient and temperature values were set to analyze the temperature field distribution of the roadway under different ventilation times.

4.1 Distribution of the surrounding rock heat-adjusting zone

Figures 5 and 6 present the temperature fields of the roadway under the two working conditions for 30, 365, 1,095, and 3,650 days. Figure 5 shows the temperature field of the roadway surrounding rock under normal working conditions. Figure 6 shows the temperature field of the roadway surrounding rock under thermal working conditions. As the ventilation progresses, the surrounding rock temperature around the roadway gradually decreases, thus forming a heat-adjusting zone.

The wall temperatures of the roadway lining for 30, 365, 1,095, and 3,650 days of ventilation from Figure 5 are 26.618, 26.307, 26.242, and 26.193°C, respectively. In Figure 6, the corresponding values are 26.381, 26.195, 26.166, and 26.141°C, respectively. These results show that the wall temperature under thermal working conditions decreases significantly. This reduction is because of the thermal insulation heat resistance circle. The temperature reduction values in percentages for 30, 365, 1,095, and 3,650 days of ventilation are 0.89, 0.43, 0.2, and 0.20%, respectively, and as the ventilation progresses, the heat insulation effect gradually weakens.

The area where the temperature reduction value of the 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, the original rock, and the center of the roadway is defined as the radius of the surrounding rock heat-adjusting zone [27]. As shown in Figures 5 and 6, the surrounding rock is continuously cooled, and the heat-adjusting zone widens over time. Figure 7 shows the

Figure 5: Temperature field of roadway surrounding rock under normal working condition: (a) 30 days; (b) 365 days; (c) 1,095 days; (d) 3,650 days.

change and fitting of the heat-adjusting zone under the two working conditions in 10 years.

Figure 7 shows that, under normal working conditions, the heat-adjusting zone radius values in 30, 365, 1,095, and 3,650 days after ventilation are 7.384, 17.374, 27.036, and 42.278 m, respectively, whereas under the thermal insulation working condition, the corresponding values are 6.316, 15.023, 23.723, and 36.690 m, respectively. These results show that the heat-adjusting zone radius under the thermal insulation working condition in 30, 365, 1,095, and 3,650 days of ventilation is reduced by 14.46, 13.53, 12.25, and 13.22%, respectively. Based on the fitting data, the heat-adjusting zone radius is in the right power index relationship with the ventilation time as expressed in the following equations:

$$R_1 = 1.512\sqrt{t} + r_0 \quad R^2 = 0.99, \quad (1)$$

$$R_2 = 0.269\sqrt{t} + r_0 \quad R^2 = 0.99, \quad (2)$$

where R_1 is the radius of the heat-adjusting zone under the normal working condition, R_2 is the radius of the heat-adjusting zone under the thermal insulation working condition, t is the ventilation time of the roadway, d , and r_0

is the distance from the center of the roadway to the surrounding rock, which is 2.82 m in this case.

4.2 Distribution of surrounding rock temperature field

Generally, the temperature field of the surrounding rock of the roadway tends to stabilize after 3 years. 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. Figure 8(a) and (b) shows the temperature distributions of the roadway surrounding rock under the two conditions with reference to the changes in the roadway lining wall, the interface between the spray and grouting layers, and the surrounding rock layer with measuring points ranging from 1 to 30 m taken during the research period.

As shown in Figure 8: (1) spatially, the temperature of the roadway wall is the lowest because of the influence of ventilation. The temperature of the other rock layers increases with the radial depth and gradually tends to be

Figure 6: Temperature field of roadway surrounding rock under thermal working condition: (a) 30 days; (b) 365 days; (c) 1,095 days; (d) 3,650 days.

Figure 7: Change and fitting of the heat-adjusting zone radius under two working conditions.

consistent with the original rock temperature. In other words, it gradually reaches the edge of the heat-adjusting zone. (2) Temporally, the temperature at each measurement point gradually decreases. In the initial stage of ventilation, the temperature of the roadway lining wall decreases sharply and tends to be flat after 30 days. After 90 days,

the temperature continues to decrease gradually and tends to stabilize. (3) Under both the working conditions, after the application of the thermal insulation spray and grouting layers, the wall temperature decreases significantly, and the original rock temperature (surrounding rock layer thickness: 30 m) is the highest at all ventilation times.

5 Analysis of influencing factors of surrounding rock temperature field

5.1 Influence of grouting layer thermal conductivity

5.1.1 Influence of grouting layer thermal conductivity on heat-adjusting zone radius

Taking 3 years of ventilation time as the research period, the change in the heat-adjusting zone radius under different thermal conductivities of the grouting layer under

Figure 8: Temperature distributions of roadway surrounding rock under two working conditions: (a) normal; (b) thermal insulation.

Figure 9: Influence of grouting layer thermal conductivity on heat-adjusting zone radius.

working condition 1 listed in Table 1 was calculated and shown in Figure 9. As shown, the heat-adjusting zone radius decreases with decreasing thermal conductivity. After 30 and 1,095 days of ventilation and cooling, the heat-adjusting zone radius of the grouting layer with a thermal conductivity of $2.4 \text{ W m}^{-1} \text{ K}^{-1}$ decreases by 33.29 and 42.95%, respectively, compared with that of the grouting layer with a thermal conductivity of $0.3 \text{ W m}^{-1} \text{ K}^{-1}$. This shows that the thermal insulation grouting layer can improve the thermal insulation ability of the roadway surrounding rock because it effectively alleviates the disturbance of airflow to the deep surrounding rock temperature field, thereby reducing the heat-adjusting zone radius.

5.1.2 Influence of grouting layer thermal conductivity on surrounding rock temperature field

The disturbance of ventilation cooling to the surrounding rock temperature field gradually weakens with the increase

in the ventilation time and radial depth of the rock layer. To explain this phenomenon, working condition 1 in Table 1 with 30 and 1,095 days of ventilation time are used as examples of the initial and long-term excavations of the roadway. Figure 10 shows the change in regularity of the surrounding rock temperature field under different thermal conductivities of the grouting layer.

Based on Figure 10, during the initial long-term ventilation of the roadway, the temperature at the interface between the spray and grouting layers decreases with the decrease in the grouting layer thermal conductivity. However, the temperature at each measurement point inside the rock layer increases with the decrease in grouting layer thermal conductivity. Moreover, it gradually tends to be consistent with the original rock temperature as the radial depth of the rock layer increases, and the greater the radial depth, the lower the increase.

From Figure 10(a), at 30 days, the temperature at the interface between the grouting and spray layers for a grouting layer thermal conductivity of $0.3 \text{ W m}^{-1} \text{ K}^{-1}$ decreases by 5.51% than that for a grouting layer thermal conductivity of $2.4 \text{ W m}^{-1} \text{ K}^{-1}$. From Figure 10(b), at 1,095 days, the temperature at the interface between the grouting and spray layers for a grouting layer thermal conductivity of $0.3 \text{ W m}^{-1} \text{ K}^{-1}$ decreases by 2.85% compared with that for a grouting layer thermal conductivity of $2.4 \text{ W m}^{-1} \text{ K}^{-1}$.

This is because the grouting layer thermal conductivity is lower than the surrounding rock thermal conductivity of the wide zone, thus effectively preventing the cooling effect of the roadway airflow on the surrounding rock temperature field. Moreover, the lower the grouting layer thermal conductivity, the better the thermal insulation effect and the closer the surrounding rock temperature to the original rock temperature.

Figure 10: Influence of grouting layer thermal conductivity on surrounding rock temperature field: (a) 30 days; (b) 1,095 days.

5.1.3 Influence of grouting layer thermal conductivity on roadway wall temperature

The wall temperature of the roadway lining has an important reference for controlling the mine thermal environment. Under working condition 1 listed in Table 1, Figure 11 shows the influence of the grouting layer thermal conductivity on the wall temperature with time.

From Figure 11(a), the wall temperature decreases sharply with the ventilation time and then gradually stabilizes after 90 days for all grouting layer thermal conductivities. From Figure 11(b), at each point in the study period, the lower the grouting layer thermal conductivity, the lower the wall temperature. In the initial 30 days of tunneling, there is a significant effect on the wall temperature reduction. The wall temperature of the grouting layer

with a thermal conductivity of $0.3 \text{ W m}^{-1} \text{ K}^{-1}$ decreases by 1.39% compared with that of the grouting layer with a thermal conductivity of $2.4 \text{ W m}^{-1} \text{ K}^{-1}$. This shows that the construction of a grouting insulation layer effectively reduces the wall temperature and improves the thermal and humid environment of the mine. After long-term ventilation of 1,095 days, the cooling effect on the wall temperature weakens. The wall temperature of the grouting layer with a thermal conductivity of $0.3 \text{ W m}^{-1} \text{ K}^{-1}$ decreases by 0.66% compared with that of the grouting layer with a thermal conductivity of $2.4 \text{ W m}^{-1} \text{ K}^{-1}$. This is because the range of the thermal insulation grouting layer is limited; hence, the original rock temperature field affects the wall temperature, and the surrounding insulation grouting layer of the roadway after the heat-adjusting zone is stable and becomes gradually consistent with the original rock temperature.

Figure 11: Influence of grouting layer thermal conductivity on wall temperature: (a) wall temperature change with time; (b) wall temperature change with grouting layer thermal conductivity.

5.2 Influence of grouting layer zone range

5.2.1 Influence of grouting layer zone range on heat-adjusting zone radius

Figure 12 shows the change in the heat-adjusting zone under different grouting layer zone ranges based on the working condition 2 listed in Table 1. The influence of the grouting layer zone range on the heat-adjusting zone is not as significant as that of the grouting layer thermal conductivity. As shown in Figure 12, the heat-adjusting zone radius gradually decreases as the grouting layer zone expands. After 30 days, the heat-adjusting zone radius of the grouting layer zone with a range of 8 m is 8.87% less than that of the grouting layer zone with a range of 1 m, and at 1,095 days, the corresponding decrease is 12.29%.

This substantiates that an increase in the range of the thermal insulation grouting layer prevents the disturbance of the roadway airflow to the temperature field of the deep surrounding rock, hence reducing the range of the heat-

Figure 12: Influence of grouting layer zone on heat-adjusting zone radius.

Figure 13: Influence of grouting layer zone on surrounding rock temperature field: (a) 30 days; (b) 1,095 days.

adjusting zone. However, it is not as significant as the decrease in the thermal conductivity of the grouting layer.

5.2.2 Influence of grouting layer zone range on surrounding rock temperature field

Figure 13 shows the temperature variation of the surrounding rock under the different grouting layer zone ranges based on working condition 2 listed in Table 1 for 30 days after excavation and 1,095 days of long-term ventilation. The influence of the grouting layer zone range on the surrounding rock temperature field is similar to that of the grouting layer thermal conductivity. The wider the range of the grouting layer zone, the lower the temperature at the interface between the spray and grouting layers. Despite this, the temperature at each measuring point inside the rock layer increases and gradually tends to be consistent with the original rock temperature.

From Figure 13, in 30 days, the temperature at the interface between the spray and grouting layers in the grouting layer zone with a range of 8 m decreases by 1.23% compared with that in the grouting layer zone with a range of 1 m; the corresponding decrease is 1.19% in 1,095 days. It can be concluded that an increase in the range of the grouting layer zone weakens the influence of the roadway airflow on the roadway surrounding rock temperature field; however, it is not as significant as reducing the thermal conductivity of the grouting layer.

5.2.3 Influence of grouting layer zone range on roadway wall temperature

Figure 14 shows the influence of the grouting layer zone range on the roadway wall temperature based on working

Figure 14: Influence of grouting layer zone on wall temperature: (a) wall temperature change with time; (b) wall temperature change with grouting layer zone range.

condition 2 listed in Table 1. Similar to the effect of the thermal conductivity of the grouting layer on the roadway temperature wall, Figure 14(a) shows that the wall temperature decreases rapidly at the beginning of ventilation and gradually stabilizes after 90 days.

Figure 14(b) shows that the wider the range of the grouting layer zone, the more significant the reduction in the wall temperature. At 30 days, the wall temperature of the grouting layer zone with a range of 8 m decreases by 0.27% compared with that of the grouting layer zone with a range of 1 m; the corresponding decrease is 0.26% at 1,095 days.

The parameters of the thermal insulation grouting layer have similar regularities in their effects on the heat-adjusting radius, surrounding rock temperature field distribution, and wall temperature. The thermal insulation grouting layer effectively alleviates the disturbance of the surrounding rock temperature field by the roadway airflow, reduces the heat transfer of the surrounding rock to the roadway airflow, controls the heat-adjusting zone, and reduces the wall temperature. The control effect continues to improve with the decrease in the grouting layer thermal conductivity and as the grouting layer zone expands. However, the surrounding rock temperature gradually coincides with the temperature of the original rock as the ventilation time increases.

Furthermore, the reduction in the grouting layer thermal conductivity is more significant than the expansion of the grouting range because the grouting range has a more significant effect on the temperature control of the roadway surrounding rock. Therefore, for the construction of an active thermal insulation structure to control mine thermal environment, efforts should be made to develop suitable thermal insulation grouting materials for underground construction because they are more effective in controlling the roadway temperature field.

5.3 Influence of spray layer thermal conductivity

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

Based on working condition 3 in Table 1, the changes in the heat-adjusting zone radius under different spray layer thermal conductivities are shown in Figure 15. Figure 15 shows that as the spray layer thermal conductivity decreases, the heat-adjusting zone radius decreases. After 30 days, the heat-adjusting zone radius of the spray layer with a thermal conductivity of $0.2 \text{ W m}^{-1} \text{ K}^{-1}$ is 9.83% less than that of the spray layer with a thermal conductivity of $1.6 \text{ W m}^{-1} \text{ K}^{-1}$; the corresponding decrease is 6.30% at 1,095 days.

The above results show that the influence of the spray layer thermal conductivity on the heat-adjusting zone radius is similar to the influence of the grouting insulation layer. These results substantiate that a

Figure 15: Influence of spray layer thermal conductivity on heat-adjusting zone radius.

concrete spray layer with a strong insulation ability can effectively alleviate the disturbance of the temperature field of the deep surrounding rock by the airflow and reduce the heat-adjusting zone. However, comparing Figures 9 and 15, we find that the influence of the spray layer thermal conductivity is much lower than that of the grouting layer thermal conductivity in each period.

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

Figure 16 shows the temperature changes in the surrounding rock under different spray layer thermal conductivities based on working condition 3 listed in Table 1. Figure 16 shows that, at each ventilation time, as the radial depth of the rock layer increases, the temperature of the rock layer gradually increases, and as the spray layer thermal conductivity decreases, the temperature at each measuring point in the rock layer increases. Moreover, as the radial depth increases, the original temperature of the rock decreases because of ventilation cooling, and the degree of temperature increase gradually weakens.

At 30 and 1,095 days, the temperature at the interface between the spray and grouting layers with a spray layer thermal conductivity of $0.2 \text{ W m}^{-1} \text{ K}^{-1}$ increases by 11.31 and 6.06%, respectively, compared with that when the thermal conductivity is $1.6 \text{ W m}^{-1} \text{ K}^{-1}$. Moreover, at each period, the influence of the thermal insulation spray layer is much lower than that of the grouting layer.

Comparatively, the influence of the spray layer thermal conductivity on the surrounding rock temperature field is similar to that of the thermal insulation grouting layer. These results confirm that a concrete spray layer with a good thermal insulation ability can effectively prevent the cooling effect of the roadway airflow on the surrounding

rock temperature field. This prevention weakens the influence of the original rock temperature on the surrounding rock, and the temperature at each measuring point of the rock layer increases. Moreover, the temperature difference is maximum at the interface between the spray and grouting layers.

5.3.3 Influence of spray layer thermal conductivity on wall temperature

Figure 17 shows the change in the wall temperature under different spray layer thermal conductivities based on working condition 3 listed in Table 1. As shown in Figure 17(a), in the initial stages of ventilation, the wall temperature rapidly decreases and then stabilizes after 90 days. Figure 17(b) shows that, at each period, as the spray layer thermal conductivity decreases, so does the wall temperature, and as the ventilation progresses, the degree of reduction gradually decreases. Furthermore, on the first day of excavation, the wall temperature of the spray layer with a thermal conductivity of $0.2 \text{ W m}^{-1} \text{ K}^{-1}$ is 6.09% less than that of the spray layer with a thermal conductivity of $1.6 \text{ W m}^{-1} \text{ K}^{-1}$. After 30 days, the decrease is only 0.33%, and then, the influence is minimal. The influence of the spray layer thermal conductivity on the wall temperature is similar to that of the grouting layer thermal conductivity. The results show that the heat dissipated by the surrounding rock to the roadway airflow is reduced, thereby reducing the wall temperature.

Comparing Figure 17 with Figure 11, in the first 10 days of roadway excavation, the reduction effect of the thermal insulation spray layer is significantly greater than that of the thermal insulation grouting layer. As the ventilation progresses, the influence degree gradually decreases and is lower than that of the thermal insulation grouting layer.

Figure 16: Influence of spray layer thermal conductivity on the surrounding rock temperature field: (a) 30 days; (b) 1,095 days.

Figure 17: Influence of spray layer thermal conductivity on wall temperature: (a) wall temperature change with time; (b) wall temperature change with spray layer thermal conductivity.

5.4 Influence of spray layer thickness

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

Figure 18 shows the change in the heat-adjusting zone radius under different spray layer thicknesses based on working condition 4 listed in Table 1. As shown, the spray layer thickness has little influence on the heat-adjusting zone radius. The variation in the heat-adjusting zone radius under different spray layer thicknesses is approximately 1% at each ventilation time. This means that an increase in the concrete spray layer thickness has little influence on the heat-adjusting zone radius and is less compared with the influence of the reduction in the spray layer thermal conductivity and the construction of a grouting insulation layer. This is because under this working condition, when a grouting insulation layer with a strong thermal insulation capacity is

Figure 18: Influence of spray layer thickness on heat-adjusting zone radius.

built around the roadway, it hinders the performance of the thermal insulation spray layer. This also indicates that thermal insulation grouting and spraying can improve the thermal environment of the roadway in a comprehensive manner.

5.4.2 Influence of spray layer thickness on surrounding rock temperature field

The temperature changes in the surrounding rock at different spray layer thicknesses shown in Figure 19 are based on the working condition 4 listed in Table 1. At 30 days, at the interface between the spray layer and original rock, the temperature with a spray layer thickness of 220 mm is 4.50% higher than that with a spray layer thickness of 80 mm (Figure 19a); the corresponding increase is 2.04% at 1,095 days (Figure 19b).

Thus, the effect of increasing the spray layer thickness on the surrounding rock temperature field is still less compared with the effect of decreasing the spray layer thermal conductivity and the application of the thermal insulation grouting layer. Furthermore, as the ventilation progresses, the effect gradually decreases, and the temperature at the interface between the spray layer and the original rock remains high.

5.4.3 Influence of spray layer thickness on roadway wall temperature

Figure 20 shows the influence of the spray layer thickness on the wall temperature based on the working condition 4 listed in Table 1. Similarly, its effect on the wall temperature is also extremely small compared with the reduction

Figure 19: Influence of spray layer thickness on surrounding rock temperature field: (a) 30 days; (b) 1,095 days.

Figure 20: Influence of spray layer thickness on wall temperature: (a) wall temperature change with time; (b) wall temperature change with the spray layer thickness.

in the spray layer thermal conductivity and the application of the thermal insulation grouting layer.

Figure 20(a) shows that at the initial 30 days of ventilation, the wall temperature decreases rapidly but then gradually stabilizes after 90 days. However, the spray layer thickness has a certain beneficial effect on reducing the wall temperature. Figure 20(b) shows that at day 1 of excavation, the wall temperature with a spray layer thickness of 220 mm decreases by 2.87% compared with that with a spray layer thickness of 80 mm, and after 30 days, the wall temperature decreases by only 0.04% and thereafter, there is almost no change in the wall temperature.

From the above results and analysis of the influence of the thermal insulation spray layer parameters on the heat-adjusting zone, surrounding rock temperature field, wall temperature, and its comparison with the influence of the thermal insulation grouting layer, we can draw the following conclusions. Despite the low influence of the thermal insulation spray layer on the control of the

surrounding rock temperature field compared with that of the thermal insulation spray layer, the concrete spray layer with thermal insulation can effectively reduce the disturbance of the roadway airflow to the surrounding rock temperature field, with the effect being more evident in the initial stages of ventilation.

Furthermore, comparing the effects of the spray layer thermal conductivity and the thickness, reducing the spray layer thermal conductivity has a greater impact on the surrounding rock temperature than increasing the spray layer thickness. Moreover, as the spray layer thickness increases and the ventilation progresses, the temperature gradient inside the spray layer increases, and the thermal insulation capacity tends to saturate.

From the analysis results obtained under different working conditions, the single-factor influences of grouting layers with different thermal conductivities and zone ranges and spray layers with different thermal conductivities and thicknesses on the heat-adjusting zone, surrounding rock

temperature field, and wall temperature were discussed. However, it was difficult to distinguish the significance and sensitivity influence of each factor on the temperature field; hence, a sensitivity analysis was carried out.

6 Sensitivity analysis of surrounding rock temperature field

Using the sensitivity analysis method, the sensitivities of each factor to the heat-adjusting zone, surrounding rock temperature field, and wall temperature are visually expressed [28–30]. The sensitivity analysis method is briefly described below.

The system model is assumed as $y = f(x_1, x_2, \dots, x_k, \dots)$, where x_k is the k th influence factor of the model, and each factor varies in a range of possible values. First, a system model should be established, and the benchmark parameter set should be given. When analyzing the influence of parameter x_k on characteristic y , the signal-factor analysis method is used. The other parameters are fixed to the benchmark parameter, and x_k is varied within its possible range. The system characteristic y is expressed as follows:

$$y = f(x_{k1}, x_{k2}, \dots, x_{kn}). \quad (3)$$

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 the different dimensional parameters, the dimensionless form sensitivity factor is defined as follows:

$$s_k = \left| \frac{x_k^*}{y^*} \times \frac{\Delta y}{\Delta x_k} \right|, \quad (4)$$

where s_k is the sensitivity of the parameter x_k , x_k^* is the benchmark 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 the characteristic y to parameter x_k in the range of parameter x_k .

When multiple systems need to be analyzed simultaneously, sensitivity factors are normalized for a comprehensive analysis. If the sum of the sensitivity factors of all the influencing parameters for the same system is 1, the sensitivity factors of the normalized parameters are as follows:

$$s'_k = \frac{s_k}{\sum_{i=1}^n s_i}. \quad (5)$$

Therefore, the grouting layer thermal conductivity, grouting layer zone, as well as the spray layer thermal conductivity and spray layer thickness are taken as the influencing parameters, denoted by x_1 , x_2 , x_3 , and x_4 , respectively. Meanwhile, the heat-adjusting zone radius, surrounding rock temperature, and wall temperature are taken as the characteristic y . The sensitivity of each parameter to the characteristic is calculated under each working condition presented in Table 1.

6.1 Sensitivity analysis of the effect of different factors on the heat-adjusting zone radius

Figure 21 shows the sensitivity analysis of the effects of different factors on the heat-zone radius. As shown, the sensitivity of the grouting layer thermal conductivity takes a larger proportion than those of the other factors. Figure 21(a) shows that in the early days of ventilation, the spray layer thermal conductivity is more sensitive than the grouting layer zone. From Figure 21(b), at 1,095 days, the sensitivity of the grouting layer zone is greater than that of the spray layer thermal conductivity. Furthermore, the spray layer thickness is the least sensitive during the entire period, and with time, the sensitivity gradually decreases to an almost negligible value.

This substantiates that a thermal insulation material with a low thermal conductivity and strong heat resistance is the primary factor in determining the range of the heat-adjusting zone, while the range of the grouting layer zone and the spray layer thickness are secondary factors in the thermal insulation grouting and spray layers of the roadway.

6.2 Sensitivity analysis of the effect of different factors on the surrounding rock temperature

Figure 22 shows the sensitivity analysis of the effect of different factors on the surrounding rock temperature field during early ventilation (30 days) and long-term ventilation (1,095 days). In both the figures, the grouting layer thermal conductivity occupies the largest proportion. Figure 22(a) and (b) shows that, at a radial depth of 5 m, the thermal conductivity and thickness of the spray layer are more sensitive than the grouting layer zone.

Figure 21: Sensitivities of different influencing factors on heat-adjusting zone radius: (a) 90 days; (b) 1,095 days.

As the radial depth of the rock layer increases, the sensitivity of the grouting layer zone gradually increases.

These results substantiate that the application of thermal insulation grouting layer and spray layer can effectively influence the surrounding rock temperature field, and at a radial depth of 5 m, the thermal insulation spray layer has a greater influence than the thermal insulation grouting layer.

6.3 Sensitivity analysis of the effects of different factors on the roadway wall temperature

Figure 23 shows a sensitivity analysis of the effects of different factors on the roadway wall temperature. As shown, the different factors have a similar effect on the roadway wall temperature as those of the heat-adjusting zone and surrounding rock temperature field. In the early stage of ventilation (30 days), the roadway wall temperature is mainly affected by the thermal insulation spray layer (Figure 23a), but as the ventilation progresses (1,095 days), the effect of the thermal insulation grouting layer surpasses that of the thermal insulation spray layer,

dominated by the grouting layer thermal conductivity, followed by the range. During the period of 1,095 days, the effect of the spray layer keeps reducing (Figure 23b).

Among the parameters of the spray layer, the thermal conductivity is more sensitive than the thickness, and among the parameters of the grouting layer, the thermal conductivity is more sensitive than the range. This shows that in the early stage of roadway excavation, the thermal insulation spray layer can reduce the wall temperature and disturbance of the surrounding rock temperature field to the airflow of the roadway, but as the ventilation time increases, the heat resistance circle constructed by the grouting insulation layer becomes more effective.

From the above analysis, under this working condition, at 30 days of short-term ventilation, the thermal insulation spray layer can prevent the heat from the surrounding rock and reduce the influence of the roadway airflow on the surrounding rock temperature field, but it gradually weakens over time. At 30 days, the surrounding rock temperature, wall temperature, and thermal conductivity of the grouting layer are decisive factors, followed by the thermal conductivity of the spray layer, and lastly the grouting layer zone and spray layer thickness. This shows that the thermal insulation grouting layer is more effective than the thermal insulation spray layer. At 1,095 days

Figure 22: Sensitivities of different influencing factors to temperature field distribution of the surrounding rock: (a) 30 days; (b) 1,095 days.

of long-term ventilation, the heat-adjusting zone gradually stabilizes and can still effectively influence the surrounding rock temperature field. Moreover, the decrease in the grouting layer thermal conductivity is more significant than the expansion of the grouting layer zone and the increase in the spray layer thickness. The thermal conductivity of the grouting layer is also the decisive factor, followed by the grouting layer zone, and lastly the spray layer thickness. Therefore, the heat-resistant circle formed by thermal insulation grouting and spraying is conducive for the control of the mine thermal environment during the construction of the roadway. The research and development of new thermal insulation injection materials with low thermal conductivity, strong thermal insulation capabilities, and active thermal insulation and cooling for mine thermal environment should be focused.

7 Conclusion

In this study, the temperature field of an active thermal insulation roadway was analyzed in detail in terms of the thermal insulation grouting and spray layers using the

numerical test method. The influences of the grouting layer thermal conductivity, range of the grouting layer zone, spray layer thermal conductivity, and spray layer thickness on the temperature field were discussed. The main findings of the study are as follows:

- (1) Comparing the temperature fields of the roadway surrounding rock under normal and thermal insulation working conditions, we found that, with the heat-resistant circle formed by the thermal insulation grouting and spray layers, the temperature field showed similar regularity under the two working conditions. The heat-adjusting zone radius increased exponentially with the ventilation time, and with the increase in the radial depth, the surrounding rock temperature increased gradually and then tended to be consistent with the original rock temperature. The wall temperature decreased sharply in the initial stage of ventilation and then tended to be flat after 30 days. Despite this, the heat-adjusting zone radius and wall temperature were significantly reduced by the thermal insulation grouting and spray layers, and at each period, the original rock layer temperature was higher under the thermal working condition than under the normal working condition.

Figure 23: Sensitivities of different influencing factors to wall temperature: (a) 30 days; (b) 1,095 days.

- (2) The use of thermal insulation injection materials with a low thermal conductivity was found to be the primary factor, while the range of the grouting layer zone and the spray layer thickness were secondary factors. They were used to construct a heat-resistant circle that reduced the heat-adjusting zone radius and to determine the surrounding rock temperature field. With the decrease in the thermal conductivities of the grouting and spray layers, and with an increase in the range of the grouting layer zone and the spray layer thickness, the wall temperature decreased, and as the ventilation progressed, the degree of influence decreased. In the initial stages of ventilation (10 days), the thermal insulation spray layer could effectively reduce the wall temperature, and after 30 days, the thermal insulation grouting layer gradually became prominent because of its significant effect on the wall temperature and heat-adjusting zone radius.
- (3) The heat-resistant circle formed by the thermal insulation grouting and spray layers could effectively control the surrounding rock temperature field, prevent and reduce the roadway airflow, and reduce the heat-adjusting zone radius and wall temperature.

Moreover, as the ventilation progressed and the radial depth of the rock layer increased, the thermophysical parameters of the grouting layer dominated. In the early 30 days, the thermal insulation spray layer could effectively prevent the transmission of heat from the surrounding rock and decrease the wall temperature; however, as the ventilation progressed, the thermal insulation grouting layer became more influential. Therefore, a heat-resistant circle formed by thermal insulation injection had a positive impact on the control of the mine thermal environment. The development of new injection materials with strong thermal insulation capabilities will be more beneficial than extending the application of thermal insulation materials.

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