Article


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Abstract: The thermal insulation method is one of the effective methods for controlling the thermal environment of a high-temperature mine. In order to explore the thermal insulation mechanism and characteristics of thermal insulation roadways in high-temperature mines, a heat transfer model for the surrounding rock of the thermal insulation roadway was established based on the steady heat transfer theory. The temperature field of the surrounding rock of the thermal insulation roadway was studied, and the effects and sensitivities of thermal insulation layer thickness and thermal conductivity, convective heat transfer coefficient between roadway wall and airflow, and roadway radius on the thermal insulation performance of thermal insulation roadway were discussed. The results suggest the following: (1) The temperature gradient inside the thermal insulation layer is greater than that inside the surrounding rock. The thermal insulation roadway reduces the temperature difference between the original rock and the outside surface of the thermal insulation layer, thereby reducing the heat dissipation of the surrounding rock. (2) As the thermal insulation layer thickness increases, the thermal insulation capacity gradually increases, but its enhancement rate gradually weakens; as the thermal conductivity of the thermal insulation layer or the roadway radius increases, the thermal insulation capacity gradually decreases and its decline rate gradually weakens; and the convective heat transfer coefficient between the roadway wall and airflow has almost no effect on the thermal insulation capacity. (3) The thermal insulation performance of the thermal insulation roadway is highly sensitive or above the thickness and thermal conductivity of the thermal insulation layer, as well as the roadway radius. The sensitivity of thickness and thermal conductivity of the thermal insulation layer is greater than that of roadway radius. Therefore, the research results have guiding significance for the application of thermal insulation methods in the prevention and control of thermal hazards in mines.

Keywords: high-temperature mine; thermal insulation roadway; steady heat transfer; temperature distribution; thermal insulation characteristics; sensibility analysis

1. Introduction

With the continuous mining and use of coal in China, shallow coal resources gradually tend to be exhausted, and mining continues to move toward the deep parts of the earth [1]. With the continuous increase in mining depth, the original rock temperature continues to rise, and the mining face presents a high-temperature working environment. This not only endangers the physical and mental health of workers, reduces labor productivity [2], but also induces gas accidents [3], seriously threatening the safety and efficiency of deep mining [4]. Therefore, there is an urgent need to prevent and control high-temperature heat hazards in mines to improve working conditions and mining productivity and ensure safe mines [5]. The global methods to prevent and control mine heat hazards include...
artificial and non-artificial cooling [6,7]. Artificial cooling refers to using a compressor or ice maker for cooling. Although a certain cooling effect has been achieved, the refrigeration unit is expensive, with large power consumption and high operation and maintenance costs [8]. Many factors cause thermal hazards in mines, among which the heat dissipation of the high-temperature surrounding rock is the primary heat source that considerably increases the temperature of the mine airflow [9,10]. The roadway thermal insulation cooling method in non-artificial cooling can isolate heat dissipation from high-temperature rock strata, and reduce the mine cooling demand, thereby reducing the cooling system power consumption [11]. Therefore, studying the thermal insulation technology of high-temperature roadway surrounding rock is significant for controlling the thermal environment of deep mines.

To study roadway thermal insulation and cooling technology, Xiao et al. [12] analyzed the heat insulation principle of nanoporous superheat insulation materials and obtained through application tests that when the heat source temperature is 200 °C, the surface temperature of the coating without aerogel thermal insulation material is 100 °C, and the thermal insulation temperature difference is 100 °C, while when the surface temperature of the coating with aerogel thermal insulation material is only 60 °C, the thermal insulation temperature difference is 140 °C. This confirms that the nanoporous superinsulation material has good insulation performance and can effectively eliminate the increase in heat transfer inside the coating. Hou et al. [13] prepared mineral insulation materials using basalt fiber, glass fiber, and vitrified microbeads as the main raw materials. Through experimental comparison, it was found that samples of thermal insulation materials containing basalt fiber had good thermal insulation effects and achieved the required compressive strength. In addition, insulation material samples containing basalt fiber had a better thermal insulation effect than ordinary concrete materials. Liu et al. [14] studied the effect of different cotton stalk fiber contents on heat insulation concrete and found that as the cotton stalk fiber content increased, the thermal conductivity of shotcrete gradually decreased. When the cotton stalk fiber content was 2 kg/m³, the shotcrete compressive and split tensile properties were excellent, and the strength reached its maximum value, meeting the thermal insulation and strength requirements of shotcrete in the high-temperature roadway.

Huang et al. [15] obtained through an orthogonal test that the composition combination with good mechanical and thermal insulation properties of shotcrete is 5% of the mass of coarse aggregate was replaced by ceramsite, 10% of the mass of fine aggregate was replaced by pottery sand, the content of basalt fiber was 0.15 vol.% of the concrete, and the content of plant fiber was 0.2 vol.% of the concrete. Wang et al. [16] developed a fly ash inorganic mineral thermal insulation shotcrete material using cement, sand, fly ash, and vitrified microbeads and analyzed their thermal insulation performance and the temperature distribution characteristics of the surrounding rock of the thermal insulation roadway. The results indicated that the thermal insulation gunite layer has an impact on the heat dissipation of the surrounding rock, the stability of the surrounding rock temperature field, the initial temperature disturbance time, the temperature disturbance range, and the rate of temperature decrease. Liu et al. [17] predicted and confirmed the effectiveness of the underground insulation layer by using finite-length models and equivalent overall heat transfer coefficient methods. The results showed that the slab models can achieve an average heat flow reduction of over 14.0%, and a reduction of 28.5% can be achieved for a cylindrical model roadway with a diameter of 2 m. Yao et al. [18] used numerical simulation method to discuss the influence of different thermophysical parameters on the temperature field of surrounding rock in insulated tunnels. The results showed that the thermal conductivities of the grouting layer and the spraying layer decrease, the grouting layer area expands, and the spraying layer thickness increases, which can effectively reduce the heat-adjusting zone radius and roadway wall temperature. The thermal conductivity of spraying and grouting materials is the main factor affecting the temperature field distribution, while the range of the grouting layer area and the thickness of the spraying layer are secondary factors. The influence of the radial depth of surrounding rock and ventilation time can be
ignored. Wang and Zhou [19] studied the heat control mechanism of the thermal insulation of deep roadways through experiments and finite element methods. The results showed that the insulation layer greatly reduced the rock wall temperature and the disturbance range of the surrounding rock temperature; The smaller the thermal conductivity of the thermal insulation layer, the greater the decrease in roadway wall temperature and the greater the rate of change of its decrease curve. Zhang et al. [20] used numerical simulation method to simulate and analyze the temperature field of the thermal insulation supporting roadway. The results showed that the temperature field of the heat insulation support structure does change significantly, but it has the effect of weakening the convective heat transfer between the surrounding rock wall and the airflow. From the research results of the above literature, it can be seen that the research on the heat transfer model of the surrounding rock of thermal insulation roadway and the analysis of their thermal insulation characteristics have guiding significance for the application of thermal insulation methods to improve the high-temperature environment of the roadway. However, the above research on roadway heat insulation and cooling technology has mainly focused on the research and development of heat insulation materials. Only some analyses have investigated the heat insulation characteristics of the heat insulation roadway based on the heat transfer law of the heat insulation structure-surrounding rock and the influence law of different physical quantities on the heat insulation effect.

This paper assumes that after a long period of ventilation in the thermal insulation roadway, the surrounding rock of the thermal insulation roadway and airflow have undergone sufficient heat exchange, and the temperature field of the surrounding rock heat-regulating circle has reached a relatively stable state. Using a steady heat transfer approach, the influence of the thermal insulation layer on the heat dissipation process of the surrounding rock and the influence of various factors on the thermal insulation performance of the thermal insulation roadway are studied. This study aims to (1) establish a one-dimensional steady-state heat transfer mathematical model of surrounding rock of thermal insulation roadway; (2) study the temperature distribution law of surrounding rock of thermal insulation roadway; (3) discuss the influence of the thermal insulation layer thickness, thermal conductivity of the thermal insulation layer, convective heat transfer coefficient between the roadway wall and airflow, and roadway radius on the thermal insulation performance; and (4) analyze the sensitivity of the thermal insulation performance of the thermal insulation layer to various influencing factors. The research reveals the internal reasons for the thermal insulation layer to block the heat dissipation of the surrounding rock and helps understand factors affecting the thermal insulation layer performance.

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The organization of this paper is as follows: Section 2 establishes a one-dimensional steady-state heat transfer physical and mathematical model of roadway thermal insulation structure-surrounding rock, and gives the initial calculation conditions. The research results and discussion are presented in Sections 3 and 4. Finally, Section 5 makes a summary conclusion.

2. Modeling


Figure 1 shows a physical model of heat transfer between the surrounding rock and airflow in the thermal insulation roadway. After excavating the roadway in the rock mass, the airflow flows through the roadway wall and is in direct contact to generate convection heat transfer. Due to the temperature difference between the rock mass and airflow, the roadway radial direction occurs from deep to shallow heat movement, and the temperature of the surrounding rock and the airflow changes. This thermal migration includes thermal convection of airflow passing through the roadway wall, and thermal conduction between the surrounding rock, thermal insulation layer, and shotcrete layer. The following assumptions were proposed for the heat dissipation process of the thermal insulation roadway to facilitate theoretical analysis and calculation:

(1) The roadway cross-sectional shape is round, and the roadway surface is dry.
(2) The heat flow direction in the thermal insulation roadway is radial, and heat radiation is not considered.
(3) The contact thermal resistances between the surrounding rock and thermal insulation layer and between thermal insulation and shotcrete layers are ignored.
(4) The surrounding rock, thermal insulation layer, and shotcrete layer of the roadway are isotropic, homogeneous, stable solids with thermophysical properties.
(5) The heat exchange situation is consistent on the roadway surface circumference, and the air temperature on the same cross-section is uniform.

Figure 1. The physical model for heat dissipation in thermal insulation roadway. Note: \( q \) is the heat flux.

This paper will select the circular thermal insulation roadway as a research object, and the heat dissipation process is shown in Figure 2. According to the established physical model of heat dissipation in thermal insulation roadway, a heat transfer model between the surrounding rock and airflow of the thermal insulation roadway is established, and the heat transfer process between the surrounding rock and airflow is theoretically analyzed. The purpose of this paper is to investigate the temperature distribution characteristics of surrounding rock of thermal insulation roadway, as well as the influence of thermal insulation layer thickness, the thermal conductivity of the thermal insulation layer, convective heat transfer coefficient between roadway wall and airflow, roadway radius and other factors on the thermal insulation performance of thermal insulation layer. Based on the actual production conditions of the mine and the range of commonly used material thermophysical parameters, this paper sets the thermophysical parameters of the thermal insulation layer, shotcrete layer, and surrounding rock, as shown in Table 1.

Figure 2. Schematic diagram of heat dissipation in thermal insulation roadway: (a) cross-section and (b) profile. Note: \( q \) is the heat flux. \( T_i, T_b, T_p, T_r, \) and \( T_y \) are, respectively, the temperature of airflow, roadway wall, original rock, the contact surface between the thermal insulation layer and surrounding rock, and the contact surface between the thermal insulation and shotcrete layers. \( r_0 \) is
the roadway radius. \( r_p, r_r, \) and \( r_y \) are, respectively, the distance between the contact surface of the thermal insulation and shotcrete layers and the center of the roadway, between the contact surface of the thermal insulation layer and surrounding rock and the center of the roadway, and from the original rock temperature boundary line to the roadway center.

<table>
<thead>
<tr>
<th>Name</th>
<th>Density (kg·m(^{-3}))</th>
<th>Thermal Conductivity (W·m(^{-1})·°C(^{-1}))</th>
<th>Specific Heat Capacity (J·kg(^{-1})·°C(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shotcrete layer</td>
<td>2400</td>
<td>1.500</td>
<td>1000</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>140</td>
<td>0.045</td>
<td>1200</td>
</tr>
<tr>
<td>Surrounded rock</td>
<td>2346</td>
<td>2.415</td>
<td>896</td>
</tr>
</tbody>
</table>

Table 1. Thermophysical parameters of the study object.

Figure 3 shows a physical model of heat transfer between the surrounding rock of the roadway without thermal insulation structure and the airflow. The conditions for the heat dissipation process of the surrounding rock of the roadway are the same as the assumptions proposed for the heat dissipation process of the surrounding rock of the thermal insulation roadway.

![Figure 3](image1.png)

Figure 3. The physical model for heat dissipation of surrounding rock of roadway without thermal insulation structure. Note: \( q \) is the heat flux.

The heat dissipation process of circular roadways without thermal insulation structure is shown in Figure 4. The thermal physical parameters of the surrounding rock are shown in Table 1.

![Figure 4](image2.png)

Figure 4. Schematic diagram of heat dissipation in roadways without thermal insulation structure: (a) cross-section and (b) profile. Note: \( q \) is the heat flux. \( T_i, T_w, \) and \( T_y \) are the temperature of airflow, roadway wall, and original rock, respectively. \( r_y \) is the roadway radius. \( r_y \) is the distance from the original rock temperature boundary line to the roadway center.


Before roadway excavation in the underground rock mass, the original rock temperature remains unchanged, and the temperature at each point is in thermal equilibrium.
However, at the moment of roadway ventilation, due to the difference between the original rock mass temperature and airflow temperature, the thermal balance of the rock mass is disturbed. The airflow in the roadway undergoes thermal convection with the roadway wall, while the interior of the roadway surrounding rock dissipates heat from the radial depth of the surrounding rock to the shallow part through thermal conduction. As the airflow flow time passes, the temperature of the surrounding rock continues to decrease, and the range of the surrounding rock cooled by the airflow continues to extend radially deep until the temperature of the surrounding rock at a certain depth is almost unaffected by the airflow temperature. The range of the distance between the original rock temperature boundary and the roadway wall that is unaffected by the ventilation temperature is called the temperature regulation sphere. The distance from the roadway center to the original rock temperature boundary of the temperature regulation sphere is called the radius of the temperature regulation sphere. The radius of the temperature regulation sphere increases with the ventilation process but gradually slows with increasing ventilation time. After sufficient ventilation time, under the condition of constant ventilation temperature, the heat dissipation from the surrounding rock towards the airflow will be in a relatively stable state, and the temperature regulation sphere is stable. At this time, the heat dissipation of the surrounding rock can be regarded as steady heat transfer.

2.2.1. Control Equation for Heat Transfer in Surrounding Rock

According to the conservation law of energy and the Fourier law, the one-dimensional governing equation of steady heat transfer inside the surrounding rock of a circular roadway is established.

\[
\frac{d^2 T}{dr^2} + \frac{1}{r} \frac{dT}{dr} = 0 \quad (1)
\]

where \( T \) is the surrounding rock temperature, °C, and \( r \) is the depth of each point inside the surrounding rock from the center of the roadway, m.

The thermal boundary conditions are expressed as:

\[
\begin{align*}
T &= T_w, \quad r = r_0 \\
T &= T_y, \quad r = r_y
\end{align*}
\]

where \( T_w \) and \( T_y \) are the roadway wall and original rock temperatures, respectively, °C; \( r_0 \) is the circular roadway radius, m; and \( r_y \) is the depth of the original rock temperature boundary line from the center of the roadway, m.

By integrating Equation (1) twice and substituting the boundary conditions in Equation (2), the temperature calculation results of various points inside the surrounding rock are as follows:

\[
T = T_w - (T_w - T_y) \frac{\ln(r/r_0)}{\ln(r_y/r_0)} \quad (3)
\]

The derivative of Equation (3) on \( r \) gives:

\[
\frac{dT}{dr} = \frac{T_y - T_w}{r \ln(r_y/r_0)} \quad (4)
\]

Substituting Equation (4) into the heat flow density equation of the surrounding rock in direction \( r \) can obtain:

\[
q_1 = \frac{\lambda_w (T_y - T_w)}{r \ln(r_y/r_0)} \quad (5)
\]

where \( q_1 \) is the heat flux density inside the surrounding rock, W/m²; and \( \lambda_w \) is the thermal conductivity of the surrounding rock, W/(m·°C).

The heat flux density \( q_2 \) when the airflow flows through the roadway wall is:

\[
q_2 = \alpha_1 (T_w - T_i) \quad (6)
\]
where $\alpha_1$ is the convective heat transfer coefficient between the roadway wall and airflow, $W/(m^2 \cdot ^\circ C)$, and $T_i$ is the airflow temperature, $^\circ C$.

At the roadway wall, $q_1 = q_2$:

$$\frac{\lambda_w(T_y - T_w)}{r_0 \ln(r_y/r_0)} = a_1(T_w - T_i) \quad (7)$$

According to Equation (7), the roadway wall temperature is as follows:

$$T_w = \frac{a_1 r_0 \ln(r_y/r_0) T_i + \lambda_w T_y}{a_1 r_0 \ln(r_y/r_0) + \lambda_w} \quad (8)$$

### 2.2.2. Mathematical Model of Heat Transfer of Thermal Insulation Roadway

Under the condition of steady heat transfer of thermal insulation roadway, the heat flux density at the interface between the thermal insulation layer and surrounding rock is equal.

$$\frac{\lambda_w}{r_g} \frac{dT_1}{dr} = \frac{\lambda_g}{r_g} \frac{dT_2}{dr} \quad (9)$$

where $\lambda_g$ is the thermal conductivity of the thermal insulation layer, $W/(m \cdot ^\circ C)$; and $T_1$ and $T_2$ are the temperatures of the surrounding rock and thermal insulation layer, respectively, $^\circ C$.

Then, using Equation (5) expression, there are:

$$\frac{\lambda_w(T_y - T_g)}{r_g \ln(r_y/r_g)} = \frac{\lambda_g(T_g - T_p)}{r_g \ln(r_g/r_p)} \quad (10)$$

where $T_g$ is the temperature at the interface between the thermal insulation layer and surrounding rock, $^\circ C$; $T_p$ is the temperature at the interface between the thermal insulation and shotcrete layers, $^\circ C$; $r_p$ is the distance between the contact surface of the thermal insulation and shotcrete layers and the center of the roadway, m; $r_g$ is the distance between the contact surface of the thermal insulation layer and surrounding rock and the center of the roadway.

Under the condition of steady heat transfer of thermal insulation roadway, the heat flux density at the interface between the thermal insulation and shotcrete layers is equal.

$$\frac{\lambda_g}{r_p} \frac{dT_2}{dr} = \frac{\lambda_p}{r_p} \frac{dT_3}{dr} \quad (11)$$

where $T_3$ is the temperature of the shotcrete layer, $^\circ C$.

Then, using Equation (5) expression, there are:

$$\frac{\lambda_g(T_g - T_p)}{r_p \ln(r_g/r_p)} = \frac{\lambda_p(T_p - T_b)}{r_p \ln(r_p/r_0)} \quad (12)$$

where $\lambda_p$ is the thermal conductivity of the shotcrete layer, $W/(m \cdot ^\circ C)$; and $T_b$ is the wall temperature of the thermal insulation roadway, $^\circ C$.

At the wall of the thermal insulation roadway:

$$\lambda_p \frac{dT_3}{dr} = \alpha_2(T_b - T_i) \quad (13)$$

According to Equation (13), the wall temperature of the thermal insulation roadway is as follows:

$$T_b = \frac{a_2 r_0 \ln(r_p/r_0) T_i + \lambda_p T_p}{a_2 r_0 \ln(r_p/r_0) + \lambda_p} \quad (14)$$
Solving Equations (10) and (12) to obtain the temperature at the interface between the thermal insulation layer and surrounding rock, and the temperature at the interface between the thermal insulation layer and shotcrete layer.

\[
T_g = \frac{AT_p + BT_y}{A + B}
\]  

\[
T_p = \frac{BT_y + (A + B)CT_f}{B + (A + B)C}
\]  

where

\[
A = \lambda_g / [r_g \ln(r_g/r_p)]; B = \lambda_w / [r_y \ln(r_y/r_g)]; C = \frac{a_2\lambda_p / [r_p \ln(r_p/r_0)]}{\lambda_g[a_2 + \lambda_p / [r_0 \ln(r_p/r_0)]] / [r_p \ln(r_g/r_p)]}
\]

3. Analysis of Influencing Factors on the Thermal Insulation Performance of Roadway

3.1. Temperature Distribution of Surrounding Rock of Roadway with Thermal Insulation Layer

Based on the actual production conditions of the mine, this paper sets the airflow temperature in a section of the roadway is 20 °C, the original rock temperature is 40 °C, the thermal conductivity of the surrounding rock, shotcrete layer, and thermal insulation layer is 2.145 W/(m·°C), 1.500 W/(m·°C), and 0.045 W/(m·°C), respectively, the convective heat transfer coefficient between the roadway wall and the airflow is 10.3 W/(m²·°C), the radius of the round roadway is 2 m, and the thickness of the thermal insulation and shotcrete layers is 0.05 m and 0.10 m, respectively, the temperature distribution of surrounding rock of roadway with thermal insulation layer is analyzed.

Figure 5 shows the variation curves of the temperature of the shotcrete layer, thermal insulation layer, and surrounding rock with distance from the center of the roadway under two conditions: the roadway without a thermal insulation layer and the roadway with a thermal insulation layer. It indicates that the temperature of the shotcrete layer, thermal insulation layer, and surrounding rock of the roadway with thermal insulation layer increases with increasing distance from the center of the roadway. The temperature of the contact surface (the inner surface of the thermal insulation layer 2.10 m away from the center of the roadway) between the thermal insulation layer and the shotcrete layer is 20.85 °C, and the temperature of the contact surface (the outside surface of the thermal insulation layer 2.15 m away from the center of the roadway) between the thermal insulation layer and the surrounding rock of the roadway is 26.33 °C. The temperature of the inner and outside surfaces of the thermal insulation layer suddenly changed, and the temperature increased by 5.48 °C from the inner surface to the outside surface, an increase of 26.3%. Similarly, in the absence of the thermal insulation layer in the roadway, the temperature of the surrounding rock in the roadway increases as the distance from the center of the roadway increases. However, the temperature of the surrounding rock from 2.10 m to 2.15 m from the center of the roadway increases from 21.00 °C to 21.42 °C, an increase of 0.42 °C, only an increase of 2.0%. Compare the temperature of surrounding rock in roadways with and without a thermal insulation layer, the temperature on the inner surface of the thermal insulation layer is 0.15 °C lower than the temperature of surrounding rock at a radial depth of 2.10 m in roadways without a thermal insulation layer, and the temperature on the outside surface of the thermal insulation layer is 4.91 °C higher than the temperature of surrounding rock at a radial depth of 2.15 m in roadways without thermal insulation layer. The temperature gradient inside the thermal insulation layer is much greater than that inside the surrounding rock. In addition, the temperature of the roadway wall with a thermal insulation layer is lower than that without a thermal insulation layer. These phenomena are mainly due to the fact that the thermal conductivity of the thermal insulation layer is much smaller than that of the surrounding rock. The thermal insulation layer hinders the heat transfer of the surrounding rock, increases the temperature at the interface between the thermal insulation layer and the surrounding rock, and thus reduces
the temperature difference between the original rock temperature and the outside surface of the thermal insulation layer, and reduces the heat dissipation of the surrounding rock, thereby achieving thermal insulation effects.

![Figure 5](image)

**Figure 5.** Temperature distribution of surrounding rock of roadway with and without thermal insulation layer.

### 3.2. The Influence of Thermal Insulation Layer Thickness on the Thermal Insulation Performance of Roadway

Under the same calculation conditions as Section 3.1, this section analyzes the thermal insulation performance of the roadway thermal insulation layer with thicknesses of 0.05 m, 0.10 m, and 0.15 m, respectively.

Figure 6 shows the temperature distribution of the shotcrete layer, thermal insulation layer, and surrounding rock under different thermal insulation layer thicknesses. With increasing the thickness of the thermal insulation layer, the temperature of the contact surface between the thermal insulation layer and the surrounding rock of the roadway (outside surface of the thermal insulation layer) increases, while the temperature of the contact surface between the thermal insulation layer and the shotcrete layer (inner surface of the thermal insulation layer) and the temperature of the roadway wall decrease. This indicates that increasing the thickness of the thermal insulation layer can enhance the thermal insulation effect of the thermal insulation layer on surrounding rock heat dissipation.

![Figure 6](image)

**Figure 6.** Temperature distribution of shotcrete layer, thermal insulation layer, and surrounding rock under different thermal insulation layer thicknesses.
Figure 7 shows the temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the thickness of the thermal insulation layer. When the thermal insulation layer thickness increases from 0.15 m to 0.50 m, the outside surface temperature of the thermal insulation layer increases from 31.14 °C to 35.95 °C, an increase of 4.81 °C. A similar increase in temperature is observed when increasing the thermal insulation layer thickness from 0.05 m to 0.15 m; the temperature increases from 26.33 °C to 31.14 °C. When the thickness of the thermal insulation layer increases from 0.15 m to 0.50 m, the temperature of the inner surface of the thermal insulation layer decreases from 20.56 °C to 20.27 °C, a decrease of 0.29 °C. A similar decrease in temperature is observed when increasing the thermal insulation layer thickness from 0.05 m to 0.15 m; the temperature decreases from 20.85 °C to 20.56 °C. It indicates that as the thickness of the thermal insulation layer increases, the outside surface temperature of the thermal insulation layer increases, while the inner surface temperature of the thermal insulation layer decreases. The temperature difference between the inner and outside surfaces of the thermal insulation layer increases, and the thermal insulation ability of the thermal insulation layer to dissipate heat from the surrounding rock increases. However, the increase in the outside surface temperature of the thermal insulation layer and the decrease in the inner surface temperature of the thermal insulation layer both slow down gradually and trend to be flat.

![Figure 7. Temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the thickness of the thermal insulation layer.](image)

Figure 8 shows the trend of temperature difference between the inner and outside surfaces of the thermal insulation layer with the thickness of the thermal insulation layer. The thickness of the thermal insulation layer increases from 0.05 m to 0.25 m, and the temperature difference between the inner and outside surfaces of the thermal insulation layer increases from 5.48 °C to 13.00 °C, an increase of 7.52 °C. The thickness of the thermal insulation layer increases from 0.25 m to 0.45 m, also increasing by 0.20 m. The temperature difference between the inner and outside surfaces of the thermal insulation layer increases from 13.00 °C to 15.33 °C, an increase of 2.33 °C. It indicates that as the thickness of the thermal insulation layer increases, the rate of increase in the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually slows down and tends to be flat, and the increase in the thermal insulation ability of the thermal insulation layer to dissipate heat from the surrounding rock gradually weakens.
Figure 8. Trend of temperature difference between the inner and outside surfaces of the thermal insulation layer with the thickness of the thermal insulation layer.

3.3. The Influence of Thermal Conductivity of Thermal Insulation Layer on the Thermal Insulation Performance of Roadway

Under the same calculation conditions as Section 3.1, this section analyzes the thermal insulation performance of the roadway thermal insulation layer with thermal conductivities of 0.045 W/(m·°C), 0.125 W/(m·°C), 0.205 W/(m·°C), 0.285 W/(m·°C), and 0.365 W/(m·°C), respectively.

Figure 9 shows temperature changes of the shotcrete layer, thermal insulation layer, and surrounding rock with distance from the roadway center under different thermal conductivities of the thermal insulation layer. The results show that the outside surface temperature of the thermal insulation layer decreases with increasing thermal conductivity of the thermal insulation layer, whereas the temperature of the inner surface of the thermal insulation layer and roadway wall increases. The results show that increasing the thermal conductivity of the thermal insulation layer weakens the thermal insulation effect of the thermal insulation layer on the surrounding rock.

Figure 9. Temperature distribution of shotcrete layer, thermal insulation layer, and surrounding rock under different thermal conductivity of thermal insulation layer.
Figure 10 shows the temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the thermal conductivity of the thermal insulation layer. It can be seen from the figure that when the thermal conductivity of the thermal insulation layer increases by 0.160 W/(m·°C) from 0.045 W/(m·°C) to 0.205 W/(m·°C), the outside surface temperature of the thermal insulation layer decreases from 26.33 °C to 22.61 °C, a decrease of 3.72 °C, and the inner surface temperature increases from 20.65 °C to 21.08 °C, an increase of 0.43 °C. When the thermal conductivity of the thermal insulation layer increases by 0.160 W/(m·°C) from 0.205 W/(m·°C) to 0.365 W/(m·°C), the outside surface temperature of the thermal insulation layer decreases from 22.61 °C to 22.01 °C, only decreasing by 0.60 °C, and the inner surface temperature increases from 21.08 °C to 21.12 °C, only increasing by 0.04 °C. Data analysis shows that as the thermal conductivity of the thermal insulation layer increases, the outside surface temperature of the thermal insulation layer decreases, while the inner surface temperature of the thermal insulation layer increases. The temperature difference between the inner and outside surfaces of the thermal insulation layer decreases, and the thermal insulation ability of the thermal insulation layer to dissipate heat from the surrounding rock decreases. The decrease in the outside surface temperature of the thermal insulation layer and the increase in the inner surface temperature of the thermal insulation layer both slow down gradually and trend to be flat.

![Temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the thermal conductivity of the thermal insulation layer.](image)

**Figure 10.** Temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the thermal conductivity of the thermal insulation layer.

Figure 11 shows the trend of temperature difference between the inner and outside surfaces of the thermal insulation layer with the thermal conductivity of the thermal insulation layer. The thermal conductivity of the thermal insulation layer increases from 0.045 W/(m·°C) to 0.205 W/(m·°C), and the temperature difference between the inner and outside surfaces of the thermal insulation layer decreases from 5.48 °C to 1.53 °C, a decrease of 3.95 °C; The thermal conductivity of the thermal insulation layer increases by 0.160 W/(m·°C) from 0.205 W/(m·°C) to 0.365 W/(m·°C), while the temperature difference between the inner and outside surfaces of the thermal insulation layer decreases from 1.53 °C to 0.89 °C, only decreasing by 0.64 °C. The results indicate that as the thermal conductivity of the thermal insulation layer increases, the rate of decrease in the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually slows down and tends to be flat, and the decrease in the thermal insulation ability of the thermal insulation layer to dissipate heat from the surrounding rock gradually weakens.
3.4. The Influence of Convective Thermal Transfer Coefficient between Roadway Wall and Airflow on the Thermal Insulation Performance of Roadway

Under the same calculation conditions as Section 3.1, this section analyzes the thermal insulation performance of the roadway thermal insulation layer with convective heat transfer coefficients between roadway wall and airflow of 4.3 W/(m²·°C), 8.3 W/(m²·°C), 12.3 W/(m²·°C), 16.3 W/(m²·°C), and 20.3 W/(m²·°C), respectively.

Figure 12 shows temperature changes of the shotcrete layer, thermal insulation layer, and surrounding rock with distance from the roadway center under different convective heat transfer coefficients between the roadway wall and airflow. As the convective heat transfer coefficient between the roadway wall and the airflow increases, both the inner and outside surface temperatures of the thermal insulation layer and the roadway wall temperature decrease.

Figure 12. Temperature distribution of shotcrete layer, thermal insulation layer, and surrounding rock under different convective heat transfer coefficients between roadway wall and airflow.
Figure 13 shows the temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the convective heat transfer coefficient between the roadway wall and the airflow. When the convective heat transfer coefficient between the roadway wall and airflow increases from 4.3 W/(m²·°C) to 8.3 W/(m²·°C), the outside surface temperature of the thermal insulation layer decreases from 26.80 °C to 26.42 °C, a decrease of 0.38 °C, and the inner surface temperature decreases from 21.51 °C to 20.97 °C, a decrease of 0.54 °C. However, when the convective heat transfer coefficient between the roadway wall and airflow increases from 8.3 W/(m²·°C) to 20.3 W/(m²·°C), the outside surface temperature of the thermal insulation layer decreases from 26.42 °C to 26.16 °C, only decreasing by 0.26 °C, and the inner surface temperature decreases from 20.97 °C to 20.61 °C, only decreasing by 0.36 °C. The results indicate that as the convective heat transfer coefficient between the roadway wall and the airflow increases, the temperature of the inner and outside surfaces of the thermal insulation layer decreases, and the decrease in temperature of the inner and outside surfaces of the thermal insulation layer slows down gradually and tends to be flat.

![Temperature variation curve](image)

**Figure 13.** Temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the convective heat transfer coefficient between the roadway wall and airflow.

Figure 14 shows the trend of temperature difference between the inner and outside surfaces of the thermal insulation layer with the convective heat transfer coefficient between the roadway wall and airflow. The convective heat transfer coefficient between the roadway wall and airflow increases from 4.3 W/(m²·°C) to 12.3 W/(m²·°C), and the temperature difference between the inner and outside surfaces of the thermal insulation layer increases from 5.30 °C to 5.51 °C, an increase of 0.21 °C. The convective heat transfer coefficient between the roadway wall and airflow increases by 8.0 W/(m²·°C) from 12.3 W/(m²·°C) to 20.3 W/(m²·°C), while the temperature difference between the inner and outside surfaces of the thermal insulation layer increases from 5.51 °C to 5.55 °C, only increasing by 0.04 °C. It indicates that as the convective heat transfer coefficient between the roadway wall and the airflow increases, the temperature difference between the inner and outside surfaces of the thermal insulation layer increases, but its rate of increase is very small. When the convective heat transfer coefficient between the roadway wall and the airflow increases to a certain value, the temperature difference between the inner and outside surfaces of the thermal insulation layer remains almost unchanged. The change in the convective heat transfer coefficient between the roadway wall and the airflow has almost no effect on the thermal insulation ability of the thermal insulation layer.
3.5. The Influence of Equivalent Radius of Roadway on the Thermal Insulation Performance of Roadway

Under the same calculation conditions as Section 3.1, this section analyzes the thermal insulation performance of the roadway thermal insulation layer with equivalent radii of the roadway of 1.5, 2.0, and 2.5 m, respectively.

Figure 15 shows temperature changes of the shotcrete layer, thermal insulation layer, and surrounding rock with distance from the roadway center under different roadway radii. As the roadway radius increases, both the inner and outside surface temperatures of the thermal insulation layer and the roadway wall temperature decrease.

Figure 14. Trend of temperature difference between the inner and outside surfaces of the thermal insulation layer with the convective heat transfer coefficient between the roadway wall and airflow.

Figure 15. Temperature distribution of shotcrete layer, thermal insulation layer, and surrounding rock under different roadway radii.
Figure 16 shows the temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the roadway radius. When the roadway radius increases from 1.5 m to 2.5 m, the outside surface temperature of the thermal insulation layer decreases from 27.18 °C to 25.73 °C, a decrease of 1.45 °C, and the inner surface temperature decreases from 20.98 to 20.76 °C, only decreasing by 0.22 °C. When the roadway radius increases from 2.5 m to 3.5 m, the outside surface temperature decreases from 25.73 °C to 24.91 °C, a decrease of 0.82 °C, and the inner surface temperature decreases from 20.76 °C to 20.65 °C, only decreasing by 0.11 °C. The comparative analysis shows that as the roadway radius increases, the temperature of the inner and outside surfaces of the thermal insulation layer decreases, and the decrease in temperature of the inner and outside surfaces of the thermal insulation layer slows down gradually. However, the decrease in temperature on the inner surface of the thermal insulation layer is smaller than that on the outside surface of the thermal insulation layer, and it tends to be flat. The thermal insulation ability of the thermal insulation layer to dissipate heat from the surrounding rock gradually decreases. Figure 16. Temperature variation curve of the inner and outside surfaces of the thermal insulation layer with the roadway radius.

Figure 17 shows the trend of temperature difference between the inner and outside surfaces of the thermal insulation layer with the roadway radius. The roadway radius increases from 1.5 m to 2.5 m, and the temperature difference between the inner and outside surfaces of the thermal insulation layer decreases from 6.20 °C to 4.97 °C, a decrease of 1.23 °C. The roadway radius increases by 1 m from 2.5 m to 3.5 m, while the temperature difference between the inner and outside surfaces of the thermal insulation layer decreases from 4.97 °C to 4.27 °C, a decrease of 0.70 °C. It indicates that as the roadway radius increases, the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually decreases, and its rate of decrease gradually slows down. The decrease in the thermal insulation ability of the thermal insulation layer to dissipate heat from the surrounding rock gradually weakens.
Figure 17. Trend of temperature difference between the inner and outside surfaces of the thermal insulation layer with the roadway radius.

4. Sensitivity Analysis of Different Factors on the Thermal Insulation Performance of Thermal Insulation Layers

4.1. Sensitivity Analysis Method

Sensitivity analysis is a method of quantitatively describing the degree to which changes in various influencing factors of a system affect its characteristics. Assuming that the thermal insulation performance of the roadway’s thermal insulation layer on the heat dissipation of surrounding rock is influenced by factors such as the thickness of the thermal insulation layer, the thermal conductivity of the thermal insulation layer, the convective heat transfer coefficient between the roadway wall and the airflow, and the roadway radius, it can be expressed as:

\[ p = f(x_1, x_2, \ldots, x_n) \]  \hspace{1cm} (17)

Given a set of benchmark values based on the actual production characteristics of the mine.

\[ p^* = f(x^*_1, x^*_2, \ldots, x^*_n) \]  \hspace{1cm} (18)

Make the influencing factor \( x_j \) change within its value range, while other influencing factors take the benchmark values and remain unchanged.

\[ p = f(x^*_1, x^*_2, x_j, \ldots, x^*_n) = \varphi_j(x_j) \]  \hspace{1cm} (19)

Thus, the sensitivity of the thermal insulation performance of the thermal insulation layer to individual influencing factors \( x_j \) can be analyzed by fitting the rate of change of curve \( p = \varphi_j(x_j) \).

In order to compare the sensitivity of the thermal insulation performance of the thermal insulation layer to changes in different dimensional influencing factors, the thermal insulation performance of the thermal insulation layer is described by the temperature difference between the inner and outside surfaces of the thermal insulation layer.

Introducing a dimensionless sensitivity function:

\[ S_i(x_i) = \frac{|\Delta p|}{p} \left( \frac{|\Delta x_i|}{x_i} \right) = \frac{\Delta p}{\Delta x_i} \left| \frac{x_i}{p} \right| \]  \hspace{1cm} (20)

where \( \frac{|\Delta p|}{p} \) is the relative error of the temperature difference between the inner and outside surfaces of the thermal insulation layer; \( \frac{|\Delta x_i|}{x_i} \) is the relative error of the influencing factor \( x_i \).
When the value of \( \frac{\Delta p}{p} \) is small, there is a sensitivity function:

\[
S_i(x_i) = \left| \frac{d \phi_i(x_i)}{dx_i} \right| \frac{x_i}{p}
\]  

(21)

Substituting \( x_i = x_i^* \) into Equation (21) to obtain the sensitivity factor value of influencing factor \( x_i \):

\[
S_i(x_i^*) = \left| \frac{d \phi_i(x_i)}{dx_i} \right| \frac{x_i^*}{p^*}
\]  

(22)

The sensitivity factor can be calculated according to Equation (22), and the sensitivity of the thermal insulation performance of the thermal insulation layer to changes in different dimensional parameters can be compared based on the sensitivity factor value. The higher the sensitivity factor value of the influencing factor, the higher the sensitivity of the thermal insulation performance of the thermal insulation layer to the changes in the influencing factor. According to the absolute value of the sensitivity factor, the sensitivity level is divided into when \( |S_i(x_i^*)| \geq 1 \), it indicates that the sensitivity is very high; when \( 0.2 \leq |S_i(x_i^*)| < 1 \), it is highly sensitive; when \( 0.05 \leq |S_i(x_i^*)| < 0.2 \), it belongs to moderate sensitivity; and when \( |S_i(x_i^*)| < 0.05 \), the sensitivity can be ignored.

4.2. Sensitivity Analysis

Sensitivity analysis is conducted on the thickness of the thermal insulation layer, the thermal conductivity of the thermal insulation layer, the convective heat transfer coefficient between the roadway wall and airflow, and roadway radius, where \( p = \Delta t = f(\delta, \lambda, a, r) \). The variation ranges of thickness \( \delta \) of the thermal insulation layer, thermal conductivity \( \lambda \) of the thermal insulation layer, convective heat transfer coefficient \( a \) between roadway wall and airflow, and roadway radius \( r \) are 0.05–0.25 m, 0.045–0.205 W/(m·°C), 4.3–12.3 W/(m²·°C), and 1.5–3.5 m, respectively. The benchmark values are: \( \delta^* = 0.15 \) m, \( \lambda^* = 0.125 \) W/(m·°C), \( a^* = 8.3 \) W/(m²·°C), \( r^* = 2.5 \) m. Table 2 provides the selected benchmark values and range of influencing factors for sensitivity analysis of the thermal insulation performance of the thermal insulation layer.

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>Thickness of Thermal Insulation Layer, (m)</th>
<th>Thermal Conductivity of Thermal Insulation Layer, (W m⁻¹ C⁻¹)</th>
<th>Convective Heat Transfer Coefficient between Roadway Wall and Airflow, (W m⁻² C⁻¹)</th>
<th>Roadway Radius, (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05, 0.10, 0.15, 0.20, 0.25</td>
<td>0.125</td>
<td>8.3</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>0.15</td>
<td>0.045, 0.085, 0.125, 0.165, 0.205</td>
<td>8.3</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>0.125</td>
<td>4.3, 6.3, 8.3, 10.3, 12.3</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>0.15</td>
<td>0.125</td>
<td>8.3</td>
<td>1.5, 2.0, 2.5, 3.0, 3.5</td>
</tr>
</tbody>
</table>

According to Table 2, change the value of one of the influencing factors, and take the benchmark value for other influencing factors for sensitivity calculation and analysis. When \( \lambda = \lambda^* = 0.125 \) W/(m·°C), \( a = a^* = 8.3 \) W/(m²·°C), \( r = r^* = 2.5 \) m, automatic fitting \( \Delta t = \Delta l (\delta) \), similarly, fit separately \( \Delta t = \Delta l (\lambda) \), \( \Delta t = \Delta l (a) \) and \( \Delta t = \Delta l (r) \). Based on the fitting function, calculate the sensitivity functions of each parameter according to Equation (21) as follows:

\[
S_\delta = \frac{|-93.898\delta + 40.213|\delta}{-46.949\delta^2 + 40.213\delta + 0.2317}
\]  

(23)

\[
S_\lambda = \frac{|-4419\lambda^2 + 1586.62\lambda - 159.56|\lambda}{-1473\lambda^3 + 793.31\lambda^2 - 159.56\lambda + 15.586}
\]  

(24)
\[ S_\alpha = \frac{\left| 0.0009\alpha^2 - 0.0216\alpha + 0.1294 \right|}{0.0003\alpha^3 - 0.0108\alpha^2 + 0.1294\alpha + 4.6914} \] (25)

\[ S_r = \frac{\left| -0.2208r^2 + 1.6288r - 3.5873 \right|}{-0.0736r^3 + 0.8144r^2 - 3.5873r + 10.231} \] (26)

Figure 18 shows the fitting function and sensitivity curve.

From the sensitivity curve analysis in Figure 16, it can be concluded that as the thickness of the thermal insulation layer increases within the range of 0.05 m to 0.25 m, the sensitivity \( S_\delta \) of the temperature difference between the inner and outside surfaces of the thermal insulation layer to the change in the thickness of the thermal insulation layer gradually decreases from 0.836 to 0.569, and there is \( 0.2 \leq S_\delta < 1 \). It indicates that the temperature difference between the inner and outside surfaces of the thermal insulation layer is highly sensitive to the thickness of the thermal insulation layer, and as the thickness of the thermal insulation layer increases, the sensitivity shows a decreasing trend. When the thermal conductivity of the thermal insulation layer increases within the range of 0.045 W/(m·°C) to 0.205 W/(m·°C), the sensitivity \( S_\lambda \) of the temperature difference between the inner and outside surfaces of the thermal insulation layer to the change in the thermal conductivity of the thermal insulation layer gradually increases from 0.442 to 1.164, and there is \( 0.2 \leq S_\lambda < 1 \) or \( S_\lambda \geq 1 \). It indicates that the thermal insulation performance of the thermal insulation layer is highly sensitive or very sensitive to the thermal conductivity of the thermal insulation layer, and as the thermal conductivity of the thermal insulation layer increases, the overall sensitivity shows an increasing trend. When the convective heat transfer coefficient between the roadway wall and the airflow increases in the range of 4.3 W/(m²·°C) to 12.3 W/(m²·°C), the sensitivity \( S_\alpha \) of the temperature difference between the inner and outside surfaces of the thermal insulation layer to the change in the convective heat transfer coefficient between the roadway wall and the airflow gradually decreases from 0.046 to 0, and there is \( S_\alpha < 0.05 \). It indicates that the sensitivity of the temperature difference between the inner and outside surfaces of the thermal insulation layer to the convective heat transfer coefficient between the roadway wall and the airflow can be ignored. When the radius of the roadway increases within the range of 1.5 m to 3.5 m, the sensitivity \( S_r \) of the temperature difference between the inner and outside surfaces of the thermal insulation layer to the radius of the roadway gradually decreases from 0.317 to 0.254, and there is \( 0.2 \leq S_r < 1 \). It indicates that the temperature difference between the inner and outside surfaces of the thermal insulation layer is highly sensitive to the radius of the roadway, and as the radius of the roadway increases, the overall sensitivity shows a decreasing trend.

Substituting the benchmark values \( \delta = \delta^\ast = 0.15 \) m, \( \lambda = \lambda^\ast = 0.125 \) W/(m·°C), \( \alpha = \alpha^\ast = 8.3 \) W/(m²·°C) and \( r = r^\ast = 2.5 \) m into Equations (20)–(23) respectively, and the sensitivity factor values are as follows:

\[ S_\delta^\ast = 0.753, \ S_\lambda^\ast = 0.734, \ S_\alpha^\ast = 0.021, \ S_r^\ast = 0.280 \]

By comparing the sensitivity factor values of the above-influencing factors, it can be concluded that the sensitivity ranking of each influencing factor on the thermal insulation performance of the thermal insulation layer is: thickness of the thermal insulation layer \( > \) thermal conductivity of the thermal insulation layer \( > \) roadway radius \( > \) convective heat transfer coefficient between the roadway wall and the airflow. If different benchmark values are selected in the analysis, the sensitivity factor values will be different, but both \( S_\delta^\ast \) and \( S_\lambda^\ast \) are greater than \( S_r^\ast \), and \( S_\alpha^\ast \) can be ignored.
(a) Δt (λ) = –1473λ³ + 793.31λ² – 159.56λ + 15.586

R Square: 0.9998

(b) Δt (α) = –46.949δ² + 40.213δ + 0.2317

R Square: 0.9999

(c) Δt (α) = 0.0003α³ – 0.0108α² + 0.1294α + 4.6914

R Square: 0.9999

Figure 18. Cont.
15, 12555

As the thickness of the thermal insulation layer increases, the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually increases and its rate of increase gradually decreases. As a result, the thermal insulation capacity of the thermal insulation roadway increases, but its enhancement rate gradually weakens; As the thermal conductivity of the thermal insulation layer or the roadway radius increases, the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually decreases and its decreasing rate gradually decreases. Therefore, the thermal insulation capacity of the thermal insulation roadway decreases and its rate of decreasing rate gradually weakens; As the convective heat transfer coefficient between the roadway wall and the airflow increases, the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually increases, but its rate of increase is very small. When the convective heat transfer coefficient increases to a certain value, the temperature difference between the inner and outside surfaces of the thermal insulation layer remains almost unchanged, and the change in the convective heat transfer coefficient has almost no effect on the thermal insulation ability of the thermal insulation roadway.

5. Conclusions

In this paper, a one-dimensional steady-state heat transfer model of the surrounding rock of roadway with and without a thermal insulation layer is established, and the temperature distribution characteristics of the surrounding rock of thermal insulation roadway are studied. The influence and sensitivity of thermal insulation layer thickness and thermal conductivity, the convective heat transfer coefficient of roadway wall, and the roadway radius on the thermal insulation performance of the thermal insulation roadway are discussed. The main conclusions are as follows:

(1) Compared with the roadway without a thermal insulation layer, the thermal insulation layer of the thermal insulation roadway reduces the temperature of its inner surface (the contact surface between the thermal insulation layer and the shotcrete layer) and increases the temperature of its outside surface (the contact surface between the insulation layer and the surrounding rock). The temperature gradient inside the thermal insulation layer is greater than that inside the surrounding rock. The thermal insulation layer of the thermal insulation roadway reduces the heat dissipation of the surrounding rock by reducing the temperature difference between the original rock and the outside surface of the thermal insulation layer.

(2) As the thickness of the thermal insulation layer increases, the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually increases and its rate of increase gradually decreases. As a result, the thermal insulation capacity of the thermal insulation roadway increases, but its enhancement rate gradually weakens; As the thermal conductivity of the thermal insulation layer or the roadway radius increases, the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually decreases and its decreasing rate gradually decreases. Therefore, the thermal insulation capacity of the thermal insulation roadway decreases and its rate of decreasing rate gradually weakens; As the convective heat transfer coefficient between the roadway wall and the airflow increases, the temperature difference between the inner and outside surfaces of the thermal insulation layer gradually increases, but its rate of increase is very small. When the convective heat transfer coefficient increases to a certain value, the temperature difference between the inner and outside surfaces of the thermal insulation layer remains almost unchanged, and the change in the convective heat transfer coefficient has almost no effect on the thermal insulation ability of the thermal insulation roadway.

Figure 18. Fitting relationship diagram and sensitivity curve. (a) The functional relationship between $\Delta t$ and $\delta$. (b) The functional relationship between $\Delta t$ and $\lambda$. (c) The functional relationship between $\Delta t$ and $\alpha$. (d) The functional relationship between $\Delta t$ and $r$. 
(3) The sensitivity of the thermal insulation performance of thermal insulation roadway decreases with the increase in thermal insulation layer thickness or roadway radius, and overall increases with the increase in thermal conductivity of the thermal insulation layer. The thermal insulation performance of thermal insulation roadway is highly sensitive or above to the thickness and thermal conductivity of the thermal insulation layer, as well as the roadway radius. If different benchmark values are selected in the analysis, the sensitivity factor values will be different. However, the influence of the thickness and thermal conductivity of the thermal insulation layer on thermal insulation performance is greater than the influence of roadway radius, and the influence of the convective heat transfer coefficient between the roadway wall and the airflow can be ignored.

This study indicates that increasing the thickness of the thermal insulation layer and reducing the thermal conductivity of the thermal insulation layer or roadway radius can enhance the thermal insulation performance of the thermal insulation roadway. However, when these parameters are increased to a certain value, the thermal insulation performance changes very little. Therefore, when using the thermal insulation method to reduce the ambient temperature of the roadway, it is necessary to comprehensively consider the influence of various factors on the thermal insulation performance of the thermal insulation roadway. In future research work, based on existing theoretical achievements, further research will be conducted on how to select thermal insulation materials. Experimental research on the heat transfer model proposed in this paper and verification of actual thermal insulation roadway will also be carried out in the future.

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