

## HEAT TRANSFER ANALYSIS OF SURROUNDING ROCKS WITH THERMAL INSULATION LAYER IN HIGH GEOTHERMAL ROADWAY

by

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*A mathematical model of heat conduction in surrounding rocks of the high geothermal roadway with thermal insulation layer was established in this paper, and its finite difference scheme was also proposed. On this basis, thermal insulation mechanism of thermal insulation layer was investigated. Results show that distinct regional temperature distribution exists in the thermal insulation layer. The temperature is continuous while the temperature gradient has a sudden fluctuation at the interface of different media. The wall temperature is lower and the inner surrounding rock temperature is higher in surrounding rocks with thermal insulation layer compared to that in surrounding rocks without thermal insulation layer. Moreover, the smaller the thermal conductivity of the medium in the thermal insulation layer, the larger the temperature gradient and the smaller the heat flux density. At the beginning of ventilation, thermal insulation of the gunite layer is better than that of the grouting layer. After three months, thermal insulation of the grouting layer is better than that of the gunite layer. Thermal insulation layer can reduce 29-40% of heat dissipation and the thermal insulation would be more significant if the thermal insulation layer was constructed earlier.*

Key words: high geothermal roadway, transient heat transfer, thermal insulation layer, temperature field

### Introduction

At present, human beings have managed to exploit solid mineral resources at about 4 km underneath [1]. With the increase of mining depth, the geo-temperature underground is getting higher and higher. As geothermal gradient of the coal measure strata in China is about 2.5~3.0 °C per hectometer, the rock temperature 1000 m deep underground is supposed to be 40~45 °C, e. g., at the level of -980 m of Sanhejian colliery and -1180 m of Suncun colliery, rock temperatures reach 46.8 °C and 45 °C, respectively [2-4]. Compared with mining at shallow level, high geo-temperature is an important determinant of high atmospheric temperature in underground mines. Up to now, there exists roughly 150 underground mines in China, where the air temperatures in the working face are normally 30~40 °C.

Originally, the rock temperature underground has not been disturbed by human project activities [5]. Once the roadway was excavated, original temperature balance would be broken, and heat would transfer from deep rock to the air-flow. Because of the complex ventilation system, long ventilation route, and long service life in China coal mines, thermal pollution would be easily formed in the underground meteorological environment. At the beginning of ventilation,

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the roadway wall temperature drops dramatically because of the large heat dissipating capacity. With the advancing of ventilation, both the temperature decreasing amplitude and heat dissipation would reduce by and by [6]. If measures could be taken to reduce the heat dissipation and the spreading of the temperature disturbance region (TDR) at the beginning of ventilation, heat in the surrounding rock can be released slowly and taken away by the air-flow timely, in this way, the air-flow temperature will not rise rapidly and the thermal pollution can be prevented. One possible mean is to build a thermal insulation structure in surrounding rocks of high geo-temperature roadway, which will prevent the heat transfer from deep to shallow in surrounding rocks. Meanwhile, ventilation can be strengthened to take away the heat in time to prevent the air temperature rise. Currently, the common used thermal insulation method is to spray a layer of thermal insulation materials onto the roadway wall. Considering the cost, fire resistance property and toxic gas emission after burning, inorganic materials such as expanded perlite, glass beads, and fly ash, *etc.*, are more applicable for thermal insulation. However, the thermal insulation effect and strength of the concrete made from these inorganic materials cannot be balanced simultaneously: when the thermal conductivity coefficient is low, the concrete strength is relatively small and when the strength is large, the conductivity coefficient is also high. Such sprayed layer has bad insulation performance or is prone to be damaged. Besides, fractures often develop in the broken rock zone, so does the hot water flow path. As the spray layer is generally thin, it can only prevent some hot water-flow instead of sealing the fractures in the surrounding rocks. All these factors result in the poor thermal insulation of the spray layer.

Based on the analysis, the thermal insulation layer (TIL) is proposed to build the thermal insulation structure. Once the roadway is excavated, concrete material is sprayed onto the wall and thermal insulation material is then injected to the broken rock zone to seal the fractures through the grouting bolt or cable. After that, thermal insulation material is sprayed onto the first concrete layer, and finally concrete material is again sprayed onto the layer of thermal insulation material. This method can create a large thermal insulation structure, which can support the roadway and prevent both heat transfer and hot water-flow in surrounding rocks. Concrete spray layer and thermal insulation material spray layer are generally known as the gunite layer. Most of the fractures in surrounding rocks can be wrapped by the thermal insulation slurries grouted into the broken rock zone, which is equivalent to the grouting layer. The gunite layer and grouting layer are collectively known as the TIL. The concrete layers in the gunite layer can be neglected if the roadway does not need too much support or the strength of thermal insulation materials meets the supporting requirements, and the thermal insulation materials can be directly sprayed onto the roadway wall.

The TIL cannot only ensure the roadway stability but realize the goal of thermal insulation. In the high temperature roadway where air conditioners are used, fresh air is often polluted by the heat before reaching the working place. The TIL can be utilized as an auxiliary cooling measure to reduce the thermal pollution, hence to improve the cooling effect of the air conditioner and ultimately reduce the power consumption of the cooling equipment. From this perspective, research on the thermal insulation mechanism of the TIL is of great significance.

## Methodologies

### *Mathematical modeling*

The structure of the TIL is shown in fig. 1, and the following assumptions were proposed at first [7]:

- the roadway cross-section is round (radius  $r = r_0$ ); its surrounding rock is a hollow cylinder with infinite radius ( $r \rightarrow \infty$ ),

- the gunite layer, grouting layer and rock mass are continuous, homogeneous and isotropous, and their thermophysical parameters are constants,
- initially when time  $\tau = 0$ , the surrounding rock temperature at each point is uniform and equal to its original rock temperature,  $t_0$ , and
- the air-flow temperature only changes along the axial direction, and remains uniform on the same radical cross-section; the heat transfer conditions are identical at the circumferential direction; heat only transfers along radical direction.

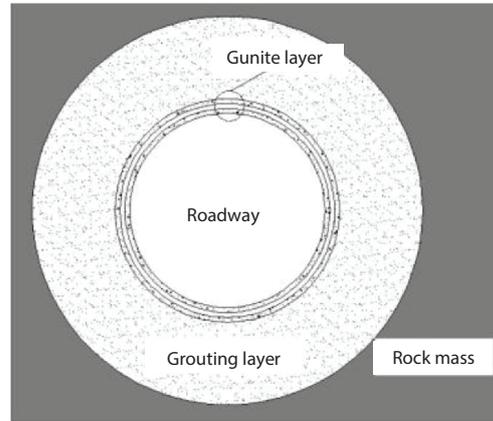


Figure 1. Schematic diagram of the TIL structure

These assumptions do not consider the heat transfer in axial direction in the surrounding rocks. In fact, the heat flux in axial direction is negligibly small, especially when the rock temperature has not been disturbed on a large scale.

The heat transfer characteristics of surrounding rocks with or without TIL will certainly be different. However, the heat conduction process must be in agreement with the general rules for heat conduction (Fourier's law) for the homogeneous and continuous gunite layer, grouting layer, and rock masses. In addition, heat conduction governing equations are the same:

$$\rho_i c_i \frac{\partial t_i}{\partial \tau} = \lambda_i \left( \frac{1}{r} \frac{\partial t_i}{\partial r} + \frac{\partial^2 t_i}{\partial r^2} \right) \quad (1)$$

where  $t_i$  is the temperature of surrounding rocks,  $\rho_i$ ,  $c_i$ ,  $\lambda_i$  are the density, specific heat capacity, and thermal conductivity of the  $i^{\text{th}}$  layer of surrounding rocks, respectively,  $\tau$  – the heat conduction time, and  $r$  – the distance from the central axis of the roadway.

Although the three layers share with the same form of the PDE for heat conduction, the conditions for definiteness are not the same. For gunite layer, the inner boundary ( $r = r_1$ ) still belongs to the heat convection boundary:

$$\lambda_1 \frac{\partial t}{\partial r} = h(t - t_f) \quad (2)$$

where  $\lambda_1$  is the thermal conductivity of the gunite layer,  $t_f$  – the air-flow temperature,  $h$  – the heat convection coefficient between the gunite layer and the air-flow.

If contact thermal resistance between the gunite layer and the grouting layer can be ignored, the outer boundary temperature of the gunite layer will be equal to the inner boundary temperature of the grouting layer and heat flux density of the interface will be equivalent too, *i. e.* the temperature and the heat flux density will be continuous. Similarly, the outer boundary temperature and heat flux density of the grouting layer will be equal to that of the rock masses.

$$t_i(\tau, r_{i+1}) = t_{i+1}(\tau, r_{i+1}) \quad (i = 1, 2) \quad (3)$$

$$\lambda_i \frac{\partial t_i}{\partial r} = \lambda_{i+1} \frac{\partial t_{i+1}}{\partial r} \quad (4)$$

The outer boundary of the rock mass (far away from the axis of the roadway) still maintains the original rock temperature, which is the boundary condition of the first kind:

$$t_3(\tau, \infty) = t_0 \tag{5}$$

At the beginning of heat conduction, the heat conduction conditions (initial conditions) of the gunite layer, grouting layer, and rock masses are supposed to be equal with each other:

$$t_i(\tau, r) = t_0 \quad (i = 1, 2) \tag{6}$$

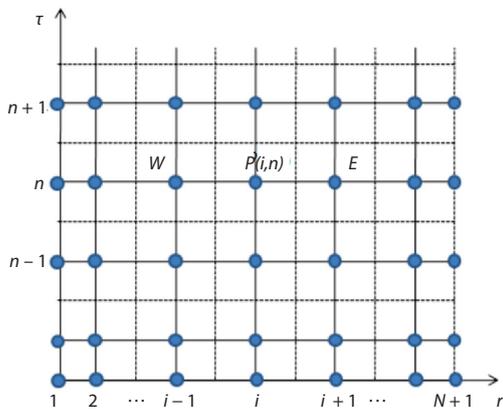
Equations (2)-(6) are conditions for definiteness of the heat conduction mathematical modeling of surrounding rocks with TIL. It describes the temperature field of a 1-D semi-infinite hollow plate made of composites. A numerical method is generally adopted to solve this problem.

A similar method has already been adopted to establish the temperature field mathematical model of the roadway surrounding rock without TIL structure, and the model has been validated by the physical test in the laboratory [8, 9]. The accuracy of the model established in this paper is expected to be guaranteed.

*Numerical method*

Given that the surrounding rocks belong to composite structure and heat balance method is not restricted by the conditions that whether the mesh is divided equally or physical properties are constant, heat balance method and the First law of thermodynamics were applied to create the finite difference scheme [10-12]. We took the node as the representative of the element and then established the heat balance equation for each element. Accordingly, the discrete equation was then determined.

The mesh was first generated, and then the nodes were determined. Surrounding rocks were divided into  $N$  parts uniformly. The first node is located on the wall, and the  $N + 1$  node is located in the outermost of the surrounding rock. The distance between two adjacent nodes (except for the two boundary nodes) is  $\Delta r(i - 1)$ .  $\Delta r$  is adopted to represent the radial position of surrounding rocks,  $\Delta \tau$  is the time step and  $n\Delta \tau$  is the time.



**Figure 2. Finite difference meshes**

As shown in fig. 2, dash lines represent the demarcation line of the grid and dots represent the nodes. Grids surrounded by the dash lines are controlled volumes of the nodes.

It can be seen from fig. 2 that heat only conducts along the radial direction of surrounding rocks and the control volume element  $P$  only conduct heat with  $W$  and  $E$ , therefore heat transferred from  $W$  and  $E$  to  $P$  is:

$$Q_{W \rightarrow P} = \frac{2\lambda_{i-1}\lambda_i}{\lambda_{i-1} + \lambda_i} \frac{t_{i-1}^{n+1} - t_i^{n+1}}{\Delta r} \left(r - \frac{\Delta r}{2}\right) \Delta \varphi \Delta z \Delta \tau$$

$$Q_{E \rightarrow P} = \frac{2\lambda_i\lambda_{i+1}}{\lambda_i + \lambda_{i+1}} \frac{t_{i+1}^{n+1} - t_i^{n+1}}{\Delta r} \left(r + \frac{\Delta r}{2}\right) \Delta \varphi \Delta z \Delta \tau \tag{7}$$

where  $\lambda_w = 2\lambda_{i-1}\lambda_i / (\lambda_{i-1} + \lambda_i)$  and  $\lambda_e = 2\lambda_i\lambda_{i+1} / (\lambda_i + \lambda_{i+1})$  are thermal conductivities at the interfaces between  $W$  and  $P$  and between  $E$  and  $P$ , respectively,  $\varphi$  and  $z$  - co-ordinates in cylindrical co-or-

dinate system, respectively. The  $\lambda_w$  and  $\lambda_c$  are obtained from the harmonic mean of the thermal conductivities of the nodes on both sides of the interface.

Thermodynamic energy increment of the element  $\Delta U$  is:

$$\Delta U = \rho_i c_i (t_i^{n+1} - t_i^n) r \Delta \phi \Delta r \Delta z \quad (8)$$

Based on the law of conservation of energy,  $Q_{W \rightarrow P} + Q_{E \rightarrow P} = \Delta U$ ,

$$t_i^n = \left[ 1 + \frac{\Delta \tau}{(\Delta r)^2} \frac{2r - \Delta r}{2\rho_i c_i r} \frac{2\lambda_{i-1}\lambda_i}{\lambda_{i-1} + \lambda_i} + \frac{\Delta \tau}{(\Delta r)^2} \frac{2r + \Delta r}{2\rho_i c_i r} \frac{2\lambda_i\lambda_{i+1}}{\lambda_i + \lambda_{i+1}} \right] t_i^{n+1} - \frac{\Delta \tau}{(\Delta r)^2} \frac{2r - \Delta r}{2\rho_i c_i r} \frac{2\lambda_{i-1}\lambda_i}{\lambda_{i-1} + \lambda_i} t_{i-1}^{n+1} - \frac{\Delta \tau}{(\Delta r)^2} \frac{2r + \Delta r}{2\rho_i c_i r} \frac{2\lambda_i\lambda_{i+1}}{\lambda_i + \lambda_{i+1}} t_{i+1}^{n+1} \quad (9)$$

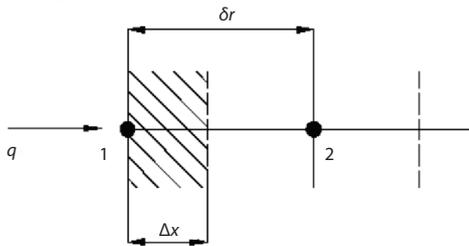
The  $\alpha$ ,  $\beta$ , and  $\gamma$  are respectively defined:

$$\begin{aligned} \alpha &= -\frac{\Delta \tau}{(\Delta r)^2} \frac{2r - \Delta r}{2\rho_i c_i r} \frac{2\lambda_{i-1}\lambda_i}{\lambda_{i-1} + \lambda_i} \\ \beta &= 1 + \frac{\Delta \tau}{(\Delta r)^2} \frac{2r - \Delta r}{2\rho_i c_i r} \frac{2\lambda_{i-1}\lambda_i}{\lambda_{i-1} + \lambda_i} + \frac{\Delta \tau}{(\Delta r)^2} \frac{2r + \Delta r}{2\rho_i c_i r} \frac{2\lambda_i\lambda_{i+1}}{\lambda_i + \lambda_{i+1}} \\ \gamma &= -\frac{\Delta \tau}{(\Delta r)^2} \frac{2r + \Delta r}{2\rho_i c_i r} \frac{2\lambda_i\lambda_{i+1}}{\lambda_i + \lambda_{i+1}} \end{aligned} \quad (10)$$

Substitute eq. (10) into eq. (9):

$$t_i^n = \alpha t_{i-1}^{n+1} + \beta t_i^{n+1} + \gamma t_{i+1}^{n+1} \quad (11)$$

Equation (11) is an implicit difference scheme, whose step size has no restrictions and the oscillation of the solutions will not appear, which means the stability of the equation is quite good.



**Figure 3. Discretization of the boundary condition**

Heat balance method was applied to Node 1 and then discrete equations for the convection boundary condition can be obtained. As reported in reference [13]:

$$t_1^n = \frac{2\lambda_1}{2\lambda_1 + h\Delta r} t_2^n + \frac{h\Delta r}{2\lambda_1 + h\Delta r} t_f \quad (12)$$

The outer boundary of surrounding rocks is under the boundary condition of the first kind and can be employed directly, namely:

$$t_N^n = t_0 \quad (13)$$

Because the wall satisfies the boundary condition of the third kind, the wall temperature is unknown boundary temperature. Equation set composed of the nodal equations in eq. (11) is not closed. In this case, discrete equations for the boundary points should be added to make the equation set close.

The roadway wall is under convective heat transfer condition. Suppose that there is a node close to the wall ( $i = 0$ ) and the distance between the node and the wall is  $\Delta x$  and  $\Delta x$  approaches zero as shown in fig. 3.

After discretization, the initial condition is:

$$t_i^0 = t_0 \quad (14)$$

Thermophysical properties of surrounding rocks with TIL are similar to that of the composite structure. Accordingly, the grids are divided into three regions and different parameters would be assigned to the nodes in the three regions. Zone discretization method and finite difference method for the composites are different. In the process of the zone discretization, the model meshes before the nodes are determined. This method can make the interfaces of different materials located at the interfaces of the node control units thereby to guarantee the continuity of the heat flux density. Heat balance method was adopted to solve the finite difference equations, which can ensure the energy conservation of the control units.

### Numerical study programs

According to the requirements of support and thermal insulation, the thickness of the spray layer is basically 80~100 mm, and the value was set as 100 mm in the simulation. The thickness of the grouting layer is calculated by the grouting depth and the ideal depth is to make the slurries full fill the broken rock zone. However, the thickness of broken rock zone is closely related to the in-situ stress, lithology, roadway size and support strength, *etc.* [14, 15] and hard to confirm. Despite all these, roadways in the deep have the characteristics of both high geo-temperature ( $t_0 \geq 31^\circ\text{C}$ ) and large broken rock zone ( $L_p \geq 1500$  mm), so the thickness of broken rock zone is supposed to be 1.5 m.

Roadway model with round cross-section and a radius of 2 m was adopted. Previous studies have shown that the TDR of surrounding rocks is commonly no more than 40 m within the service life of the roadway [16, 17], therefore, suppose the distance between the outer boundary of the roadway and the grouting layer is 48.4 m, so that the total thickness of surrounding rocks can reach 50 m.

Because the temperature variation range is small, thermophysical properties of surrounding rocks are supposed to be constant. The thermal conductivity of rock masses,  $\lambda_3$ , is 2.0 W/mK and those of the grouting layer and gunite layer are  $\lambda_2$  and  $\lambda_1$ , respectively, which need to be adjusted according to the experiments. Thermophysical properties of the gunite layer can be easily determined by the mix proportion test in the lab. However, the thermophysical properties of the grouting layer are difficult to be solved. The formed rock media belongs to composite porous media after grouting in the broken rock zone [18-20]. The distribution of the joint fractures in the broken rock zone is hard to grasp. The coupled heat transfer mechanism of joint fractures and slurries is still not clear. Despite all these, equivalent thermal conductivity coefficient should be between that of the grout materials and rock masses. Different sections of surrounding rocks are assumed to be homogeneous, isotropy and continuous.

Convective heat transfer occurs between the internal surface of the roadway and the air-flow. The air-flow temperature is set to be a constant value of  $20^\circ\text{C}$  and the convective heat transfer coefficient between the air-flow and the internal surface is  $25\text{ W/m}^2\text{K}$ , [21, 22]. The outer boundary of the roadway satisfies the first kind of boundary condition, *i. e.*  $t = t_0 = 37^\circ\text{C}$ . At the beginning of the transient heat conduction, temperatures of the inner and outer boundary are equivalent, both of them are  $37^\circ\text{C}$ . The contact thermal resistance between the gunite layer and the grouting layer was ignored, so did that between grouting layer and rock mass.

Based on the aforementioned assumptions, the model would be a 1-D hollow plate, whose inner diameter is 2 m and outer diameter equals 50 m. The thickness of the gunite layer and grouting layer are 0.1 m and 1.5 m, respectively. The distance between the outer boundary

and the grouting layer is 48.4 m. The grid spacing is 0.02 m and the time step is 3600 seconds. There are totally  $2.5 \cdot 10^3$  grids and  $3 \cdot 10^4$  time steps. The simulation period is set as 3 years. The test programs are demonstrated in tab. 1.

**Table 1. Numerical simulation test programs**

Parameters	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
$\lambda_1$ [Wm <sup>-1</sup> K <sup>-1</sup> ]	2.0	0.8	0.2	0.2	0.2
$\lambda_2$ [Wm <sup>-1</sup> K <sup>-1</sup> ]	2.0	2.0	2.0	1.2	0.8
$\lambda_3$ [Wm <sup>-1</sup> K <sup>-1</sup> ]	2.0	2.0	2.0	2.0	2.0

To acquire the fundamental laws of temperature, space and time, a dimensionless method is used to process the three parameters.

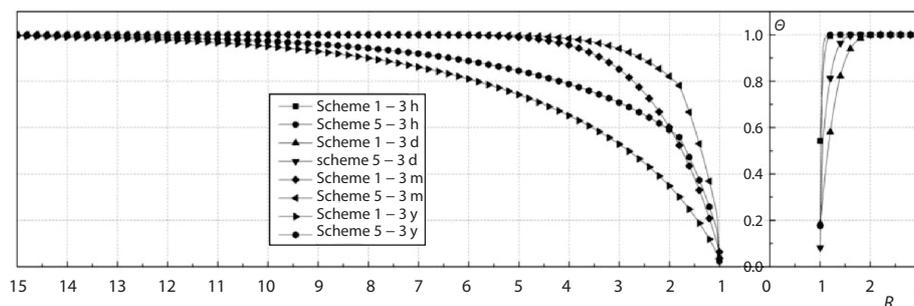
$$\Theta = (t - t_f) / (t_0 - t_f), \quad R = r / r_0 \quad (15)$$

where  $\Theta$  is the dimensionless temperature,  $t$  – the temperature of surrounding rocks in the roadway,  $t_f$  – the air-flow temperature,  $t_0$  – the original rock temperature,  $R$  – the dimensionless radius, and  $r$  – the distance from the measure points to the central point of roadways.

## Results and discussion

### Temperature distribution characteristics in surrounding rocks

As shown in tab. 1, surrounding rock in Scheme 1 has no TIL structure, but in Scheme 5 the TIL characteristic is prominent. Therefore, we compared the two schemes to study the influence of TIL on temperature distribution in surrounding rocks. The relationship between dimensionless temperature and dimensionless radius of surrounding rocks was plotted and four-time points were chosen, which are 3 hours, 3 days, 3 months, and 3 years, as shown in fig. 4.



**Figure 4. Location-temperature curve of surrounding rocks; h – hours, d – days, m – months, and y – years**

As shown in fig. 4, temperature distribution characteristics of surrounding rocks with TIL is similar to that without TIL along the radial direction. With the increase of the dimensionless radius, dimensionless temperature rises constantly while the increasing trend slows down gradually. However, temperature in surrounding rocks with TIL is higher than that in surrounding rocks without TIL within the TDR, and the maximum difference is found on the interface of the grouting layer and rock masses, which indicates that heat dissipation in surrounding rocks is hindered by the TIL, and the temperature decreasing rates in deep surrounding rock obviously diminishes.

Compared to surrounding rocks without TIL, temperature decreasing rate of the wall is much larger than that in surrounding rocks with TIL at the beginning of ventilation. But after 3 months of ventilation, the difference between the two rates becomes very small, suggesting that TIL can help to reduce the amount of heat transferred from the deep surrounding rocks to the wall, and sequentially, make the wall temperature drop rapidly.

Therefore, compared to the temperature field in surrounding rocks without TIL, the temperature field in surrounding rocks with TIL is lower in wall temperature and higher in inner temperature.

### Temperature distribution characteristics in the TIL

The dimensionless radius at the interface of the grouting layer and gunite layer is 1.05, and that of the grouting layer and rock masses is 1.8. The relationship between dimensionless temperature and dimensionless radius of the TIL at four-time points was plotted in fig. 5.

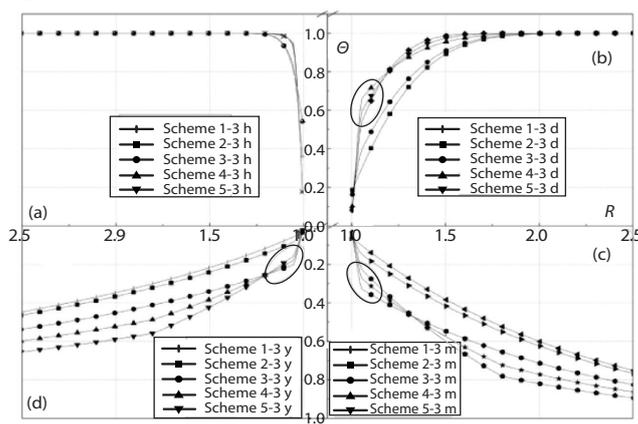


Figure 5. Temperature distribution in the TIL

ly at first. When TDR extends deeper, heat continuously transfers from the deep to the shallow. When extending to the interface of TIL and rock masses, the heat conduction is hindered and accumulated at the interface. As a result, the heat dissipation rate drops, a higher temperature gradient between the shallow part of TDR and the interface would thus be generated.

- As shown in figs. 5(a), 5(b), and 5(d), it is obvious that temperature gradient of gunite layer would decrease a little bit when thermal conductivities of the grouting layer decreases and temperature gradient increases. Intercepted by the grouting layer, heat transferred to the gunite layer decreased. Heat could not be replenished at the interface of the two layers. Consequently, both temperature and temperature gradient in the interface becomes lowered. Hence grouting layer can reduce the temperature gradient of the gunite layer, and lead to further reduction of heat flux density.
- As shown in fig. 5(c), the smaller the thermal conductivities of the TIL, the lower the temperatures on the wall and the higher the temperatures in the rock masses. On one hand, the wall loses a lot of heat because heat convection with the air-flow, on the other hand, as the low thermal conductivity of the gunite layer cannot be replenished in time, the temperature decreasing amplitude is relatively large, hence the smaller the thermal conductivity of the

As shown in fig. 5, the temperature distribution in the TIL has the following characteristics:

- In the TIL, the smaller the thermal conductivities of surrounding rocks, the bigger the temperature gradients. By the comparison of Scheme 1-3, it is found that the smaller the thermal conductivities of gunite layer, the larger the slopes of the  $\Theta$ - $R$  curve. The rule also applies to the grouting layer through the comparison of Scheme 3-5. During the ventilation, the TIL temperature decreases dramatically.

TIL, the lower the temperature on the surface of the wall. Owing to the heat interception by the TIL, the decreasing speed of temperature slows down, and therefore the smaller the thermal conductivity, the higher the temperature in the deep.

- When thermal conductivities of gunite layer remain unchanged, there is always a small area in the grouting layer where temperature distribution is against the law that the smaller the thermal conductivity, the higher the temperature. As shown in the elliptic frame in the first, second and third quartiles of fig. 5, temperature distribution of the grouting layer demonstrates two different regional phenomenon: the better the heat conductivity, the higher the temperature in a small region close to the gunite layer while the better the heat conductivity, the lower the temperature in most regions close to rock masses. The major reasons are that the better the heat conductivity of grouting layer, the more heat transfers from the deep to the shallow, which leads to the slow decreasing speed of temperature in the shallow grouting layer and vice versa.
- Lithology change of the TIL often results in a significant transition of the  $\Theta$ - $R$  curve. As shown in Scheme 1-3, thermal conductivities of grouting layer are consistent with that of the rock masses. There are no inflection points at the interface of grouting layer and rock masses and the curve is relatively smooth. However, due to the existence of the grouting layer in Scheme 4 and 5, the thermal conductivities of the grouting layer are all lower than that of the rock masses. There are inflection points at the interface and the same phenomenon is more obvious in the gunite layer.

According to the principle of energy conservation, the absorbed heat equals the released heat on both sides of the composites interface. As thermal conductivities are different on the two sides of the interface, temperature gradient mutated at the interface. However, this phenomenon does not violate scientific laws because heat conduction of the interface is in accordance with the law of conservation of energy, namely, the heat flux densities are the same on both sides of the interface. To verify this phenomenon, Scheme 5 is taken as an example, four-time points *i. e.* 3 hours, 3 days, 3 months, and 3 years were chosen, and the analysis result is revealed in fig. 6.

As shown in fig. 6, inflection points are located at the interface of the grouting layer and gunite layer ( $R = 1.05$ ) and interface of the grouting layer and rock masses ( $R = 1.8$ ). At these interfaces, the mutation occurs not on the temperature but the temperature gradient, which means that the temperature curves are non-derivable at these inflection points. The phenomenon indicates that the basic role of TIL is to change the temperature gradient distribution rules of surrounding rocks.

#### Heat flux density in the TIL

To judge whether the TIL has the thermal insulation effect, the key is to determine whether the TIL can prevent the heat dissipation, or whether heat flux density of the wall decreases after the decline of the thermal conductivity coefficient of the TIL. In response, we investigated the heat flux density distribution in TIL through the simulation tests of the five schemes listed in tab. 1. The test results are shown in fig. 7.

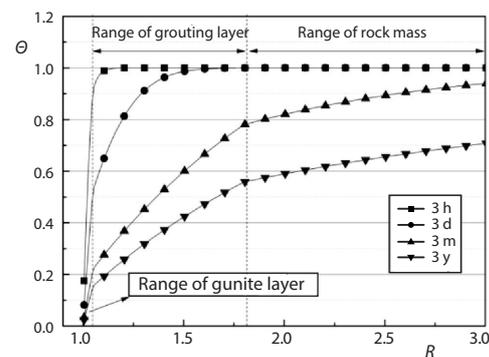


Figure 6. Temperature distribution characteristics of TIL

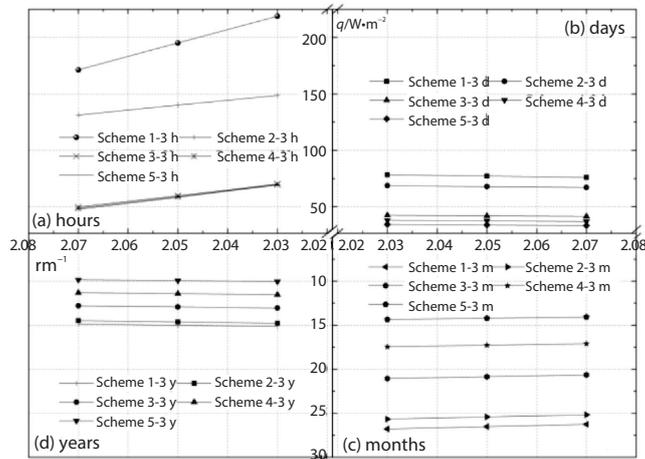


Figure 7. Heat flux density distribution in TIL

heat flux densities become steady in all schemes, suggesting that at the beginning of ventilation, after the rapid decline of the gunite layer temperature, only limited heat can be provided, resulting in a mild increasing trend of the heat flux from the interface of grouting layer and gunite layer to the wall.

Heat flux density curves of gunite layer of Scheme 3-5 are almost overlapped. After 3 days of ventilation, the curves eventually tend to be stable and the differences among them become larger. Schemes in tab. 1 can be divided into two groups. The first group includes Scheme 1-3, and their corresponding thermal conductivities of grouting layers are equivalent. In comparison, the second group contains Scheme 3-5 and their corresponding thermal conductivities of gunite layers are equivalent. After 3 hours of ventilation, TDR merely exists in shallow grouting layers of TIL and the difference of the thermal conductivities of grouting layers is still not obvious. With the increase of ventilation time, TDR extends to the rock masses. When losing heat from itself, the grouting layer also transfers the heat passing from the rock masses at the meantime. Therefore, the gunite layer is relatively sensitive to the thermophysical properties of the grouting layer. When TDR extends to deep surrounding rocks, both the heat dissipation of grouting layer itself and the heat transferred from the rock masses decrease remarkably, so the gunite layer is slow to respond to the thermalphysical property change of grouting layer.

As shown in Schemes 1-3 of the fig. 7, the smaller the thermal conductivity of the gunite layer, the lower the heat flux density and the better effect of the thermal insulation. Also, comparison among Schemes 3-5 indicates that when the thermal conductivity of the grouting layer gets smaller, the heat flux density of the gunite layer becomes lower and the effect of thermal insulation becomes better. Comparison of Schemes 1, 2, and Scheme 3, 5 manifests that at the beginning of ventilation, under the same decreasing amplitude, thermal insulation of the gunite layer is better than that of the grouting layer, but after 3 months of ventilation, the condition is just the opposite.

#### Evolution of the temperature field in TIL

– Evolution law of the temperature distribution in TIL

Four points in TIL were chosen and temperature variations of these points were observed. The four points are  $r = 2.03$  m (shallow of the gunite layer),  $2.07$  m (deep of the gunite layer),  $2.13$  m (shallow of the grouting layer), and  $3.57$  m (shallow of the grouting layer), respec-

As shown in fig. 7, heat flux density in the gunite layer shows a decreasing trend with the increase of depth. In addition, the decreasing amplitude of heat flux density at the time point of 3 hours is larger than those at 3 days, 3 months, and 3 years. As shown in fig. 5(a), TDR is approximately  $1.15$  and locates in the shallow grouting layer. Temperatures in grouting layer and deep rock masses are nearly undisturbed. Therefore, energy replenished to the gunite layer is limited and mainly self-supplied.

After 3 days of ventilation, the

tively. Figures 8 and 9 are the temperature-time curve of gunite layer and grouting layer, respectively.

As shown in figs. 8 and 9, at the beginning of ventilation, the temperature in gunite layer drops sharply and soon come close to the air-flow temperature, while the temperature decreasing amplitude in the grouting layer is much smaller. In shallow gunite layer ( $r = 2.03$  m), temperatures in all schemes are close to each other. In deep gunite layer ( $r = 2.07$  m), temperatures difference in corresponding schemes become significant. With the increase of depth of surrounding rocks in TIL, differences of the temperature distribution become greater and greater.

As shown in fig. 9, in shallow grouting layer ( $r = 2.13$  m), the larger the thermal conductivity, the higher the temperature. Whereas, in deep grouting layer ( $r = 3.57$  m), the smaller the thermal conductivity of the grouting layer, the higher the temperature, which is in accordance with the law in fig. 5.

With the increase of the ventilation time, the temperature in TIL gradually lessening and no signs of temperature curve overlap are found, which means that thermal insulation is effective in the whole process of roadway service.

– The TDR evolution

Figure 10 lists out the TDR of surrounding rocks at twelve-time points, including 1~3 hour, 1~3 day, 1~3 month, and 1~3 year in Schemes 1-5. According to the TDR and ventilation time curve, the smaller the thermal conductivity of the TIL, the smaller the TDR, but the difference value of the TDR is not very large.

*Thermal insulation effect and cost analysis*

According to the structure of TIL, heat dissipation of surrounding rocks,  $Q$  can be divided into three parts, which are heat dissipation of gunite layer, heat dissipation of grouting layer and heat dissipation of rock masses:

$$Q = \sum_{i=1}^n c_i m_i \Delta t_i = 2\pi \Delta l \left[ \rho_1 c_1 \int_{r_0}^{r_1} r \Delta t(r) dr + \rho_2 c_2 \int_{r_1}^{r_2} r \Delta t(r) dr + \rho_3 c_3 \int_{r_2}^{\infty} r \Delta t(r) dr \right] \quad (16)$$

where  $[r_0, r_1)$  is the range of gunite layer,  $[r_1, r_2)$  – the range of grouting layer,  $[r_2, \infty)$  – the range of rock masses,  $\rho_1, \rho_2,$  and  $\rho_3$  are densities of the gunite layer, grouting layer, and rock masses,

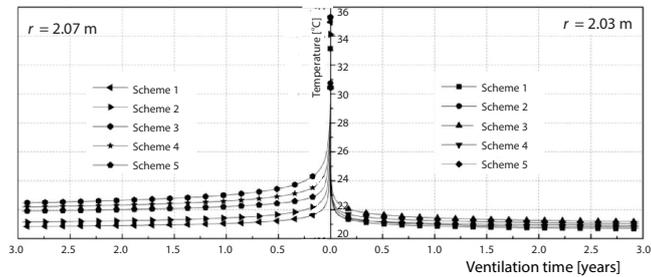


Figure 8. Temperature-time curve of gunite layer

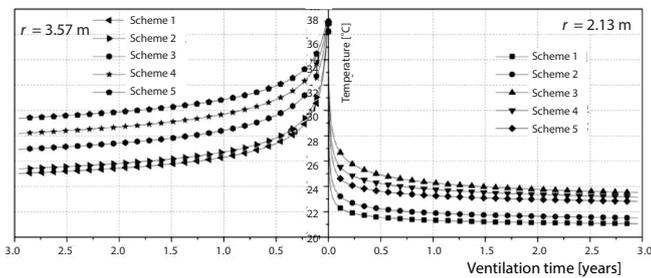


Figure 9. Temperature-time curve of grouting layer

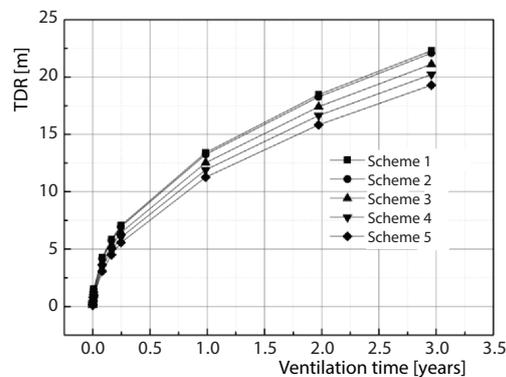
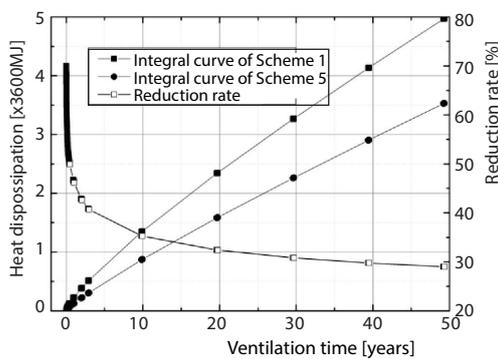


Figure 10. Relationship curve between TDR and ventilation time

respectively. The  $c_1$ ,  $c_2$ , and  $c_3$  are specific heat capacities of the gunite layer, grouting layer, and rock masses, respectively, and  $\Delta t(r)$  is the temperature decreasing amplitude.

Heat dissipation in surrounding rocks always transmits from the wall to the air-flow in the end, so  $Q$  certainly equal to the time integral of heat flux of the wall. Compared to the heat flux transmitted from unit area of the wall,  $Q$  can be converted into the time integral of the heat flux density  $q_w$  of the wall, namely:

$$Q = 2\pi\Delta l \int_0^{\tau} q_w d\tau \quad (17)$$



**Figure 11. Heat dissipation per unit area and emission reduction ratios**

As shown in fig. 11, after the first day of roadway excavation, TIL can reduce almost 70% of the heat dissipation. The reduction ratios are 46.37%, 35.31%, and 29% after 1 year, 10 years, and 50 years, respectively. So it is clear that the earlier construction of TIL is beneficial for the emission reduction. Generally, during the service life of the roadway (including the development, preparation, and mining of roadway), emission reduction ratios of TIL ranges from 29% to 40%, which means TIL has a remarkable thermal insulation effect.

The cost of rock roadway support with bolt-mesh-spruting supporting is about 15050 CNY\*\*/m. Support with the TIL structure will cost around 21630 CNY/m, 43.7% more expensive than the common support without TIL. The extra expenditure mainly contains the cost of insulation material and the grouting operation. Taking one-year ventilation as an example, the heat dissipation of the surrounding rock will reach 4468 MJ/m. If air conditioners are used in the underground mine, assuming that the EER is 3 and the cold loss is 24.5%, the electric charge will be 6933 CNY/m. Therefore, the cost of support with TIL structure would decrease by 353 CNY/m compared to the common support with air conditioner cooling. Taking the air conditioner cost into consideration, the support with TIL structure will have an economic advantage.

## Conclusions

According to structural features of the TIL, a transient mathematical model for heat conduction in surrounding rocks of high temperature roadway with TIL was established in this article. Energy balance method was adopted to discrete the governing equation of the transient temperature field of surrounding rocks. Mesh was generated first and then the node was determined. In addition, the harmonic mean method was employed to solve the continuity of

\*\* 1 CNY = 0.149 US\$

the temperature and heat flux density in the finite difference equations. The thermal insulation mechanism of TIL was simulated. The conclusions are as follows.

- The temperature distribution in TIL is obviously regional. At the interface between the gunite and grouting layer, and the interface between grouting layer and rock masses, although the temperature is continuous, the temperature gradient is mutational, namely, there exist inflection points at the interface of the temperature-radius curve and the curve is non-differential at the inflection points.
- Compared to surrounding rocks without TIL, the wall temperature in surrounding rocks with TIL is relatively lower and temperature in deep surrounding rocks is higher. In surrounding rocks with TIL, the decreasing speed of wall temperature is faster during the initial period of ventilation. The lower the conductivity coefficient of gunite layer, the lower the wall temperature.
- In terms of the temperature disturbance range, temperature of surrounding rocks with TIL is generally higher than that without TIL. The largest difference value is located at the interface between grouting layer and rock masses. Temperature distribution in the grouting layer presents two different phenomena. For the small area in grouting layer close to the gunite layer, the better the heat conductivity of grouting layer, the higher the temperature. For most areas in grouting layer that close to rock masses, the better the heat conductivity, the lower the temperature.
- In both the gunite and grouting layers, the lower the thermal conductivity, the larger the temperature gradient. The heat flux density is low, and thermal insulation effect is more significant. During the preliminary stage of ventilation, thermal insulation of gunite layer is better than that of grouting layer with the same decreasing amplitude of heat conductivity. But, thermal insulation of grouting layer is better than that of gunite layer after 3 months of ventilation. Therefore, grouting and spouting should be combined to make the thermal insulation more effective.
- Preliminary research shows that the TIL can effectively reduce the heat dissipation of surrounding rocks. The emission reduction ratio ranges from 29-40%. The cooling effect is more obvious if the TIL was constructed earlier, which theoretically verified the fact that the spouting of the heat insulating materials can lower the temperature.

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### Nomenclature

$c_i$  – specific heat capacity of the  $i^{\text{th}}$  layer of surrounding rocks, [ $\text{Jkg}^{-1}\text{K}^{-1}$ ]  
 $h$  – heat convection coefficient between the gunite layer and the airflow, [ $\text{Wm}^{-2}\text{K}^{-1}$ ]  
 $Q$  – heat dissipation of surrounding rocks, [J]  
 $R$  – dimensionless radius  
 $r$  – distance from the central axis of the roadway, [m]  
 $r_0$  – radius of the roadway, [m]  
 $t_i$  – temperature of the  $i^{\text{th}}$  layer of surrounding rocks, [ $^{\circ}\text{C}$ ]

$t_f$  – air-flow temperature, [ $^{\circ}\text{C}$ ]  
 $t_0$  – original rock temperature, [ $^{\circ}\text{C}$ ]

#### Greek symbols

$\lambda_i$  – thermal conductivity of the  $i^{\text{th}}$  layer of surrounding rocks, [ $\text{Wm}^{-1}\text{K}^{-1}$ ]  
 $\rho_i$  – density of the  $i^{\text{th}}$  layer of surrounding rocks, [ $\text{kgm}^{-3}$ ]  
 $\tau$  – heat conduction time, [s]  
 $\Theta$  – dimensionless temperature

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