COMPUTER SIMULATION STUDY ON HEAT TRANSFER OF SURROUNDING ROCK IN MINE ROADWAY OF COAL MINE ENTERPRISES

by

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The thesis theory combined with computer simulation, according to the thermal theory, the heat transfer process of the surrounding rock in the coal mine roadway is simplified into an unstable state process, and the influencing factors of the unstable heat transfer coefficient of the surrounding rock are found, and the computer experimental system is used as the basis. At the same time, the paper constructs an experimental receipt according to the similarity theory, and uses the concrete specimen simulation like the thermal performance of the surrounding rock of coal mine as the coal mine roadway to realize the real-time simulation of the heat transfer process of the roadway. The unstable heat transfer coefficient of the surrounding rock under different wind speeds and ventilation specimens was tested to find the law of variation. Finally, in the actual coal mining industry, different roadways are selected for borehole temperature measurement, and the temperature record body with temperature recording function is used for measurement. The calculation formula of the original rock layer temperature at different depths of the mine area is obtained, and the accuracy of the model is verified.

Key words: *unstable heat transfer coefficient of roadway, numerical simulation, surrounding rock heat dissipation, cooling load cooling*

Introduction

China is a big country in the production and consumption of mineral resources. The development of the national economy is highly dependent on mineral resources. Coal accounts for about 70% of China's disposable energy and plays a pivotal role in the national economy. Due to the limited total amount of coal resources, as the mining progresses, the mining space of the coal mine must extend downward. Due to the influence of geothermal heat, the deeper the mining, the higher the rock temperature of the surrounding rock of the mine, and the greater the heat dissipation of the surrounding rock. In addition, with the improvement of mechanization of mining, the heat dissipation of mechanical equipment has also increased significantly, which

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has led to an increase in the number of high temperature mines, and the degree of damage has become increasingly serious [1].

China's *coal safety regulations* stipulates: The air temperature of the mining face shall not exceed 26 °C, and the temperature of the electromechanical chamber shall not exceed 30 °C. In the local locations where the local temperature is overheated, the air volume is increased, the local temperature is lowered*, etc.* After the measures, if the air temperature specified in this paper is still exceeded, it shall be reported to the provincial (region) coal bureau for approval, and the air temperature regulation may be appropriately increased, but the air temperature of the mining face shall not exceed 30 °C. However, some mining work in China The temperature of the surface not only exceeds 26 °C, but some has exceeded 30 °C [2]. For example, the temperature in the face of the Sanhejian mine has been above 32 °C. Workers work under high temperature and high humidity conditions, which not only affects the health of workers, but also labor. Productivity has been greatly affected by the increase in accident rate. According to foreign data, the temperature is 30-34 °C. The above work surface has 1.5 times increase in the accident rate of the work surface below 30 °C. The work surface at 34-37 °C is 2.3 times higher than the work surface below 30 °C. The construction task in the third quarter only completed 61.74% of the plan. If the high temperature problem cannot be solved well, it will cause serious damage to the normal construction of the mine.

As the heat dissipation of various heat sources in the roadway increases, the high temperature problem becomes more and more serious. When relying on ventilation and cooling cannot meet the cooling requirements, it is necessary to consider the mechanical cooling, and use the refrigeration equipment to forcibly cool the inflow air-flow of the working face. To choose a refrigeration unit, you first need to determine the cold load in the roadway.

The main heat sources in the mine are: heat dissipation from surrounding rock, heat dissipation from electromechanical equipment, oxidation and heat dissipation, and self-compression of wind flow. According to statistics, among these heat sources, the surrounding rock heat dissipation accounts for 57%, the electromechanical equipment heat dissipation accounts for 15-20%, the oxidation heat accounts for 12%, and the self-compression heat accounts for 9%. The temperature rise of the mine air is mainly affected by the heat dissipation of the surrounding rock. Studying the temperature of the surrounding rock in the mine, the heat dissipation law and the heat exchange with the wind flow become the primary problem to improve the high temperature in the mine. The heat exchange between the surrounding rock and the downhole flow is a complex and unstable heat transfer process. During the mining process, when the rock mass is exposed, the surrounding rock of the newly exposed surface transfers heat to the air at a faster rate, along with the rock wall. Gradually cooled by the wind, the heat transfer of the rock wall and the air gradually decreases, and finally the temperature of the rock wall approaches the temperature of the air. Since the heat transfer between the rock wall and the air is unstable, the temperature field inside the rock mass and the temperature of the air are also constantly changing, combined with the irregular shape of the roadway, the complexity of the interface between the air and the surrounding rock, and the surrounding rock and underground. The heat exchange process of the wind current is often accompanied by the mass exchange, so it is difficult to accurately calculate the heat that the surrounding rock transmits to the downhole air. In most cases, some simplified assumptions are made before calculation [3].

Main heat source of the mine

The increase of mine temperature is mainly caused by the exothermic effect of various heat sources in the mine. The main heat sources are:

– The surrounding rock cooling and exothermic, the heat release depends on the exothermic coefficient, the original temperature, the heat dissipation area and the rock. Factors such as exposure time, as shown in fig. 1, are the dynamic processes of changes in surrounding rock temperature.
– Oxidation exotherm, that is, the heat released from coal by underground coal, coal dust and wood support.
– Exothermic work of mining machinery, such as rock excavator, rock loader*, etc.* when working;
– Transport aircraft.
– The work of the indoor electromechanical equipment is exothermic, such as the water pump in the pump house, the transformer in the substation, the hoist in the winch room*, etc.*
– The heat release of the ventilation system For example, downhole fan and duct release.
– Mine water cooling and exothermic, some mines have higher fissure water temperature, which constitutes the influence of hot water on temperature rise.
– When workers work during heat release and heavy physical labor. A worker's heat release for one hour is equal to 250 J.

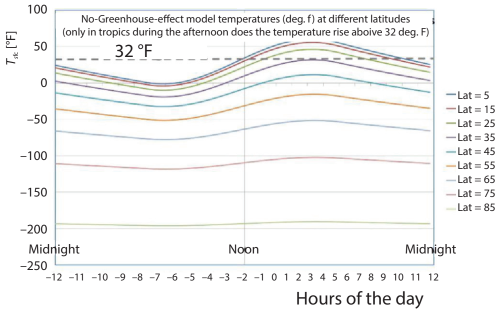

Figure 1. Dynamic process of variation of surrounding rock temperature

Heat transfer around the surrounding rock

The thermal state of the earth's crust

The earth is a hot body that constantly dissipates heat into space while receiving the radiant heat of the Sun. The balance between heat dissipation and heat absorption determines the temperature field at the top of the crust. The total heat radiated from the interior of the Earth and then through the ground to the space is about 1.025×1021 J, while the surface of the Earth receives about 2.345×1024 J of solar radiation, which is three orders of magnitude larger than the former. Therefore, the stability of the surface and the outermost layer of the crust is essentially determined by the thermal radiation of the Sun. Since the solar thermal radiation has a periodic change, a diurnal change in temperature, an annual change, and a long-term change in the century are generated in the uppermost layer of the earth's crust.

Influence of ground temperature cycle change on ground temperature

The temperature at a certain part of the Earth's surface is mainly related to the intensity of sunlight radiation and the angle between the Sun and the ground, the location of the Earth in the orbit of the solar system, the absorption of the local atmosphere, the distribution of vegetation, topography and surface water. For rock formations with flat ground, uniform lithology and isotropic, it can be considered that the temperature at any time varies only with depth.

Thermostatic belt and its determination

The temperature of the surface layer of the earth's crust is affected by the periodic variation of the ground temperature, which is weakened with the increase of the depth. At a certain depth, the effect will almost disappear and the ground temperature will remain basically constant. A layer in which the ground temperature remains constant throughout the year is called a constant temperature zone or a neutral zone. Above the constant temperature zone, the ground temperature is periodically affected by solar radiation and is called a variable temperature zone or an outer zone [4]. Below the constant temperature zone, the change in ground temperature is subject to the internal heat of the Earth and increases continuously as the depth increases, known as the warming zone or the inner tropics. The thermostatic zone is the interface between the inner and outer tropics. The depth and temperature of the zone's thermostatic zone can be measured by drilling. It must be noted that the selected observation holes should be able to represent the natural conditions of the area. Within one year, the ground temperature observation is appropriate once a month. A depth temperature curve is made based on each observation data to find a layer break whose temperature change tends to be constant, thereby determining the depth and temperature of the constant temperature zone.

The problem of the solution of the surrounding rock low temperature field in the shaft

Rock mass temperature is one of the largest heat sources in heat-damaged mines. The phenomenon that geothermal heat transfer to the wind through the surrounding rock is related to the heat conduction of the surrounding rock itself, the convective heat transfer of the roadway wall to the wind flow, and the evaporation of water on the wall. In order to simplify the conditions and facilitate the discussion of its essence, this paper assumes that the supply temperature of the starting point of the ventilation tunnel is constant, there is no water evaporation on the wall surface of the roadway, the rock mass is homogeneous, and the same nature. By controlling the differential equations and the conditions of the solution, the problem of the solution of the surrounding rock in the surrounding rock can be obtained:

$$\frac{\partial \theta}{\partial t} = a\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial t}\right) \qquad \left(r_0 < r < R;\ t > 0\right) \tag{1}$$

$$\theta(r,t)|_{t=0} = \theta_0 \qquad \left(r < r_0 \leq R\right) \tag{2}$$

$$\frac{\partial \theta}{\partial r}|_{r=r_0} = \frac{\alpha}{\lambda}\left(\theta_w - \theta_a\right) \qquad (t > 0) \tag{3}$$

$$\theta(r,t)|_{r=R} = \theta_0 \qquad (t \geq 0) \tag{4}$$

where θ is the temperature distribution function of the surrounding rock low temperature field, r – the radial variable of the limited geothermal field, t – the radial ventilation time variable, a [m^{2}s^{-1}] – the rock thermal conductivity coefficient, λ [Wm^{-1}°C^{-1}] – the thermal conductivity of the rock, r_0 [m] – the circular tunnel radius, or equivalent radius, R [m] – the represents the radial depth of the finite geothermal field (heating coil depth), θ_0 [°C] – the initial rock temperature, θ_w [°C] – the wall temperature of the well, θ_α [°C] – the well Wind flow temperature, α [Wm^{-1}°C^{-1}] – the heat transfer coefficient of the wall of the roadway.

The mathematical model of eqs. (1)-(4) is a model of an unstable finite-temperature field. If $R \to \infty$ is used in eq. (4):

$$\theta(r,t)|_{r\to\infty} = \theta_0 \qquad (t \geq 0) \tag{5}$$

Then eqs. (1)-(3) and eq. (5) together form a fixed solution problem for the unsteady semi-infinite temperature field of surrounding rock in the roadway. The infinite field can be used as a special case of the finite field, and in the geothermal field, their isothermal distribution law is the same, but it is different on the outer boundary. Therefore, the study of the distribution law of the geothermal field can also be described by the mathematical model of the semi-infinite plane temperature field when the temperature distribution does not affect the outer boundary:

$$\frac{\partial \theta}{\partial t} = a\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial t}\right) \qquad \left(r > r_0,\ \ t > t_0\right) \tag{6}$$

$$\theta(r,t)\,|_{t=0} = \theta_0 \qquad (r > r_0) \tag{7}$$

$$\frac{\partial \theta}{\partial r}\,|_{r=r_0} = \frac{\alpha}{\lambda}\left(\theta_w - \theta_a\right) \qquad \left(t > 0\right) \tag{8}$$

$$\theta\left(r,t\right)|_{r\to\infty} = \theta_0 \qquad \left(t \ge 0\right) \tag{9}$$

If the analytical solution of the solution problems (6)-(9) is obtained, the temperature distribution law in the temperature field of the surrounding rock of the well can be expressed. Since the control differential eq. (6) is difficult to solve, the distribution law of the geothermal field cannot be expressed in the simple form and approximate analytical solution is in practical use. The analytical solutions obtained from the references are:

$$\theta\left(r,t\right) = \theta_0 + \frac{\alpha\left(\theta_w - \theta_a\right)}{\lambda} r \ln\left(\frac{r}{r_0}\right) \operatorname{erfc}\left[\frac{\ln\dfrac{r}{r_0}}{2\sqrt{st}}\right] - \frac{2\alpha r\left(\theta_w - \theta_a\right)}{\lambda}\sqrt{\frac{st}{\pi}}\exp\left[-\frac{\ln^2\left(\dfrac{r}{r_0}\right)}{4st}\right] \tag{10}$$

where

$$\operatorname{erfc}\left(z\right) = 1 - \operatorname{erf}\left(z\right) = 1 - \frac{2}{\sqrt{\pi}}\int_z^0 \mathrm{e}^{-u^2}\mathrm{d}u, \quad \text{is called the residual probability integral}$$

Numerical simulation of surrounding rock heat dissipation based on fluid dynamics software FLUENT

The tunneling face is always in the newly exposed rock mass. The surrounding rock temperature is close to the original rock temperature and the thermal damage load is large. The complex 2-D flow system in the tunneling face is used as the simulation object. By appropriate simplification, the CFD software FLUENT is used. Simulate the temperature field of the roadway.

Model assumptions

The heat exchange between the surrounding rock and the wind flow in the underground roadway is a very complicated problem, which is affected by many factors, such as: thermophysical properties of surrounding rock, water flow in surrounding rock, wind temperature, wind speed*, etc.* It is almost impossible to build a mathematical model completely according to the actual situation. Therefore, according to the content of the study, we must grasp the contradiction, ignore the secondary contradictions, and make appropriate assumptions.

The surrounding rock of the roadway is homogeneous and isotropic

The thermophysical properties of the surrounding rock are affected by geology and thus vary widely. Different regions, different mines, and different depths have different structural characteristics. Even in the same area, in the same mine, in the same depth of the roadway, the surrounding rock may show different properties in all directions. If the different properties and characteristics of surrounding rock are considered in the calculation of heat and humidity, the problems studied will be complicated and difficult to calculate. Therefore, it is assumed in this paper that the surrounding rock is homogeneous and isotropic.

At the beginning of the analysis, the temperature inside the surrounding rock is uniform and equal to the original rock temperature

Below the constant temperature layer, it can be considered that the temperature of the rock is only related to the depth, and the surrounding rock at a certain depth is constant. However, in reality, due to the influence of groundwater flow in rocks, the original rock temperature of a certain depth of rock is not necessarily uniform, and some places may be slightly higher, some places may be slightly lower, but at the same depth. The variation of rock temperature is not very large, so it can be assumed that the original rock temperature is uniform at a certain depth, and at the beginning of the analysis, the temperature of the surrounding rock is the original rock temperature at that location [5].

The cross-sectional area of the roadway is circular and the heat flow direction is radial

In practice, the shape of the roadway is different due to different mining conditions, and the common ones are trapezoidal, semi-circular, and the like. It is difficult to reflect the influence of shape factors on the heat transfer process from the model. Therefore, it is only possible to select a relatively common basic shape close to the general roadway, that is, a circular shape for analysis. In fact, the temperature field of the surrounding rock in different shapes of roadway is only limited to a small distance from the wall surface of the roadway. The temperature field of the rock mass is already concentric, so the shape of the roadway section is opposite to the underground. The huge rock mass has a small impact and it can be assumed that the roadway section is circular. In order to further simplify the problem, the heat transfer in the longitudinal direction of the surrounding rock of the roadway is neglected, and only the radial heat transfer is considered.

The entire roadway has the same heat exchange conditions along the length direction and the circumferential direction

Due to different support methods, the surrounding wall of the roadway has different heat transfer conditions on the wall. In order to analyze the problem, it is assumed that the heat transfer conditions of a certain roadway are the same everywhere, in the circumferential direction of the roadway section. The heat transfer conditions are the same.

Theoretical basis of mathematical models

The physical conditions of the wind flow in the heading face are complicated and have many influencing factors. The following assumptions are made for the convenience of research:

- the ventilation air-flow is regarded as an incompressible gas, ignoring the heat dissipation caused by the work of the fluid viscous force, excluding water vapor evaporation and gas desorption, the physical property parameters of solids and gases are regarded as constant,
- the turbulent viscosity of the flow is isotropic, the turbulent viscosity coefficient A is regarded as scalar processing,
- the flow is steady-state turbulence; the Bossiness assumption is satisfied, and
- there is no chemical reaction between the components of the gas stream.

The flow of the air-flow in the roadway complies with the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy.

The governing equation is a mathematical description of these conservation laws. The governing equations, combined with specific boundary conditions and initial conditions, constitute the mathematical model of the wind flow in the tunneling face. Mass conservation or a continuity equation can be expressed:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(p u_i\right)=s_m \tag{11}$$

where ρ is the gas density, t – the time, u_i – the velocity in the i-direction on the co-ordinate system, x_i – the spatial position in the i-direction of the co-ordinate system, and the source term s_m – the mass added to the continuous phase or other custom source phase. The momentum conservation equation can be expressed:

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\rho \mathrm{g}_\mathrm{i}+F_i \tag{12}$$

where x_j is the spatial position in the j-direction of the co-ordinate system, u_j – the velocity in the j-direction of the co-ordinate system, p – the static pressure, τ_{ij} – the stress tensor, and g_i and F_i are the gravity and external in the i-direction. The energy conservation equation can be expressed:

$$\frac{\partial}{\partial t}(\rho T)+\operatorname{div}(\rho \vec{\mathrm{u}} T)=\operatorname{div}\left(\frac{h}{c_p} \operatorname{grad} T\right)+S_T \tag{13}$$

where T is the temperature, $\vec{\mathrm{u}}$ – the velocity vector, h – the heat transfer coefficient of the fluid, c_p – the specific heat capacity, and S_T – the other volumetric heat source.

Selection of the main control equation

Considering the problem of incompressible air-flow, the basic equation is the Reynolds equation, the time-averaged term of each variable is omitted, and the turbulence model is model k-ε. Equations k and ε are shown in eqs. (14) and (15), respectively:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial\left(\rho k u_i\right)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(v+\frac{v_i}{\sigma_k}\right) \frac{\partial k}{\partial x_j}\right]+G_k-\rho \varepsilon \tag{14}$$

$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial\left(\rho \varepsilon u_i\right)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(v+\frac{v_1}{\sigma_{\varepsilon}}\right) \frac{\partial \varepsilon}{\partial x_j}\right]+C_{1 \varepsilon} \frac{\varepsilon}{k} G_k-C_{2 \varepsilon} \rho \frac{\varepsilon^2}{k} \tag{15}$$

$$G_k=v_1\left[\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right] \tag{16}$$

where k, ε, and v are turbulent flow energy, turbulent flow energy dissipation rate, and layer flow force viscosity coefficient, respectively, $C_{1\varepsilon}$, and $C_{2\varepsilon}$ are empirical constants, σ_k and σ_ε are Prandtl numbers corresponding to k and ε, respectively, G_k – the turbulent energy caused by the average velocity gradient produces a term. In the k-ε two-equation model, the model constants are taken as $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $\sigma_k = 1.00$, and $\sigma_\varepsilon = 1.30$ according to the recommended values and experimental verification.

Establishment of physical model

Model geometry and meshing

For the convenience of analysis, the roadway for excavation is simplified into a 2-D roadway space, the specific size is. There is a boring equipment at the heading face, which is simplified in size. When working with the boring machine, the temperature of the boring machine is higher, the measured local temperature is reachable, and the average temperature of the body is the main heat source for the boring face. The heading face is press-fitted with a single-layer canvas air duct for air supply. The distance from the outlet of the air duct to the heading face is that the outlet temperature of the air duct is about [6].

Determination of boundary conditions and calculation methods

According to the physical model of the roadway, the entrance of the air duct is set as the entrance boundary of the model, and the free section of the roadway is used as the exit boundary of the model. The inlet boundary conditions are: inlet temperature $T = 298$ K, inlet wind speed $v = 20$ m/s, (general constant c is usually taken as 0.5-1.5%), $\varepsilon = 100\, ck^{2/3}/0.03$. The exit boundary condition is $p = p_{\text{out}}$, there is no relative pressure, and k and ε slide freely. Wall boundary conditions: all walls have no sliding boundary conditions. In combination with the selected main control equation, the implicit separation 2-D steady flow solver is selected, the speed is absolute speed, the gradient unit based on volume unit is used, the SIMPLEC algorithm is used to solve the flow velocity and pressure coupling, and the pressure gradient effect is used to strengthen the wall surface treatment. In this way, the standard k-ε turbulence model is used to close the time-average equation. The excuse viscosity coefficient and density take the arithmetic mean of the adjacent nodes. The pressure field adopts the standard discrete method, and the other uses the second-order up-style discrete.

Temperature measuring instruments and methods

The original rock temperature of the coal mine roadway and the air parameters in the roadway were measured. Six roadways with a mining time of less than one year are selected, with elevations of –540 m, –580 m, –640 m, –690 m, –750 m, and –790 m. In each lane, a hole is opened in the horizontal direction (0°) and the upward inclination (75°), and the aperture is 3 cm. It can be seen that the radius of the roadway heating circle within one year is less than 10 m, so the drilling depth is set to 10 m.

Simulation results

According to the actual situation of the mine, after comparative analysis, it is preferred that the air supply volume of the excavation roadway is the thermal environment evaluation of the two ventilation schemes in order to select the optimal ventilation scheme. In the case of two air supply volumes, the air-flow temperature of the roadway is shown in fig. 2:

– During the process of the wind flow exiting from the exit of the air duct to the heading face, due to the high original rock temperature on the wall of the roadway and the large heat dissipation of the excavation equipment, the wind flow is subjected to intense heat and moisture exchange, along the flow direction of the wind flow, the wind flow. The temperature of the tunnel is gradually increased. In the air-flow of the same section, due to the influence of the airlifting force, the hot air-flow rises continuously, and the temperature of the tunnel section gradually decreases from top to bottom.

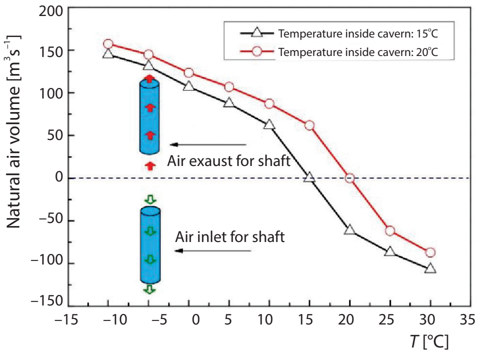

Figure 2. Distribution of air-flow temperature in roadway with different air volum

– With the continuous expansion of the wind flow toward the roof, the floor and the side wall, the temperature of the air-flow gradually increases. The air volume increases, and the temperature of the jet is longer. Due to the limited space of the roadway, the effect of the attachment is the better, the higher the temperature of the attached temperature and the lower the temperature.
– When the air supply volume is A, the air-flow temperature in the roadway exceeds 28 °C, and the wind temperature in the tunneling face is as high as 33 °C. Increasing the air supply volume, the air-flow temperature in most areas of the roadway is lower than 36 °C, and only the local area temperature is higher. Because when the air supply volume increases, the momentum of the air-flow also increases, the amount of cooling caused by the air-flow also increases, and the temperature in the roadway is also lower. As the supply air volume increases, the temperature of the tunneling tunnel gradually decreases as the wind speed increases. The excavation working face of the high-temperature mine increases the air supply volume and increases the wind speed, which can reduce the working surface temperature and improve the working surface climate. Appropriately increasing the air supply volume is an effective measure for cooling the roadway and should be given priority.

Conclusion

The paper uses theoretical analysis, laboratory measurement and field measurement to study the unstable heat transfer coefficient of surrounding rock and the original rock temperature of the roadway. Before carrying out the thermal calculation of roadway and surrounding rock, firstly study the heat transfer mechanism of surrounding rock and air-flow in the roadway. Through the analysis of the source of the surrounding rock heat, the influence factors of the surrounding rock heat transfer and the influence of the wind flow on the surrounding rock of the roadway, the heat transfer law of the surrounding rock and the wind flow of the whole roadway is understood, which lays a foundation for the next mathematical modelling and formula derivation.

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