Study on suitable air volume for cooling in horizontal roadway

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Abstract. In the deep mining of mines, the choice of air volume needs to consider both the cooling effect and the energy consumption. In order to obtain the basis for selecting the suitable air volume in the horizontal roadway, based on the theory of heat transfer and thermodynamics, the heat transfer relationship in the horizontal roadway is analyzed. The study found that the suitable air volume mainly considers the influence of three parameters: air self parameters, roadway specification parameters and temperature boundary parameters. As the air volume increases, the cooling effect gradually decreases, and the energy consumption gradually increases. After the air volume reaches a certain value, the cooling effect is basically unchanged, and the energy consumption is too high to bear.

1. Introduction
As mining moves deeper, heat damage is getting worse [1-2]. At present, ventilation and artificial refrigeration are the main solutions to this problem [3-4]. Ventilation is the most economical and effective measure. When the fresh air flow into the roadway, the heat exchange between the rock and air flow occurs, and the air flow has an important influence on it [5-6]. The magnitude of air flow determines the severity of heat damage. At the same time, the reasonable energy consumption of air flow has become a problem that must be considered. Mastering the relationship between ventilation and heat transfer in roadway has become an important part of research [7-8].

In a ventilated horizontal roadway, if the local heat source and humidity exchange have little effect on the thermal environment, the wind flow temperature change only needs to consider the influence of convective heat transfer between the rock and the wind flow [9]. In the case where the thermal physical parameters and ventilation parameters of the roadway are determined, the convective heat transfer amount is equal to the air heat increase. Under different air volume conditions, the convective heat transfer conditions change, and the convective heat transfer and air heat increase will change [10-11].

In the actual production of deep mines, in the face of heat damage in the working environment, it is generally solved by ventilation. After the air volume increases to a certain value, the cooling effect of continuing to increase the air volume will gradually weaken. Therefore, the determination of the suitable air volume that meets the cooling requirements without wasting excessive power consumption is the key to solving this problem.

Based on the air-solid coupling heat transfer theory in horizontal roadway, the frictional resistance under different air volume conditions is analyzed and the applicable air volume calculation equation is...
established. The conclusions of this paper can provide reference for the selection of air volume in horizontal roadway.

2. Mathematical model for suitable air volume

The heat transfer relationship of the roadway is shown in Figure 1. The airflow temperature at the inlet section of the ventilation tunnel is \( t_1 \), the wind flow temperature at the exit section is \( t_2 \), the rock wall temperature is \( t_w \), and the tunnel length is \( L \).

\[
\Phi = hS(t_w - t_f) = hUL\left(t_w - \frac{t_1 + t_2}{2}\right)
\]

(1)

Where: \( \Phi \) is the heat flux of convective heat transfer (W); \( h \) is the convection heat transfer coefficient (W·m\(^{-2}\)·K\(^{-1}\)); \( S \) is the convection heat transfer area (m\(^2\)); \( t_w \) is the rock wall temperature (℃); \( t_f \) is the average temperature of the wind flow (℃); \( U \) is the circumference of the roadway (m); \( L \) is the length of the roadway (m); \( A \) is the cross sectional area (m\(^2\)); \( t_1 \) is the wind flow temperature of the entrance section of the roadway (℃); \( t_2 \) is the airflow temperature at the exit section of the roadway (℃).

The convective heat transfer coefficient and correlation coefficient are calculated as follows:

\[
h = \frac{\lambda}{D} N\nu = \frac{\lambda}{D} 0.023 \text{ Re}^{0.8} \text{ Pr}^{0.4}
\]

(2)

\[
\text{Re} = \frac{\rho v D}{\mu}
\]

\[
\text{Pr} = \frac{c_p \mu}{\lambda}
\]

\[
D = \frac{AA}{U}
\]

Where: \( \lambda \) is the fluid thermal conductivity, air thermal conductivity is 0.025 W/(m·K); \( D \) is the feature
length (m); $Nu$ is Nusselt number; $Re$ is Reynolds number; $Pr$ is Prandt number; $n$ is 0.4 when the air is heated, and 0.3 when the air is cooled; $\rho$ is the air density (kg/m$^3$); $v$ is the air flow velocity (m/s); $\mu$ is the dynamic viscosity coefficient (Pa·s); $c_p$ is the specific pressure heat capacity (J·kg$^{-1}$·K$^{-1}$).

The parameters are taken into equation (1) and simplified, and the convective heat transfer is:

$$\Phi = \frac{0.01743 U^{1.2} L^{0.6} c_p^{0.4} \rho^{0.4} U^{0.8} v^{0.8}}{A^{0.2} \mu^{0.4}} \left( t_x - \frac{t_1 + t_2}{2} \right)$$  \hspace{1cm} (3)

The formula for calculating the ventilation of the roadway is $Q = vA$. The wind speed $v$ in the formula is replaced by the air volume $Q$, and the heat transfer amount in the formula is:

$$\Phi = \frac{0.01743 U^{1.2} L^{0.6} c_p^{0.4} \rho^{0.4} Q^{0.8}}{A^{0.2} \mu^{0.4}} \left( t_v - \frac{t_1 + t_2}{2} \right)$$  \hspace{1cm} (4)

The formula for calculating the air heat increment in the roadway is:

$$\Phi_q = c_pM(t_2 - t_1) = c_p \rho Q(t_2 - t_1)$$  \hspace{1cm} (5)

Where: $\Phi_q$ is the wind flow heat increment (W); $M$ is the mass flow (kg/s); $Q$ is the air volume (m$^3$/s).

The heat flux for convective in the ventilated tunnel is equal to the air heat increment, so $\Phi = \Phi_q$. The formula changes to:

$$Q^{0.2} = \frac{0.008715 U^{1.2} L^{0.6}(2t_v - t_1 - t_2)}{c_p^{0.6} \rho^{0.2} A^{0.4}(t_2 - t_1)}$$  \hspace{1cm} (6)

According to the exponential function algorithm, the formula can be obtained:

$$Q = \frac{5.03 \times 10^{-11} U^{6} L^{11} A^{3}(2t_v - t_1 - t_2)^5}{c_p^3 \rho A^6 \mu^2 (t_2 - t_1)^3}$$  \hspace{1cm} (7)

In the actual ventilation tunnel, the air parameters change very little, $\lambda$, $\rho$, $c_p$ and $\mu$ are close to the fixed value. These parameters are summarized into $N$ (unit:m$^2$/s), and the formula can be further simplified as:

$$N = \frac{5.03 \times 10^{-11} A^3}{c_p^3 \rho \mu^2}$$

$$Q = N \cdot \left( \frac{U^6 L}{A^3} \right) \cdot \left( \frac{2t_v - t_1 - t_2}{t_2 - t_1} \right)^5$$  \hspace{1cm} (8)
In the actual roadway ventilation process, the suitable air volume to meet the requirements is usually difficult to determine. Where $t_2$ can be considered as the temperature of the wind flow after the wind reaches the exit. It can be used to determine the appropriate air volume according to formula (8).

The first term $N$ on the right side of the formula represents the influence of the air's own parameters on the suitable air volume, which is mainly affected by the air temperature, humidity and pressure. The $\frac{U^6L^5}{A^5}$ in the formula reflects the influence of the roadway specification parameters—circumference, length and area on the suitable air volume. the $\left(\frac{2t_w - t_1 - t_2}{t_2 - t_1}\right)^5$ in the formula reflects the influence of the air wall temperature parameters on the suitable air volume. In the analysis of the relationship between the ventilation and cooling of the horizontal roadway, the suitable air volume mainly considers the influence of the air's own parameters, the roadway specification parameters and the air wall temperature boundary parameters.

The theoretical model is verified by measured data and numerical simulation experiments.

3. Experimental verification of theoretical model

3.1. Field measured data
The thermal physical parameters of the 900m long roadway in the No.1 well of Xiadian gold mine were selected and verified. The arched roadway has a sectional area of $10.9m^2$, a circumference of 13m, a wind speed of 1.6m/s, an atmospheric pressure of 110.3kPa, an inlet airflow temperature of 25.5℃, an outlet airflow temperature of 27.7℃, and an average rock wall temperature of 27.9℃ (the fluctuation range is 27.5~28.3℃). The distance between the temperature measurement points in the roadway is 30m, and the measurement point monitors the air temperature change of the section. The experiment uses the trace method to test. The air temperature changes along the wind flow are shown in Table 1.

| Ventilation distance /m | Air temperature /℃ | Ventilation distance /m | Air temperature /℃ |
|------------------------|---------------------|------------------------|---------------------|
| 0                      | 25.5                | 480                    | 26.7                |
| 30                     | 25.4                | 510                    | 26.7                |
| 60                     | 25.4                | 540                    | 26.7                |
| 90                     | 25.4                | 570                    | 26.7                |
| 120                    | 25.4                | 600                    | 26.8                |
| 150                    | 25.5                | 630                    | 26.8                |
| 180                    | 25.5                | 660                    | 26.9                |
| 210                    | 25.8                | 690                    | 27.2                |
| 240                    | 25.8                | 720                    | 27.2                |
| 270                    | 25.8                | 750                    | 27.3                |
| 300                    | 25.9                | 780                    | 27.5                |
| 330                    | 26                  | 810                    | 27.6                |
| 360                    | 26.2                | 840                    | 27.6                |
| 390                    | 26.3                | 870                    | 27.7                |
| 420                    | 26.5                | 900                    | 27.7                |
| 450                    | 26.7                |                        |                     |
3.2. Numerical simulation experiment parameters setting

The numerical simulation experiments are carried out by using ANSYS Fluent 19.0. A numerical calculation model is established based on the measured data. The model is shown in Figure 2.

![Horizontal roadway model diagram](image)

The model is meshed, and the number of meshes is 113,000. The maximum skewness of the mesh is 0.2. The number and quality of the meshes meet the experimental needs.

The model and grid data are imported into Fluent, and the parameters setting informations in Fluent are shown in Table 2.

| Parameters name          | setting informations | Parameters name         | setting informations |
|--------------------------|----------------------|-------------------------|----------------------|
| Solver                   | Pressure base solver | Inlet speed             | 1.6m/s               |
| Time                     | steady state         | Inlet air temperature   | 25.5°C               |
| Energy equation          | on                   | Entrance boundary type  | speed entrance       |
| Model standard           | k-ε model            | Export boundary type    | free entrance        |
| Turbulence intensity     | 3.20%                | Wall temperature boundary| 27.9°C                |
| Hydraulic diameter       | 3.28m                | Solution method         | SIMPLE                |

3.3. Analysis of results

The $N$ value is calculated from the dry air parameters at an air pressure of 110.3kPa and a temperature of 25.5°C. $\lambda=0.025\text{W/(m·K)}$, $\rho=1.28 \text{ kg/m}^3$, $c_p=1006.7\text{J/(kg·K)}$, $\mu=1.84\times10^{-5}\text{Pa·s}$, $N$ is calculated to be $1.78\times10^{-15}\text{m}^2/\text{s}$. Substituting the parameters in the roadway into Equation 8, obtaining $t_2=28.05^\circ\text{C}$.

The air temperature data in the numerical simulation experiment are collected and the average temperature data are calculated. The average temperature data and the measured data of the Xiadian gold mine are shown in Figure 3.
Figure 3. Temperature data of simulation and field experiments.

It can be seen from Figure 3 that the measured temperature is stepwise as a whole, and the outlet temperature is 27.7 °C. The simulated experimental temperature value rises briefly in the entrance section of the roadway, and then the temperature rises quickly. The temperature of the simulated experiment increases with the ventilation distance, and the increase rate gradually slows down. The outlet temperature value is 27.76. The two temperature curves have a large separation in the middle, but the difference at the exit is extremely small. The theoretical calculation of the outlet temperature value is 28.05 °C, which is different from the simulated experimental temperature and the measured temperature by 0.4 °C or less. The theoretical calculation results can reflect the change of the airflow temperature at the exit of the horizontal ventilation tunnel.

4. Air volume and outlet temperature
With the increase of air volume, energy consumption is also increasing. The main ventilation resistance in horizontal roadway is friction resistance. The calculation formula of friction resistance in ventilation roadway is as follows:

\[ h_f = \alpha \frac{LUQ^2}{A^2} \]  \hspace{1cm} (9)

Where: \( h_f \) is the friction resistance (Pa); \( \alpha \) is the friction resistance coefficient (N·s²/m⁴).

According to the table calculation, the friction coefficient of the experimental roadway is 0.008 N·s²/m⁴, and the friction resistance is 21.98Pa under the condition of the air volume.

According to formula 8, other parameters are set unchanged, only air volume is changed, and the changes of outlet temperature and friction resistance are analyzed. The experimental air volume is 17.44m³/s, and the range of air volume is set to be 1-5 times of that value. After calculation, the values of \( t_2 \) and \( h_f \) are obtained, as shown in Figure 4.
Figure 4. Relationship between outlet airflow temperature, frictional resistance and air volume.

As shown in Figure 4, the air volumes are 17.44m$^3$/s, 26.16m$^3$/s, 34.88m$^3$/s, 43.6m$^3$/s, 52.32m$^3$/s, 61.04m$^3$/s, 69.76m$^3$/s, 78.48m$^3$/s, 87.2m$^3$/s respectively, $t_2$ are 28.05℃, 27.96℃, 27.89℃, 27.83℃, 27.79℃, 27.75℃, 27.72℃, 27.69℃, 27.67℃ respectively, and $h_f$ are 21.98Pa, 49.46Pa, 87.93Pa, 137.39Pa, 197.85Pa, 269.29Pa, 351.73Pa, 445.16Pa, 549.58Pa respectively. When the air volume increases from 17.44m$^3$/s to 87.2m$^3$/s, the air volume increases by 5 times. The outlet airflow temperature $t_2$ only drops less than 0.5℃, while the frictional resistance increases by nearly 25 times, and the energy consumption is severe. It is also unreasonable to consider the economics of ventilation. As can be seen from the figure, even if the air volume is increased a lot, the cooling effect is still not ideal. The ventilation cooling effect should be judged by considering the length of the roadway and the thermal boundary parameters.

When the air volume is 26.16m$^3$/s, the outlet airflow temperature is less than 28℃, which meets the requirements of the China Metal Non-Metal Mine Safety Regulations. The frictional resistance is 49.46Pa, and the resistance is also within the acceptable range. Considering comprehensively, the air volume can be determined as the suitable air volume for ventilation cooling.

5. Conclusion
The conclusions of this paper are as follows:

(1) In the horizontal roadway, the suitable air volume for cooling should consider the influence of three parameters: air self parameters, roadway specification parameters and air wall temperature boundary parameters. The air self parameters refer to air temperature, humidity and pressure; the roadway specification parameters refer to the circumference, length and area of the roadway; the gas wall temperature parameters refer to the wall surface temperature and the inlet temperature.

(2) As the air volume increases, the cooling effect gradually decreases, and the energy consumption gradually increases. After the air volume reaches a certain value, the cooling effect is basically unchanged, and the energy consumption is too high to bear. The suitable air volume objectively exists in a reasonable range.

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