Analysis on the Factors of Heat Transfer Rate and Air Volume in Tunnel

Cuifeng Du and Menglong Bian
School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China
243519027@163.com

Abstract. In order to obtain the relationship between ventilation and heat transfer of tunnel under certain conditions, the paper analyses the convective heat transfer phenomenon under the limited conditions of driving tunnel. A simplified mathematical formula is established between heat transfer rate and air volume, which explained a phenomenon that the cooling effect is hard to be improved as air volume is increasing and in actual ventilation. According to the established mathematical formula, the ratio of heat transfer rate to air volume is analyzed in different circumstances through the field experiment and numerical simulation. A conclusion is drawn that the ratio of $\Phi / Q$ can be proposed to evaluate the ventilation cooling effect.

1. Introduction
With the depletion of shallow mineral resources, many mines have entered deep mining [1]. The heat hazard is caused by high ground temperature in deep mining [2-3]. Heat hazard is derived from compressed air, high temperature rock and equipment [4-5]. At present, the main methods to solve heat hazard are ventilation cooling, air conditioning and refrigeration, isolated heat, individual protection [6-7]. The air-conditioning system is accounted for more than 20% of all electricity costs in mine for solving the heat hazard [8-10]. Ventilation is an economical and effective way of cooling, and it can solve the problem of heat hazard which is not serious. Grasping the relationship between ventilation and heat transfer is the basis to solve the problem of heat hazard, especially in the tunnel [11-12].

Excavated tunnel has the most serious heat hazard underground for heat is easy to accumulate due to its unique form of space. It is very important to prevent and control underground heat hazard by studying the laws of ventilation and cooling in excavated tunnel and the optimal setting of ventilation parameters.

Based on the basic theory of heat transfer, a simplified mathematical formula is established between the convective heat transfer rate and air volume, which explains a phenomenon that the cooling effect is hard to be improved as air volume is increasing and in actual ventilation. The ratio of $\Phi / Q$ can be proposed to evaluate the ventilation cooling effect through field experiment and numerical simulation.

2. Convective heat transfer model of tunnel head
There exists heat exchange in the form of thermal convection and thermal radiation between air and rock [13]. The thermal radiation can be neglected because the main components in the air are $O_2$ and
N₂ which neither emits nor absorbs radiation as two-atom gas [14]. Excluding the impact of water, only thermal convection needs to be considered in the cooling of surrounding rock.

After a long time of mine ventilation, the tunnel surface temperature is basically stable and the air which regarded as an incompressible fluid also has a stable temperature [15]. Without considering the heat and moisture exchange and other heat sources, it can be concluded that the heat dissipation of the surrounding rock is only caused by the thermal convection. In order to simplify the analysis process, this paper analyzes the heat convection in “Heat exchange area”, as shown in Figure 1.

![Figure 1. Sketch drawing of heat convection in tunnel.](image)

As shown in Figure 1, the fresh air temperature of the forced ventilation is set to be constant, and the air flow is heat exchange in the space between the outlet of the air duct and the head of the tunnel. The temperature of the rock wall is also constant, so only the ventilation air volume has an effect on the heat exchange. In this paper, the relationship between convective heat flow and ventilation air flow is established. According to convective heat flow calculation formula:

$$\Phi = qA$$

(1)

Where: $\Phi$ is convective heat transfer rate (W or J/s); $q$ is heat flux (W/m²); $A$ is convective heat transfer area (m²); The calculation formula of $q$:

$$q = h (t_w - t_f)$$

(2)

Where: $t_w$ is the temperature of rock surface(℃); $t_f$ is the average temperature of the fluid(℃); $h$ is convective heat transfer coefficient(W/m²•K). The calculation formula of $h$:

$$h = \frac{\lambda}{D} N_u$$

(3)

Where: $\lambda$ is thermal conductivity of the fluid (W/m•K), and the thermal conductivity of air is 0.025 W/m•K; $D$ is characteristic length (m); $N_u$ is Nusselt number (dimensionless).

According to the experimental formula of forced convection tube, the calculation formula of $N_u$:

$$N_u = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}$$

(4)

Where: $Re$ is Reynolds number:

$$Re = \frac{\rho vD}{\mu}$$

$\rho$ is fluid density (kg/m³); $v$ is fluid velocity (m/s); $\mu$ is dynamic viscosity coefficient (Pa•s). $Pr$ is Prandt number:

$$Pr = \frac{C_p \mu}{\lambda}$$

$C_p$ is specific heat at constant pressure (kJ/kg•K). The calculation formula of $C_p$:

$$C_p = 1.05 - 0.365\theta + 0.85\theta^2 - 0.39\theta^3$$
\[ \theta = \frac{T}{1000} = 273.15 + t \]

Substituting (2), (3) and (4) into formula (1), a conclusion is obtained:

\[ \Phi = 0.023 \frac{\lambda^{0.6} \rho^{0.8} C_p^{0.8} A (t_y - t_f)}{D^{0.2} \mu^{0.4}} \]

(5)

According to the air volume calculation formula: \( Q = v \cdot S \), substituting it into formula (5).

\[ \Phi = 0.023 \frac{\lambda^{0.6} \rho^{0.8} C_p^{0.8} A (t_y - t_f)}{D^{0.2} \mu^{0.4} S^{0.8}} \]

(6)

When the temperatures of rock surface and inlet air are constant, the data such as \( \lambda \), \( \rho \), \( C_p \), \( A \), \( D \), \( \mu \) and \( S \) are basically stable. The formula (6) is simplified as:

\[ \Phi = k Q^{0.8} (t_y - t_f) \]

(7)

The coefficient of \( k \) in the formula is considered to be constant:

\[ k = 0.023 \frac{\lambda^{0.6} \rho^{0.8} C_p^{0.8} A}{D^{0.2} \mu^{0.4} S^{0.8}} \]

The convective heat flow is directly proportional to the 0.8th power of the air volume and the temperature difference between air and wall. The temperature difference is constant after a long time of mine ventilation, and the air temperature is falling not noticeable due to the increased air flow along with the heat flow. This is the reason that the air cooling effect is not obvious as the air flow is increasing. The field experiment and numerical simulation are used to analyze the relationship next.

3. Field experiment

In the field experiment, an arch tunnel is selected that is 5.4 m² of sectional area and is 8.9 m of perimeter. A ventilator was set in the tunnel, and the model is JK67-2 with the power of 11 kW. A flexible duct connected to the ventilator has a diameter of 0.4 m and there is 10 m between inlet air and tunnel head face. The inlet air temperature is 22.5 °C, the rock wall temperature is 29 °C, and the air temperature is 29 °C in the area before the ventilation. In the field experiment, the measuring points are arranged in several sections of the area, and the average temperature of the section is monitored. The 1 hour experimental data as shown in Table 1.

| time (min) | \( t_f \) (°C) | time (min) | \( t_f \) (°C) | time (min) | \( t_f \) (°C) | time (min) | \( t_f \) (°C) | time (min) | \( t_f \) (°C) |
|-----------|----------------|-----------|----------------|-----------|----------------|-----------|----------------|-----------|----------------|
| 1         | 29             | 11        | 25             | 21        | 24.7           | 31        | 24.2           | 41        | 24             | 51        | 23.8           |
| 2         | 27             | 12        | 24.9           | 22        | 24.7           | 32        | 24.1           | 42        | 24             | 52        | 23.8           |
| 3         | 26.3           | 13        | 24.9           | 23        | 24.6           | 33        | 24.1           | 43        | 24             | 53        | 23.8           |
| 4         | 25.3           | 14        | 24.9           | 24        | 24.6           | 34        | 24.1           | 44        | 23.9           | 54        | 23.8           |
| 5         | 25.3           | 15        | 24.8           | 25        | 24.6           | 35        | 24.1           | 45        | 23.9           | 55        | 23.8           |
| 6         | 25.2           | 16        | 24.8           | 26        | 24.4           | 36        | 24.1           | 46        | 23.9           | 56        | 23.8           |
| 7         | 25.2           | 17        | 24.7           | 27        | 24.5           | 37        | 24.1           | 47        | 23.9           | 57        | 23.8           |
| 8         | 25.1           | 18        | 24.7           | 28        | 24.3           | 38        | 24             | 48        | 23.9           | 58        | 23.8           |
| 9         | 25.1           | 19        | 24.8           | 29        | 24.3           | 39        | 24             | 49        | 23.8           | 59        | 23.8           |
| 10        | 25             | 20        | 24.7           | 30        | 24.3           | 40        | 24             | 50        | 23.8           | 60        | 23.8           |

Table 1 presents a variation of air temperature with ventilation time. The convective heat flow was analyzed after one hour of ventilation: \( \lambda = 0.025 \) W/m·K, \( \rho = 1.183 \) kg/m³, \( C_p = 1006.31 \) J/kg·K, \( T = 11000 \) K, \( w = 0.025 \) W/m²·°C.
$A = 94.4 \text{ m}^2$, $D = 2.43 \text{ m}$, $\mu = 1.825 \times 10^5 \text{ Pa}\cdot\text{s}$, $S = 5.4 \text{ m}^2$. Substituting these data into equation (6) and (7), $\Phi = 652 \text{ W}$, $k = 75.5$. Due to the experimental conditions, the numerical simulation software FLUENT is used to study the heat transfer process under different air flow conditions.

4. Numerical simulation

4.1. Tunnel model
In accordance with the experimental site conditions, the establishment of model is shown in Figure 2. The total length of the tunnel is 11m, and the length of duct is 1m.

![Figure 2. The tunnel model.](image)

4.2. Meshing
The model which is shown in figure 3 is meshed with unstructured meshes, the number of mesh is 137963, and the number of nodes is 31632.

![Figure 3. The meshed model.](image)

4.3. Parameters setting
The parameters are set as table 2. Table 2 presents the performance parameters of Fluent.

| name          | setting information |
|---------------|---------------------|
|               |                     |

Table 2. Fluent parameter settings.
Solver
  time
  Energy equation
    model
    Turbulence intensity
    Hydraulic diameter
    Entry boundary type
    Exit boundary type
Pressure - based solver
  Unsteady state
  on
    Realizable k-ε model
    Turbulence intensity
    3.75% - 5%
    Hydraulic diameter
    2.43m
    Entry boundary type
    velocity
    Exit boundary type
    outflow

4.4. Simulation results

The temperature field was simulated after 1 hour’s ventilation which the air volumes are respectively as 0.38 m$^3$/s, 0.63 m$^3$/s, 0.88 m$^3$/s, 1.13 m$^3$/s, 1.38 m$^3$/s, 1.88 m$^3$/s, 2.39 m$^3$/s, 2.89 m$^3$/s, 3.39 m$^3$/s. Figure 4, figure 5, figure 6, figure 7 are respectively the temperature field of 0.38 m$^3$/s, 1.13 m$^3$/s, 1.88 m$^3$/s, 3.39 m$^3$/s.

Figures presents that the larger the air volume, the greater the influence range of the jet and the more stable the air temperature. The air volume in Figure 6 is the same as that in the experiment. The average air temperature is 23.8°C after one hour of ventilation (Table 1), and the numerical simulation result is 23.7°C, the two values are very close.
In order to analyze the relationship between air volume and convective heat flux, the wall and air temperature values must be determined. Starting from the outlet of the duct, a cross section is selected every 2.5 m, the arithmetical mean of the five sections is taken as the average temperature $t_f$.

### 4.5. Data analysis

After processing the data, $t_f$, which under different air volumes are obtained. According to the formula (7), the calculated data are shown in Table 3, $\Delta t = t_w - t_f$, $t_w = 29^\circ C$, $k = 75.5$.

Table 3 presents that $Q$ is increased from $0.38 \text{ m}^3/\text{s}$ to $3.39 \text{ m}^3/\text{s}$ by 8.92 times, and $\Phi$ is increased by 8.23 times from $137.6 \text{ W}$ to $1132.8 \text{ W}$. Combined with the data to form the air volume $Q$, $\Phi$ and $\Delta t$ changes in Figure 8.

| Q/ m$^3$·s$^{-1}$ | $t_f$/°C | $\Delta t$/°C | $\Phi$/W | $\Phi/Q$/J·m$^{-3}$ |
|-----------------|---------|--------------|----------|--------------------|
| 0.38            | 25      | 4            | 137.6    | 365.1              |
| 0.63            | 24.5    | 4.5          | 232.9    | 370.9              |
| 0.88            | 24.2    | 4.8          | 330.3    | 375.7              |
| 1.13            | 24      | 5            | 414.1    | 366.4              |
| 1.38            | 23.9    | 5.1          | 493      | 356.8              |
| 1.88            | 23.7    | 5.3          | 664.7    | 352.8              |
| 2.39            | 23.5    | 5.5          | 824.6    | 345.5              |
| 2.89            | 23.4    | 5.6          | 985.8    | 341.3              |
| 3.39            | 23.3    | 5.7          | 1132.8   | 334                |

**Figure 8. Relation of $Q$, $\Phi$ and $\Delta t$.**

Figure 8 presents that heat flow will increase with the air volume from the growth trend of $Q$ and $\Phi$. This is consistent with the formula (7). The data of $\Phi/Q$ and $\Delta t$ from Table 3 are formed in Figure 9.
Figure 9. Relation of $\Phi/Q$ and $\Delta t$.

Figure 9 presents that $\Phi/Q$ have different numbers at different $\Delta t$, $\Phi/Q$ has maximum at $\Delta t=4.8 \, ^\circ C$ when $\Phi/Q = 375.7 \, J/m^3$ and $Q = 0.88 \, m^3/s$. The unit of $\Phi/Q$ is $J/m^3$. $\Phi/Q$ can be expressed as the heat transfer in the average unit volume of air, the bigger the number, the more the heat transfer, the greater cooling effect of ventilation. Therefore, $\Phi/Q$ can be used as a cooling indicator to evaluate the effect of ventilation. Strictly speaking, $\Phi$ is a constantly changing number, but the thermal parameters of ventilation and tunnel are stable after a few years or even decades of ventilation, and the heat transfer process is stable, the heat flow is also basically stable. Ventilation and heat transfer are widely existed in mine ventilation. Whether the heat source is from surrounding rock, gushing water or equipment, there exists the maximum number of $\Phi/Q$ in the mine ventilation. The ratio has broad applicability to evaluate the ventilation cooling effect. Under the experimental conditions, the maximum number of $\Phi/Q$ appears only when $\Delta t = 4.8 \, ^\circ C$ and $Q = 0.88 \, m^3/s$. Therefore, the ventilation can solve the problem that heat hazard is not serious in the mine.

5. Conclusion

The conclusions of this paper are as follows:

1) The problem of convective heat transfer in tunnel under limited condition is studied. A simplified mathematical formula is established between heat transfer rate and air volume, which explained a phenomenon that the cooling effect is hard to be improved as air volume is increasing and in actual ventilation.

2) Through the field experiment and numerical simulation, the temperature field data of the tunnel under different air volumes are obtained, and the calculation method of convective heat transfer rate is provided according to the formula (7).

3) The ratio of $\Phi/Q$ can be proposed to evaluate the ventilation cooling effect. It needs to be further verified by theory and practice.

6. References

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