Application of Thermal Pressure Ventilation Technology in Extra Long Construction Tunnel with High Ground Temperature

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Abstract. The feasibility of thermal pressure ventilation technology for ventilation and cooling of extra long construction tunnel with high altitude and high ground temperature was discussed. A physical model was built with a proportional factor of 1:1 based on the design documents of Zilashan tunnel in China. The CFD model considering buoyancy effects was used to evaluated the influence of the initial rock temperature, the insulation performance of the left tunnel and the outdoor air temperature on the effect of thermal pressure ventilation. Results show that the effect of thermal pressure ventilation increases by 12.2%, and the effect of cooling enhances by 3.7% when the left tunnel has no insulation. Compared with the initial rock temperature, the outdoor air temperature has a greater influence on thermal pressure ventilation. When the initial rock temperature is below 54 ℃, outdoor air temperature is below 17.5 ℃ and the left tunnel has no insulation, thermal pressure ventilation technology is feasible for ventilation and cooling of Zilashan tunnel with a shaft of 450 m height. The thermal pressure ventilation technology provides a reference for other construction tunnel projects as a design of ventilation and cooling.

1. Introduction
With the rapid development of economy and technology in recent years, a large number of underground tunnel projects have been built, such as railway, hydropower station and coal mine, and so on. For the construction of deep buried tunnels, the problem of high ground temperature is often encountered. At present, most projects adopt ventilation [1-3] to reduce the tunnel air temperature. When ventilation fails to meet the cooling requirements, artificial refrigeration [4], sprinkling and ice cooling are needed. However, for extra long tunnels, the mechanical ventilation system needs to consume enormous electric energy to drive the jet fans for ventilation and cooling. Thermal pressure ventilation caused by the indoor-outdoor temperature difference is undoubtedly an energy saving technology. At present, thermal pressure ventilation is mainly applied to the experimental study of surface constructions [5, 6] and the ventilation study of shallow underground buildings [7, 8]. However, there are few literatures on the application of thermal pressure ventilation in cooling of construction tunnel with high ground temperature.

Zilashan tunnel is located in Tibet, China. The average annual temperature is 6.5 ℃ and the calculated outdoor ventilation temperature in summer is 18 ℃. The designed length of the TBM section is about 13 km and the maximum temperature of the initial rock is 68.9 ℃. Therefore, thermal pressure ventilation has good potential for ventilation and cooling of Zilashan tunnel. This study aims to analyze the feasibility of thermal pressure ventilation for ventilation and cooling of extra long construction tunnel with high rock temperature. The CFD model considering buoyancy effects was built in ANSYS FLUENT software. Combining the air temperature and mass flow rate of the tunnel, this study evaluated the effect of thermal pressure ventilation under different initial rock temperature, insulation performance of the left tunnel and outdoor air temperature.
2. Model description

2.1 Physical model

The ventilation physical model was built with a proportional factor of 1:1 based on the design schemes of Zilashan tunnel in China. Figure 1 displays the dimensions of the main section of the physical model. As seen in Figure 1, the model consists of left tunnel, right tunnel, contact hole, shaft and adit. The sectional dimensions are 6.9 m (width) × 7.5 m (height) , 6.9 m (width) × 7.5 m (height) , 8.0 m (width) × 7.5 m (height) , 6.9 m (width) × 9.5 m (length) , 9.5 m (width) × 5.3 m (height) , respectively. The simplified sectional dimensions have the same hydraulic diameter as the actual sectional dimensions. The thermal pressure, generated by density difference and height difference at the inlet and outlet of the tunnel, can be used for tunnel ventilation and cooling. The outdoor cold air flow into the tunnel from the inlet of right tunnel, then passes through right tunnel, contact hole, left tunnel, shaft, adit and finally discharge from the outlet of adit, while the inlet of left tunnel is blocked.

![Figure 1. Schematic diagram of three-dimensional physical model.](image)

2.2 Mathematical models

In this study, the characteristics of air flow and heat transfer in the tunnel are obtained by solving the corresponding steady control equation in ANSYS FLUENT software.

The continuity equation is shown below:

$$\frac{\partial p u_j}{\partial x_j} = 0$$  \hspace{1cm} (1)

The momentum equation is shown below:

$$\frac{\partial p u_i u_j}{\partial x_j} = \rho f_i - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \mu \frac{\partial x_j}{\partial x_j} \right)$$  \hspace{1cm} (2)

The energy equation is shown below:

$$\frac{\partial p u_i T}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \lambda \frac{\partial T}{\partial x_i} \right) + S_t$$  \hspace{1cm} (3)

Where \(\rho\) is the air density, \(u_i\) and \(u_j\) are the air velocity, \(x_i\) and \(x_j\) are the coordinates of name, \(f_i\) is the unit mass force, \(p\) is the turbulence effective pressure, \(\mu\) is the viscosity coefficient, \(T\) is the air temperature, \(\lambda\) and \(c_p\) are the heat conductivity coefficient and specific heat ratio of the air, respectively, \(S_t\) is the viscous dissipation term.

Since the accuracy, robustness and computational economy of the standard \(k-\varepsilon\) turbulence model, it has been widely used in numerical calculation of various ventilation systems [9-11]. Thus, the standard \(k-\varepsilon\) turbulence model was chosen to solve the turbulence. For three dimensional steady incompressible fluid, the \(k-\varepsilon\) transport equations are:

$$\frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_k}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_i + G_e - \rho c\varepsilon$$  \hspace{1cm} (4)
\[
\frac{\partial (\rho u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_1 \epsilon \frac{G_k}{k} - C_2 \rho \frac{e^3}{k} \tag{5}
\]

Where \( k \) is the turbulent kinetic energy, \( \epsilon \) is the turbulent dissipation, \( G_k \) denotes the generation term of turbulent kinetic energy caused by average velocity gradient, \( G_b \) denotes the generation term of turbulent kinetic energy caused by buoyancy, \( C_1 \), \( C_2 \) and \( C_3 \) are model constants, \( \sigma_k \) and \( \sigma_\epsilon \) are the turbulent Prandtl numbers for \( k \) and \( \epsilon \), respectively. \( \mu_t \) is the turbulent viscosity coefficient, which the expression is as follows:

\[
\mu_t = \frac{C_\mu \rho k^2}{\epsilon} \tag{6}
\]

According to the recommended by Launder et al. [12], the model constants are expressed as: \( C_1 = 1.44 \), \( C_2 = 1.92 \), \( C_3 = 0.09 \), \( \sigma_k = 1.0 \) and \( \sigma_\epsilon = 1.3 \). When the main flow is parallel to the direction of gravity, \( C_3 = 1.0 \); When the main flow is perpendicular to the direction of gravity, \( C_3 = 0 \). The air density is a constant value in all governing equations, except that it follow the boussinesq model in the momentum equation [13, 14], which is expressed as:

\[
\frac{\rho - \rho_0}{\rho_0} = -\beta \frac{T - T_0}{T_0} \tag{7}
\]

Where \( \rho_0 \) and \( T_0 \) are the reference density and temperature, \( \beta \) is the thermal expansion coefficient, which is expressed as [15]:

\[
\beta = \frac{1}{T + 273.15} \tag{8}
\]

2.3 Boundary conditions

The pressure-inlet and pressure-outlet boundary condition are applied to the inlet of right tunnel and the outlet of the adit (see Figure 1), respectively. The gauge pressure and temperature of inlet and outlet are equal to 0 Pa and 18 ℃, respectively. The operating pressure is set to 66 750 Pa. Besides, the wall of contact hole, left tunnel and right tunnel are set to convective heat transfer boundary condition, while the wall of shaft and adit are considered to be adiabatic boundary.

The maximum initial rock temperature of the tunnel is 68.9 ℃, while the temperature between 50 ℃ and 60 ℃ accounts for a large proportion. Therefore, the initial rock temperature is set to 55 ℃. Table 1 displays the structure parameter of surrounding rock from inside to outside. The thickness of Gneiss denotes the radial distance from rock surface to the rock of initial temperature.

| Material                  | Thickness (mm) | Heat conductivity coefficient (Wm⁻¹K⁻¹) |
|---------------------------|----------------|----------------------------------------|
| Gneiss                    | 2000           | 3.489                                  |
| Sand                      | 300            | 0.582                                  |
| Polyurethane rigid foam   | 100            | 0.026                                  |
| Concrete                  | 500            | 1.163                                  |

The convection heat transfer coefficient \( h \) between the wall and air is calculated by formula (9) [16, 17]:

\[
h = 0.023 \frac{\lambda}{D} \text{Re}^{0.8} \text{Pr}^n \tag{9}
\]

Where \( D \) denotes the hydraulic diameter, \( n \) denotes the index which is 0.4 when air is heated and 0.3 when air is cooled.

Although the convection heat transfer coefficient \( h \) varies with the airflow velocity, its value has little influence on the total heat transfer coefficient. Supposing the tunnel airflow velocity is 3 m/s, the total heat transfer coefficient is 0.22 W/(m²·K).

2.4 Mesh independence study
The structured meshes were used to mesh the physical model in ICEM_CFD software. Then, a mesh independence study with four kinds of mesh densities was carried out to ensure the accuracy and save the computation time. The total cells number of different meshes are about 0.51 million, 1.52 million, 4.33 million and 8.57 million, respectively. The accuracy of mesh densities has been evaluated by comparing the mass flow rate of outlet. Simulation results show that the mass flow rate corresponding to the four mesh densities are 234.13 kg/s, 250.66 kg/s, 229.44 kg/s and 220.50 kg/s, respectively. As the mass flow rate difference is small, the mesh density of 0.51 million cells were used in the further simulations.

3. Result and discussion

3.1 Effect of insulation performance of the surrounding rock wall on thermal pressure ventilation

In the design of tunnel construction scheme, it is worth noting whether left tunnel insulation has an effect on thermal pressure ventilation effect. As shown in Table 2, when left tunnel without insulation, the mass flow rate of outlet increases by 26.96 kg/s (accounts for 12.2%) and the average air temperature at the end of right tunnel drops by 1.1 ℃ (accounts for 3.7%). Thus, if the right tunnel serves as a traffic passage and left tunnel without insulation is used as a special ventilation passage, it will enhance the effect of thermal pressure ventilation. However, the average air temperature at the end of right tunnel still fail to meet the specification requirements of not higher than 28 ℃, which needs to be solved by other measures, such as adding an air cooler or increasing the height of shaft.

| Insulation of left tunnel | mass flow rate of outlet (kg/s) | average air temperature at the end of right tunnel (℃) |
|--------------------------|-------------------------------|-----------------------------------------------|
| with                     | 220.46                        | 29.5                                          |
| without                  | 247.42                        | 28.4                                          |

3.2 Effect of initial rock temperature on thermal pressure ventilation

When the outdoor air temperature is 18 ℃ and left tunnel without insulation, the simulation results of thermal pressure ventilation effect under different initial rock temperature are presented in Figure 2. The mass flow rate of outlet and average air temperature at the end of right tunnel increase roughly proportionally with the increase of surrounding rock temperature. As the initial rock temperature increases by 1 ℃, the mass flow rate of outlet increases by about 2.42 kg/s and the average air temperature at the end of right tunnel increases by about 0.2 ℃. As shown in Figure 2, when the initial rock temperature is lower than 54 ℃, the average air temperature at the end of right tunnel does not exceed 28 ℃, which indicates that thermal pressure ventilation can meets the cooling requirement.

3.3 Effect of outdoor air temperature on thermal pressure ventilation

When the initial rock temperature is 55 ℃ and left tunnel without insulation, the simulation results of thermal pressure ventilation effect under different outdoor air temperature are showed in Figure 3. The mass flow rate of outlet decreases approximately proportionally with the increase of outdoor air temperature, while the average air temperature at the end of right tunnel raises roughly proportionally with the increase of outdoor air temperature. With the outdoor air temperature improves by 1 ℃, the mass flow rate of outlet drops by about 2.68 kg/s and the average air temperature at the end of right tunnel increases by about 0.8 ℃. Figure 3 shows that when the outdoor air temperature is not higher than 17.5 ℃, the average air temperature at the end of right tunnel is below 28 ℃, which demonstrates that thermal pressure ventilation is suitable for tunnel ventilation and cooling.

4. Conclusion

In this study, the numerical simulation, adopting ANSYS FLUENT software, has been conducted to assess the impact of the initial rock temperature, insulation of left tunnel and outdoor air temperature on the effect of thermal pressure ventilation. The results showed that while the left tunnel without insulation
is used as a special ventilation passage, the effect of thermal pressure ventilation increases by 12.2%, and the effect of cooling enhances by 3.7%. Compared with the initial rock temperature, the outdoor air temperature has a greater influence on thermal pressure ventilation. As the initial rock temperature is below 54 °C, outdoor air temperature is below 17.5 °C and the left tunnel has no insulation, thermal pressure ventilation technology is feasible for ventilation and cooling of construction tunnel with a shaft of 450 m height. In this study, the radial distance from rock surface to the rock of initial temperature is assumed to be 2 m. The precision needs further experimental and theoretical investigations. Besides, the effects of different insulation materials and shaft height on the thermal pressure ventilation should be researched in the future.

![Figure 2. Effect of initial rock temperature on thermal pressure ventilation.](image)

![Figure 3. Effect of outdoor air temperature on thermal pressure ventilation.](image)

5. References

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