Study on the influence of temperature differences in the tunnel on ventilation system energy consumption

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Abstract. The formula of the atmospheric pressure difference caused by the temperature difference in the tunnel and the environment outside the tunnel was established in this paper based on the Clapeyron equation to study the influence of the temperature difference between inside and outside the tunnel on the energy consumption of the ventilation system. Then, a scaled-down model tunnel is established. The air inside the model is heated by electric heating, the temperature and velocity of airflow along the center of the tunnel model are measured in detail, and the atmospheric pressure difference and wind speed in the model tunnel with different slopes are discussed. The results indicate that the tunnel has an obvious natural ventilation effect under specific temperature difference between inside and outside, and it becomes better as the slope increases. The shaft-type natural ventilation can promote the overall tunnel ventilation, and making full use of natural wind can save 15% of the energy consumption of mechanical ventilation.

1. Introduction

Tunnels are relatively closed space, and the pollutants from automobile exhaust cannot be discharged efficiently sometimes. The ventilation system plays a significant role in keeping the environment in the tunnel clean and guaranteeing the safety of drivers [1]. However, mechanical ventilation is extremely energy-consuming, and the annual power consumption for mechanical ventilation in the Nanshan Highway tunnel in Qinling Mountain exceeds 70% of the operating cost [2]. Therefore, making full use of natural ventilation is the key to perform the concept of environmental protection. Besides, there is an obvious temperature difference in the air between inside and outside for a long time because the underground environment is hot and cars emit heat during the driving process. Monitoring in The East Yanan Road tunnel in Shanghai revealed that the average temperature rise of air in the tunnel could reach 2.5 °C - 5 °C per kilometer when traffic volume was high, and the temperature rising speed can reach 6.5 °C /km when the traffic volume was overloaded. The temperature difference between the inside and outside of the tunnel and the atmospheric pressure difference caused by the different heights between the two ends of the tunnel and shafts are crucial factors in making natural wind. Rational use of natural ventilation can effectively solve the problem of waste gas in the tunnel and save the cost of a mechanical ventilation system in the tunnel.

Many pieces of research have been conducted on ventilation. Although many factors influence the wind in constructions, the temperature is a significant factor affecting the natural wind speed [3-5].
Fernando r. Mazarron recorded the ventilation of underground buildings throughout the year, demonstrating that the important factor influencing natural ventilation is the temperature difference between inside and outside [6]. Mao evaluated three kinds of mechanical ventilation combined with practical engineering, compared and analyzed the economic benefits of natural ventilation and jet fan ventilation, and revealed that natural ventilation can reduce the total investment by 30% and has a remarkable energy-saving effect [7]. With the concept of environmental protection and energy-saving gaining popularity, the use of natural ventilation to reduce mechanical energy consumption has gradually become a common method in tunnel design [8-9]. Based on the tunnel with an obvious temperature difference at the exit, Guo discovered that the temperature difference had a significant promotion effect on ventilation. The fan configuration method was optimized, and the optimal energy saving ratio was 43.2%, providing a method for energy-saving and ventilation design of tunnel in the climate isolation zone [10]. Besides Xie investigated the feasibility of hot pressure ventilation technology in ventilation and cooling of a super-long tunnel with high altitude and high surface temperature. The results indicated that the temperature difference between inside and outside the tunnel has a dramatic influence on the thermal pressure ventilation, contributing to improving the overall ventilation effect of the tunnel by 12.2%. Thus, the thermal pressure ventilation technology provides a new idea for tunnel ventilation design [11]. Yoon explored the natural wind pressure caused by the temperature difference between the upper and lower shafts, illustrating that the natural ventilation pressure could reach 29.26% of the mechanical ventilation pressure, which could improve the efficiency of the overall ventilation system [12]. Zhang investigated the role of shaft-type natural ventilation in tunnel ventilation, and observed that temperature difference had a significant impact on ventilation. Natural ventilation can save energy consumption of mechanical ventilation, verifying that energy consumption of 10-12 jet fans can be reduced when natural wind reaches 3 m/s [13]. Although there have been some studies on the utilization potential of atmospheric pressure difference in tunnels, a systemic formula to guide engineering has not been formed. Therefore, in this paper, the formula of atmospheric pressure caused by different temperatures in the tunnels and shafts was deduced based on the Clapeyron equation; then, a scaled-down model was established. Afterward, the atmospheric pressure difference and wind speed in the model tunnel with different slopes were analyzed to verify that the formula. Finally, energy-saving design guidance could be provided for the road tunnel ventilation system.

2. The calculation method of atmospheric pressure

Due to the influence of the height difference between the two sides of the mountain, tunnels are often designed to be a one-way slope. For example, Beijing Yanqing to Hebei Chongli Expressway under construction has the elevation of Chongli that is much higher than that of Beijing, where, the road climbs from east to west; besides, 5 extra-long tunnels on the road; Songshan Tunnel (9.4 km), Longquankou Tunnel (3.7 km), Xinglinbao Tunnel (5.0 km), Jinjiazhuan Tunnel (4.1 km), and Qipanliang Tunnel (5.9 km) are one-way slope tunnels, with the average gradient of 1.70%, 1.88%, 1.98%, 1.88%, and 1.95%, respectively. Since the height difference between the two ends is 77-160m, the temperature difference between inside and outside the tunnel would have a significant impact on the scheme of the tunnel ventilation system. Therefore, this paper firstly deduces the formula of atmospheric pressure difference caused by temperature difference between inside and outside the tunnel and up and bottom of the shaft based on the change equation of ideal gas physical quantity.
2.1. The pressure difference in the tunnel

As illustrated in Figure 1, two ends of the tunnel have different height differences that result in different temperatures, causing an obvious impact on ventilation. Then, a study was performed to clarify the relationship between them. The Clapeyron equation is provided as follows:

$$\Delta p = \frac{\rho_1 \cdot T_3 \cdot g}{k} (\ln T_4 - \ln T_5)$$ (1)

$$dp = \frac{\rho_1 \cdot T_1 \cdot g}{T_1 + k \cdot l} \cdot dh = \frac{\rho_1 \cdot T_1 \cdot g}{T_1 + k \cdot l} \cdot i \cdot dl$$ (2)

$$\Delta p = \int_0^l \frac{\rho_1 \cdot T_1 \cdot g}{T_1 + k \cdot l} \cdot i \cdot dl = \frac{\rho_1 \cdot T_1 \cdot g}{T_1 + k \cdot l} \int_0^l (T_1 + k \cdot l) = \frac{\rho_1 \cdot T_1 \cdot g}{T_1 + k \cdot l} \cdot i \cdot \left(\ln T_2 - \ln T_1\right)$$ (3)

where $T_1$ and $\rho_1$ are the gas thermodynamic temperature (K) and density (kg/m$^3$) at the entrance of the tunnel; $T_2$ and $\rho_2$ is the temperature (K) and density (kg/m$^3$) at the exit of the tunnel; $K$ denotes the temperature gradient (K/m); $i$ refers to the tunnel slope (%), $L$ represents the length from the entrance of the tunnel at any position (m); $g$ is the gravitational acceleration (m/s$^3$); $l$ is the total length of the tunnel (m).

Using the formula derived above, the atmospheric pressure differences of Songshan Tunnel with a slope of 1.70% is calculated, and the atmospheric pressure differences under the following two conditions are calculated: 1) the slope of the tunnel is 1.7%, and the temperature difference between the two ends is -10°C, -5°C, 0°C, 5°C and 10°C; 2) the slope of the tunnel changes from -2% to 2%, and the temperature difference between the two ends is 10°C. The results are recorded as follows:

| $\Delta T$ / °C | -10 | -5 | 0 | 5 | 10 |
|------------------|-----|----|---|---|----|
| $\Delta P$ /Pa   | 32.80 | 16.21 | 0 | 15.85 | 31.34 |
Table 2. Pressure differences between two ends of Songshan Tunnel with slope changes

| $i / \%$ | 2 | -1 | 0 | 1 | 2 |
|----------|---|----|---|---|---|
| $\Delta P / \text{Pa}$ | -36.87 | -18.44 | 0 | 18.44 | 36.87 |

2.2. The pressure difference in the shaft

Similarly, the atmospheric pressure difference caused by the temperature difference between the top and bottom of the shaft can be derived as Eq. (4).

$$
\Delta P = \frac{\rho_i \cdot T_i \cdot g}{k} (\ln T_a - \ln T_i)
$$

(Eq. 4)

According to No.2 shaft which is 600m deep in Zhongnanshan Tunnel in Tuoqinling Mountains, the atmospheric pressure differences under the temperature difference between the top and bottom of the shaft of -10°C, -5°C, 0°C, 5°C, 10°C, 15°C, and 20°C are calculated. The results are as follows:

Table 3. Pressure differences when the temperature differences between the top and bottom shaft vary

| $\Delta T / \degree \text{C}$ | -10 | -5 | 0 | 5 | 10 | 15 | 20 |
|-------------------------------|-----|----|---|---|----|----|----|
| $\Delta P / \text{Pa}$        | 132.40 | 65.38 | 0 | 63.80 | 126.09 | 186.93 | 246.36 |

3. Experiment

A longitudinal temperature field experiment and a shaft temperature field experiment are carried out in the 1:10 scale model tunnel to verify the influence of temperature difference between inside and outside on tunnel ventilation.

3.1. Longitudinal temperature field experiment of tunnels with different slopes
The tunnel test was conducted in a semi-circular model tunnel with a length of 20 m and a radius of 0.86 m. The temperature and wind speed sensors were arranged on the central axis of the tunnel with a distance of 0.4 m (Figure 2). The right end of the tunnel was heated to be stable by electric heating with a power of 45 W/m, as presented in Figure 3. During the experiment, it was ensured that the laboratory was closed to eliminate the influence of natural wind; the surface of the tunnel was covered with a 10 mm thick insulation layer the temperature formed from left to right on both ends of the tunnel temperature was within 20.67-31.29 °C; then, the height difference was formed by adjusting the height of the support at the bottom of the tunnel; finally wind speeds in the tunnel model with the slope of -4%, 3%, 2%, 1%, 0%, 1%, 2%, 3%, and 4% were recorded and analyzed (Figure 3). The temperature, pressure difference and wind speed inside the tunnel were measured when the gradient changed without the influence of external natural wind and the power of the electric heating was constant. During the experiment period, the ambient temperature at the left end of the tunnel was about 21.19 °C, and the temperature at the right end of the tunnel was about 29.92 °C. The results of air pressure difference and wind speed under nine kinds of slope changes are exhibited in Figure 1 and Figure 5.

By analyzing the experimental data, the following conclusions can be drawn:
1) When the slope of the tunnel is 0%, the pressure difference caused by temperature difference can form wind, with the wind speed reaching 0.35 m/s.
2) When the slope of the tunnel is between -4% and 0%, the greater the height difference between the two ends of the tunnel, the greater the wind volume, that is, when the temperature difference is fixed, the greater the longitudinal slope, the better the ventilation effect will be.
3) When the slope of the tunnel is between 0% and 4%, the ventilation volume in the tunnel caused by the pressure difference is small and decreases to zero with the increase of longitudinal slope, which is not conducive to natural ventilation.

3.2. Shaft temperature field experiment
The shaft experiment was performed in a cylindrical metal model shaft with a length of 2 m and a radius of 0.48 m. The temperature sensor spacing was 0.7 m (Figure 6). The two ends of the model were open. The average temperature at the top of the shaft was about 22.46 °C, and the temperature at the bottom was about 23.71 °C. Although the temperature difference is small, the wind speed measured by the three wind speed sensors was between 0.44 m/s and 0.57 m/s, and the average wind speed is 0.51 m/s, which are all at a high level. Therefore, the shaft is very beneficial to natural ventilation.
4. Project example
Cangling tunnel in Zhejiang, China is to use the combination of mechanical ventilation and shaft natural ventilation to achieve effective ventilation, analyzing the influence of temperature difference between inside and outside the tunnel on ventilation. From June to February of the next year, the temperature and wind speed inside and outside the tunnel and at both ends of the shaft of the Cangling Tunnel were monitored with the data extraction time point of 2:00, 8:00, 14:00, and 20:00. The temperature difference is exhibited in Figure 8.

![Figure 6. Schematic diagram of model shaft size](image1)

![Figure 7. Model shaft](image2)

Figure 6. Schematic diagram of model shaft size

Figure 7. Model shaft

![Figure 8. Temperature difference between inside and outside the tunnel](image3)

a) 2:00  
b) 8:00
According to the long-term monitoring data of Cangling Tunnel, the temperature difference between inside and outside the tunnel and the laws of natural wind are concluded as follows:

1) In the evening of winter (20:00-8:00 of the next day), the temperature inside the tunnel is significantly higher than that outside the tunnel. The temperature at the bottom of the shaft is about 10.5°C higher than that at both ends of the tunnel and 11.8°C higher than that at the top of the shaft. The chimney effect is significant, and the value of natural wind speed can reach 1.5 m/s, which is favorable for ventilation.

2) At 14:00 in the daytime of winter, the temperature inside the tunnel is still higher than that outside the tunnel. The temperature at the bottom of the shaft is 3.4°C higher than that at both ends of the openings and 6.2°C higher than that at the top of the shaft. The chimney effect is significant, and the value of natural wind speed can reach 0.9 m/s, which is beneficial to ventilation.

3) In the evening of summer (20:00-8:00 of the next day), the temperature difference between inside and outside the tunnel is not obvious. The temperature at the bottom of the shaft is only 0.2°C higher than that at both ends of the holes and 2.8°C higher than that at the top of the shaft. The measured value of wind speed is low, and the effect of natural wind is not obvious.

4) At 14:00 in summer, the temperature inside the tunnel is lower than that outside the tunnel. The temperature at the bottom of the shaft is about 5.3°C lower than that at both ends of the hole and 2.3°C lower than that at the top of the shaft, which is not conducive to ventilation.

5) The maximum natural wind speed detected at the bottom of the shaft is 2.8m/s, with an average of 0.6 m/s, exhibiting a preferable ventilation effect.

The total length of the Cangling Tunnel is 7530 m with a slope of 1.8%. According to the temperature and pressure difference monitored at different time points in different seasons, the following data are calculated:

| Table 4. Temperature differences and air pressure differences in different seasons in Cangling Tunnel |
|-----------------------------------------|-----------------|-----------------|
| time                                    | △T/°C | △P/Pa         |
| summer                                  |       |                |
| 8:00-20:00                              | 0.2   | 0.58           |
| 20:00-8:00                              | 5.3   | 15.67          |
| winter                                  |       |                |
| 8:00-20:00                              | 3.4   | 9.8            |
| 20:00-8:00                              | 10.5  | 29.88          |
In Winter, the temperature difference inside and outside the tunnel is conducive to the ventilation, and the natural wind can reach the average wind speed of 1.2 m/s. Referring to the output full pressure formula of axial flow fan [14], the output power of natural wind in winter is calculated to be 29.21 kw in the daytime and 48.70 kw at night, saving 1870 kw/h electricity every day, which is about 15% of the energy consumption of mechanical ventilation in ordinary tunnels.

5. Conclusion
In this study, several different slope tests of the tunnel were conducted by designing the experiment model; besides, the influence of temperature difference inside and outside the tunnel and the slope on natural ventilation was analyzed.

The conclusions are drawn as follows:
1) When the temperature of the upper part of the tunnel is higher than that of the lower part, the natural wind in the tunnel is formed, the effect of the shaft chimney is significant, and the natural wind speed is maintained at a higher state, promoting the overall ventilation.
2) When the temperature of the upper part of the tunnel is lower than that of the lower part, the natural wind inside the tunnel is difficult to form, which is not conducive to ventilation.
3) The slope has a significant influence on the formation of natural wind in the tunnel with temperature difference. The natural wind volume increases as the longitudinal slope increase.
4) In winter, the natural wind in the tunnel is obvious, which can reduce the power consumption of mechanical ventilation and save 15% electricity per day on average.

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