Study on Wind Effect of Train Piston in Railway Tunnel with High Altitude and High Rock Temperature

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Abstract. The piston wind effect in the tunnel of the Sichuan-Tibet railway under high rock temperature and low-pressure environment was studied and analyzed to provide theoretical support for the tunnel's thermal environment analysis and ventilation design. The calculation model of piston wind for trains running under low pressure is established, and the influence of atmospheric pressure and tunnel wall temperature on the piston wind effect in the tunnel is increased. By comparing the impact of different factors on the piston wind effect in the tunnel, the fitting rule function between train speed and piston wind speed is obtained. The results show that atmospheric pressure and tunnel wall temperature have little influence on the piston wind effect in the tunnel and can be ignored. Natural ventilation and train speed significantly influence the piston wind effect in the tunnel. Reasonable use of natural ventilation and train speed control can effectively reduce the piston wind effect, reduce the heat accumulation in the tunnel, and ensure the safety and comfort of the tunnel.

1 Introduction

Sichuan-Tibet Railway is a critical construction project in the national "13th Five-Year Plan". It plays an essential role in connecting the hinterland of Southwest China, central and eastern China, and Tibet with the fastest and most convenient passenger and cargo transportation main channel, and its function is positioned as a high-standard interregional high-speed trunk railway with both passenger and cargo [1]. However, due to the high altitude, thin air, significant temperature difference, and complex and changeable meteorological environment along the route [2], the piston wind effect generated during train operation not only affects traffic safety but also negatively affects the convective heat transfer between the air and the lining in the tunnel and the heat conduction between the lining and the surrounding rock for a long time under the extreme environment of high rock temperature and low pressure. Thus, the safety and service life of the tunnel structure are affected [3]. Therefore, studying the piston wind effect in railway tunnels with high altitudes and rock temperatures is urgent.

Research on the piston wind effect in tunnels has been conducted at home and abroad. Cui Jingdong, Chen Rong, et al. established a two-dimensional dynamic grid model of piston wind to simulate the dynamic changes of the velocity and pressure fields inside the tunnel under different train speeds [4-5]. Bao et al. verified the formation process of the piston effect through FLUENT numerical calculation [6]. Wang et al. used theoretical methods to study the piston effect [7]. Gilbert T et al. used dynamic grid technology to simulate and analyze the size and variation rule of train piston wind generated when trains run in tunnels with different cross-sectional areas and lengths [8]. Tahereh Izadi et al. simulated the train movement in subway tunnels and stations with a three-dimensional computational model and studied the transient airflow field around the train [9].

The above scholars have studied the piston wind effect of trains using different methods from different angles. The research theory of piston wind in general tunnels in plain areas is relatively mature. However, in these studies, there are still some limitations on the piston wind effect in the tunnel under high altitude and high rock temperature environment, and the influence of atmospheric pressure and tunnel wall temperature on the piston wind effect is ignored.

Therefore, to fill the research gap, this paper established the piston wind calculation model of train operation under low pressure and added the factors that influence atmospheric pressure and tunnel wall temperature on the piston wind effect. The effect of different factors on train piston wind under a low-pressure environment is analyzed and compared, and the fitting rule function between train piston wind speed and train speed is obtained. This work provides the necessary theoretical reference for the thermal environment analysis and ventilation design control measures in high altitude and high rock temperature tunnels.

2 Physical Model

2.1 Physical Model

Based on the Sangzhuling Tunnel in the Lalin section of the Sichuan-Tibet Railway, Sangzhuling Tunnel is located

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in Sangka Canyon District, Sangri County, Shannan City, Tibet, Yarlung Zangbo River. The area of the entrance to Woka station and the exit to Bayu station is a double-track tunnel, and the remaining sections are a single-track tunnel. The designed speed is 160km/h, and the equivalent hydraulic radius of the tunnel's positive hole is 3.5m [10]. Sangzhuling Tunnel shows prominent high geothermal characteristics, with the highest rock temperature of 89.9℃ and the highest ambient temperature of 56℃ in the tunnel [11]. This paper selects a single-line tunnel without a transverse tunnel as the physical model.

Since the actual geometry of tunnels and trains is particularly complex, it is simplified by using two-dimensional physical model simulation. To facilitate the study of piston wind in tunnels, the following assumptions are made about the conditions of tunnels and trains:(1) There is only one train in the tunnel; (2) The whole train runs in the tunnel; (3) The tunnel has no slope, and the cross-sectional area remains unchanged; (4) Simplify the irregular shape of tunnels and trains, using their equivalent diameters as the stereotyped dimensions.

Finite element software ANSYS was used for numerical simulation, SPACE CLAIM established a two-dimensional geometric model, and MESHIMNG was used to divide the grid. The tunnel size is 1000m×7m; the train is based on the model of the Fuxing GR200JS-G plateau internal electric double-source EMU running in this section; the size is 232.5m×4.436m.

2.2 Grid Independence Verification

The efficiency and accuracy of the numerical simulation process are closely related to the quality of the grid, so the establishment of grid independence is a necessary condition for analysis [12]. This paper uses MESHIMNG to divide the grid and generate three kinds of unstructured discrete grid models with different densities. The grid-independent study is carried out based on the change of piston wind speed when the train travels at a 200km/h speed. The grid number of the three models is 79548 cells (grid 1), 173216 cells (grid 2), and 1239176 cells (grid 3), respectively, as shown in Table 1. The three physical models obtained from this are shown in Fig. 1.

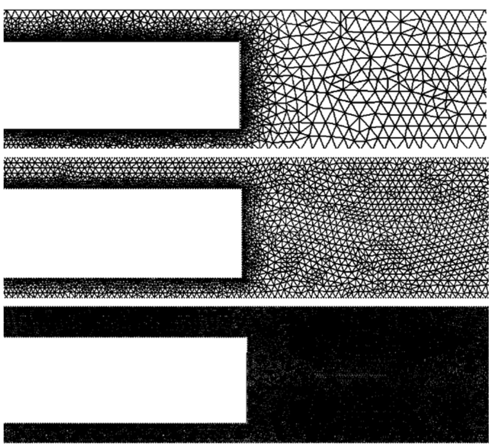

Fig. 1. Different grid physical models.

Table 1. The number of nodes and the number of units in different precision grids.

	Grid 1	Grid 2	Grid 3
Number of nodes	44134	92353	632027
Number of units	79548	173216	1239176

The simulation results are shown in Fig. 2. The simulation results of grid 1 and grid 2 are more similar, indicating no correlation between the number of grids and the simulation results. The results show that the piston wind speed increases with the increase of grid number. Considering the calculation accuracy and cost, grid 2 is chosen as the grid calculation model in this paper. The minimum mesh mass of grid 2 is 0.56202, the maximum mesh mass is 0.93243, and the overall mesh quality is very high, which can be used for subsequent numerical simulation.

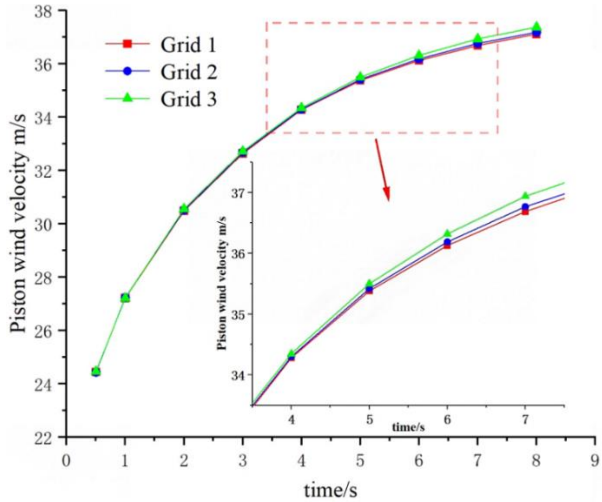

Fig. 2. Grid independence verification.

3 Mathematical Methods

3.1 Mathematical Model

To facilitate the calculation, this paper makes reasonable simplification of the calculation model based on satisfying the conditions:(1) Fluid in the tunnel is regarded as incompressible fluid;(2) The fluid flow in the tunnel is turbulent;(3) The fluid in the tunnel has homotropic turbulent viscosity, which satisfies the Boussinesq hypothesis;(4) The train runs at a constant speed inside the tunnel. Since the flow generated by the train running in the tunnel is assumed to be incompressible, the turbulence model in this paper adopts the standard k-ε two-path model [4]. The flow also satisfies the following equations:

Mass conservation equation:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

Momentum conservation equation:

$$\frac{du_i}{dt}=f_i-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\gamma\frac{\partial u_i}{\partial x_j}-\overline{u_i u_j}\right) \tag{2}$$

k equation:

$$\frac{dk}{dt}=\frac{\partial}{\partial x_i}[(\nu+\frac{\nu_t}{\sigma_k})\frac{\partial k}{\partial x_i}]+G_k-\varepsilon \quad (3)$$

ε equation:

$$\frac{d\varepsilon}{dt}=\frac{\partial}{\partial x_i}[(\nu+\frac{\nu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_i}]+C_{1\varepsilon}\frac{\varepsilon}{k}p_k-C_{2\varepsilon}\frac{\varepsilon^2}{k} \quad (4)$$

where: u_i and u_j are velocity component, m/s; x_i and x_j are coordinate component;t is time, s; f_i is the mass force, m/s²;ν is the laminar dynamic viscosity coefficient, Pa·s; ν_t is turbulence viscosity coefficient, $\nu_t=C_u K^2/\varepsilon$, Pa·s;γ is the coefficient; k is turbulent kinetic energy, m/s²; G_k is the turbulent kinetic energy generation term caused by the mean velocity gradient, $G_k=\nu_t\frac{\partial u_i}{\partial x_j}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i})$; p_k is the average pressure at the time of correction, Pa; ε is the dissipation rate of turbulent kinetic energy, m^2/s^2; Other constants in the equation are σ_k=1.0, σ_ε=1.33, $C_{1\varepsilon}$=1.44, $C_{2\varepsilon}$=1.92, C_u=0.09.

When the influence of rock temperature is considered, the airflow in the tunnel satisfies the three equations of mass conservation, momentum conservation, and energy conservation. The general governing differential equation is as follows:

$$\frac{\partial(\rho\Phi)}{\partial t}+div(\rho\upsilon\Phi)=div(\Gamma grad\Phi)+S \quad (5)$$

In equation (5), from left to right, the unsteady term, convection term, diffusion term, and source term.

3.2 Mathematical Model Verification

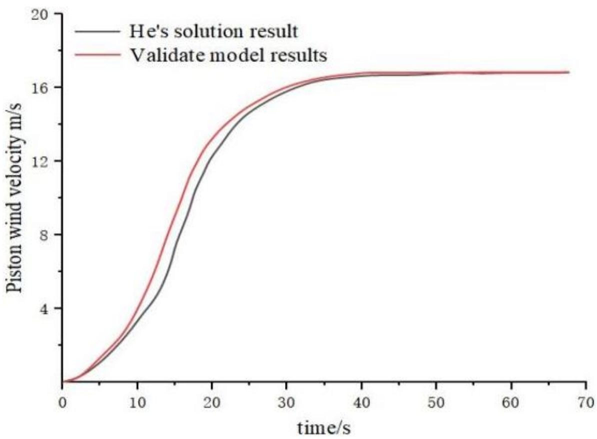

Fig. 3. Model verification.

He's model [13] was used to verify the mathematical model, referring to the specific parameters in his paper. The piston wind speed in the tunnel is taken as the result. (see Fig. 3). The results show that the piston wind speed increases gradually with the increase of train running time. When the train runs for about 40 seconds, the piston wind speed reaches a stable state. The root mean square error (RMSE) of the model is 0.81m/s. This phenomenon is because the simulation process sets the low-pressure environment, and the two-dimensional model is simplified compared with the three-dimensional model. Therefore, the simulated value of piston wind speed may be higher than that calculated by the He's model. The simulation results are consistent with the verification model, proving the mathematical model's accuracy and rationality.

3.3 Setting of Boundary Conditions

Set the left boundary of the tunnel as the inlet boundary and the right boundary as the outlet boundary. The upper and lower sides of the tunnel are selected as the solid wall boundary with a surface equivalent rough height of 5mm. The four sides of the train are set as the wall-LC with a surface equal rough height of 9.2mm [13]. See Table 2 for specific Settings.

Table 2. Setting of boundary conditions of numerical model.

Project	Boundary type	Dynamic setting
Tunnel entrance	Pressure-inlet/Velocity-inlet	Stationary
Tunnel exit	Pressure-outlet	Stationary
Tunnel wall	Wall	Deforming
Train wall	Wall	Rigid body

3.4 Dynamic Grid Settings

Establishment of dynamic grid model. According to existing studies, the dynamic grid is more consistent with tunnel piston wind development theory than the sliding grid, and the calculation idea of modeling is consistent with our understanding of practical problems [14]. Considering the internal flow field change caused by the train running in the tunnel with time, the dynamic grid model is established using Fluent software. The flow field in the tunnel is divided into a moving train region and a non-moving fluid region: The train area is a rigid body motion, UDF compiles its motion mode, and the speed value is assigned to the four sides of the train. The air in the flow field area moves due to the train's movement, which belongs to the deformation movement. Dynamic Settings are shown in Table 2.

3.5 Solution Strategy

In the software, Fluent, a transient solver is used, and the velocity is set to absolute velocity. The model is based on the mass conservation equation of unsteady incompressible fluid and Reynolds mean Navier-Stokes equation. The coupling problem of pressure and speed adopts a SIMPLE algorithm to accelerate the convergence speed in a single iteration step, making the calculation more accurate.

Sichuan-Tibet Railway is a first-class railway with ordinary passenger and cargo lines, and there are EMU trains, regular passenger trains, and cargo trains [15], which are simulated with their respective running speeds of 200km/h, 160km/h, and 120km/h respectively. The standard atmospheric pressure of 1atm, the low pressure of 0.1atm, and the atmospheric pressure of 0.6atm in the Sangzhuling Tunnel location were selected for simulation. Tunnel wall temperature was affected by choosing the raw

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rock temperature [10] of the Sangzhuling tunnel at 63℃, 51℃, and 38℃. Natural ventilation wind speed is 1.5m/s in a single-line tunnel according to Article 5.1.4 of the Code for Design of Ventilation for Railway Tunnel Operation (TB10068-2010) [16]. Parameters are set in Table 3.

Table 3. Simulation parameter Settings.

Parameter	Numerical value
Train speed	200km/h, 160km/h, 120km/h
Atmospheric pressure	1atm, 0.6atm, 0.1atm
Tunnel wall temperature	63℃, 51℃, 38℃
Natural wind speed	1.5m/s

4 Results and Discussion

4.1 Effect of Atmospheric Pressure on the Variation of Piston Wind Speed in the Tunnel

Under the condition that the same train speed is 200km/h, the change curves of the piston wind speed in the tunnel with the train running time under the atmospheric pressure of low 0.1atm, 0.6atm, and standard atmospheric pressure of 1atm are compared. (see Fig. 4(a)). The results show that under the first two low-pressure environments, the difference between the piston wind speed and the standard atmospheric pressure 1atm environment is only 0.015% and 0.026%, respectively, indicating that the lower the atmospheric pressure, the smaller the impact on the piston wind speed in the tunnel.

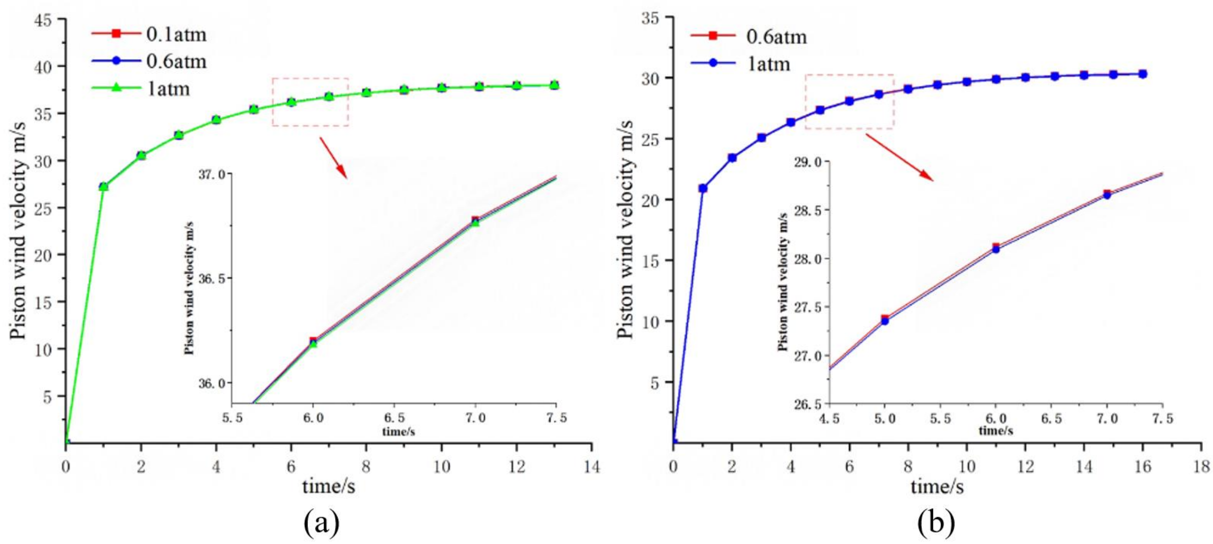

Fig. 4. Comparison of variation curves of piston wind speed in the tunnel under different atmospheric pressures: (a) Vtrain=200km/h, and (b) Vtrain=160km/h.

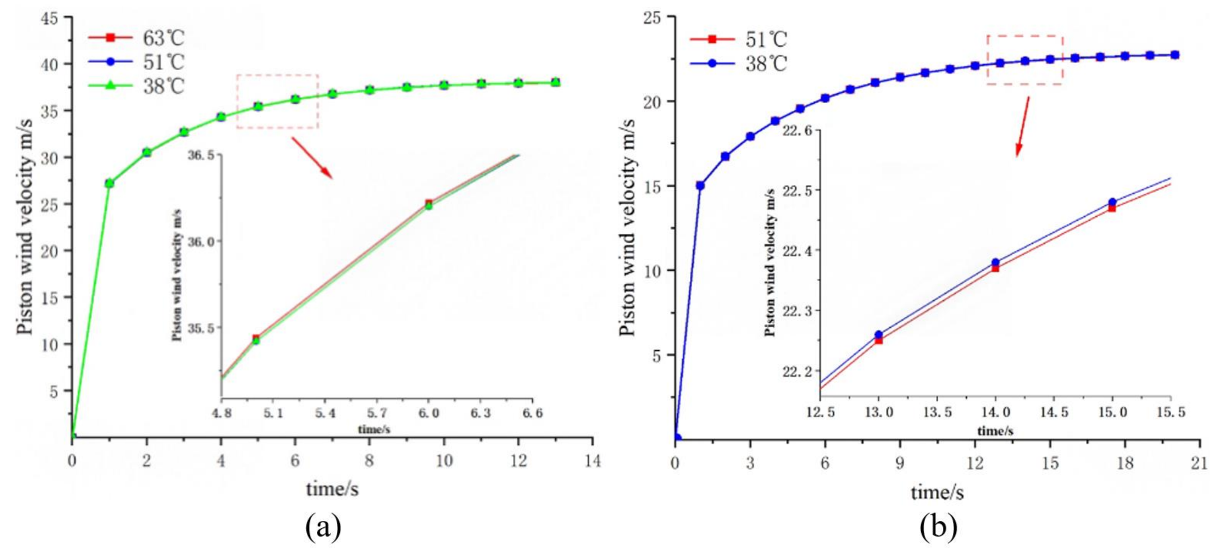

Fig. 5. Comparison of variation curves of piston wind speed in the tunnel under different tunnel wall temperatures: (a) V_{train}=200km/h, and (b) V_{train}=120km/h.

When the train runs at 160km/h, the change curve of piston wind speed with train running time under atmospheric pressure of 0.6atm and 1atm is compared. (see Fig. 4(b)). The results show that the difference in piston wind speed between the two is 0.028%, which is slightly higher than the difference of 0.026% when the train speed is 200km/h, which indicates that the influence of atmospheric pressure on piston wind speed is gradually reduced with the increase of train speed.

Fig. 4 shows that under different atmospheric pressure conditions, the piston wind speed in the tunnel changes little, the low-pressure environment has little influence on the piston wind effect, and the pressure change does not significantly change the velocity in the tunnel.

4.2 Influence of Tunnel Wall Temperature on the Variation of Piston Wind Speed in the Tunnel

When the train runs at a 200km/h speed under a low pressure of 0.6atm, the change curves of the piston wind speed in the tunnel with the train running time when the tunnel wall temperature is 63℃, 51℃ and 38℃ are compared.(see Fig. 5(a)).The results show that the difference between the piston wind speed at the first two temperatures and that at 38℃ is 0.026% and 0.022%, respectively, indicating that the higher the tunnel wall temperature, the greater the impact on the piston wind speed.

When the train runs at 120km/h, the change curve of piston wind speed with train running time when the tunnel wall temperature is 51℃ and 38℃ is compared. (see Fig. 5 (b)). The results show that the difference in piston wind speed between the two is 0.017%, which is slightly lower than the difference of 0.022% when the train speed is 200km/h, indicating that the influence of tunnel wall temperature on piston wind speed gradually increases with the increase of train speed.

Fig. 5 shows that the piston wind speed in the tunnel varies a little under different tunnel wall temperatures, and the high rock temperature has little influence on the piston wind effect in the tunnel.

4.3 The Relationship Between Train Speed and Piston Wind Speed

Under the condition of low-pressure 0.6atm, when the Sichuan-Tibet Railway EMU train, ordinary passenger train, and cargo train pass through the tunnel at 200km/h, 160km/h, and 120km/h, respectively, the average piston wind speed at different times when the train runs in the tunnel is shown in Table 4, Table 5 and Table 6. The change relation curve of piston wind over time and its fitting function curve are shown in Fig. 6 (a), (b), and (c), respectively.

When the train speed is 200 km/h, 160 km/h and 120 km/h, the expressions of the fitting function are $y=-20.38355x^{-0.32175}+47.34753$, $y=-20.65404x^{-0.23847}+41.37556$ and $y=15.484x^{0.13815}-0.02633$, respectively. R^2(COD) were 0.999, 0.99899, and 0.99666; Reduced Chi-Sqr were 0.09906, 0.08732, and 0.1693, respectively. All fits converge.

Table 4. Average piston wind speed in the tunnel at different times.

Train running time (s)	1	2	3	4	5	6	7	8	9	10	11	12	13
Train speed (km/h)	200												
Piston wind speed (m/s)	27.23	30.52	32.68	34.30	35.42	36.19	36.77	37.19	37.50	37.70	37.83	37.92	37.99
Natural wind speed(m/s)	1.5												

Table 5. Average piston wind speed in the tunnel at different times.

Train running time(s)	2	4	6	8	10	12	14	16
Train speed(km/h)	160							
Piston wind speed (m/s)	23.44	26.37	28.12	29.10	29.7	30.05	30.25	30.35
Natural wind speed(m/s)	1.5							

Table 6. Average piston wind speed in the tunnel at different times.

Train running time(s)	2	4	6	8	10	12	14	16	18	20
Train speed (km/h)	120									
Piston wind speed (m/s)	16.75	18.83	20.19	21.10	21.69	22.10	22.38	22.56	22.68	22.75
Natural wind speed(m/s)	1.5									

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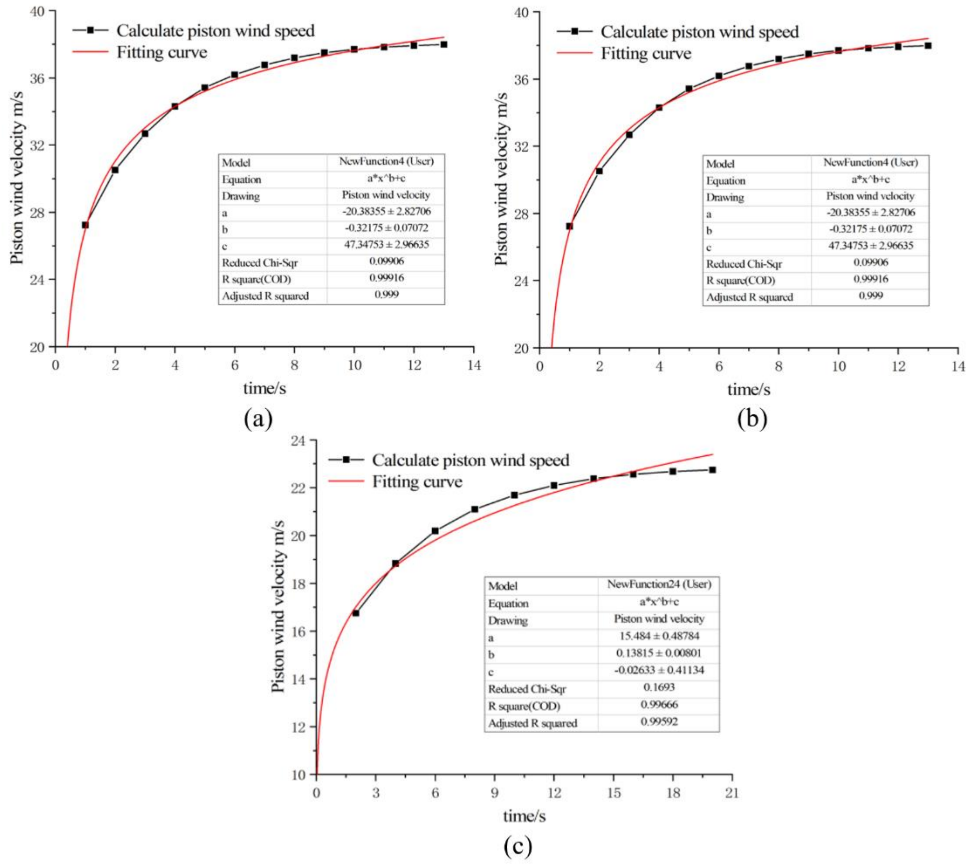

Fig. 6. Change curve of piston wind speed with train running time: (a) V_{train}=200km/h, (b) V_{train}=160km/h and (c) V_{train}=120km/h.

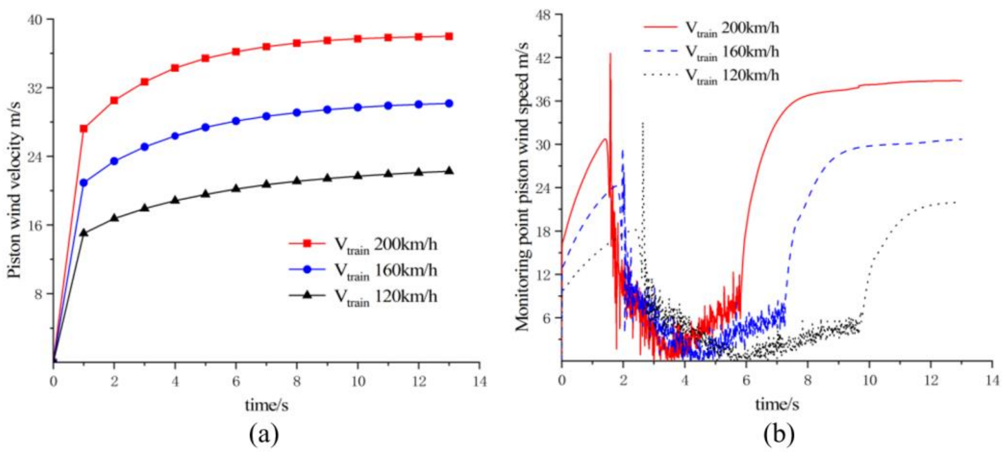

Fig. 7. Comparison of variation curves of piston wind speed in tunnel with different train speeds: (a) average velocity, and (b) monitoring point velocity.

4.4 Effect of Train Speed on Variation and Distribution of Piston Wind Speed

The change curves of the piston wind speed in the tunnel with the train running time when the train runs at 120km/h, 160km/h, and 200km/h under a low-pressure environment of 0.6atm are compared. (see Fig. 7(a)). The results show that the greater the train speed, the greater and faster the piston wind speed. In addition, when the piston wind speed tends to be stable, the speed of the piston wind increases by 7-8m/s for every 40km/h increase in the train running speed.

The change curve of piston wind speed is compared when the train passes through the monitoring point 350m away from the tunnel entrance and 6m above the ground at different speeds. (see Fig. 7(b)). The results show that when the train passes the monitoring point, the piston wind speed will have a sudden drop, and the sudden drop degree increases with the increase of the train speed.

The piston wind speed cloud image was compared when the train traveled at 120km/h, 160km/h, and 200km/h (from top to bottom). (see Fig. 8). As shown in the figure, the piston wind speed of the train is more prominent in the wake area and smaller on both sides of the car body, offering a relatively uniform velocity distribution. In addition, with the increase in train speed, the tunnel's piston wind effect becomes increasingly apparent, and the affected fluid area increases.

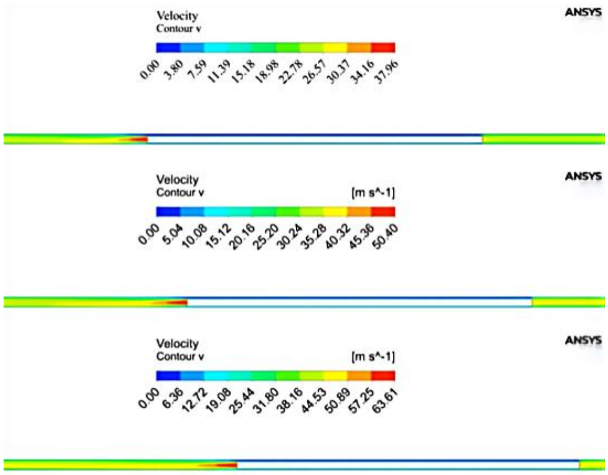

Fig. 8. Comparison of piston wind speed cloud image in the tunnel with different train speed.

4.5 Effect of Natural Ventilation on the Variation and Distribution of Airflow Velocity in Tunnel

Under the condition of low pressure of 0.6atm, the change curve of airflow velocity in the tunnel was compared when the train was running at 160km/h under the condition of no natural ventilation, downwind natural ventilation, and upwind natural ventilation (boundary condition inlet and outlet position interchange). (see Fig. 9). The results show that when there is natural ventilation, the airflow velocity in the tunnel decreases and the growth rate slows down. When the airflow velocity in the tunnel tends to be stable, the velocity difference between natural and no natural ventilation is 16-17m/s, indicating that natural ventilation significantly influences the airflow velocity in the tunnel.

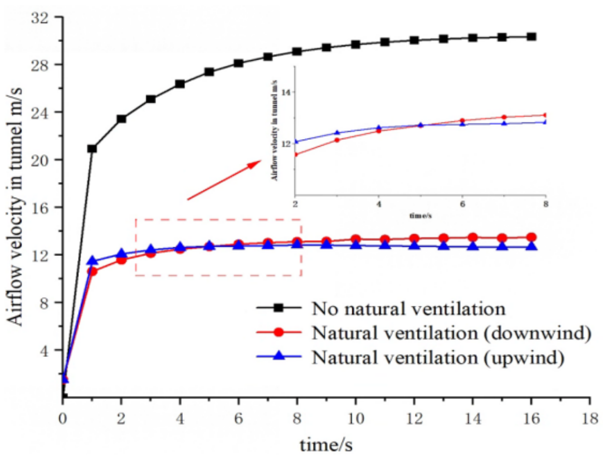

Fig. 9. Comparison of airflow velocity changes in tunnels under different ventilation conditions.

In addition, in the early stage of train operation, the airflow speed in the tunnel increased faster when the train was running against the wind. With the increase in train running time, the airflow speed in the tunnel gradually increases slowly when the train is running upwind, and eventually, it is lower than that when the train is running downwind. In the process of train operation, the average difference in airflow speed in the tunnel when the train is running downwind and upwind is 1.93%, and the overall trend is the same.

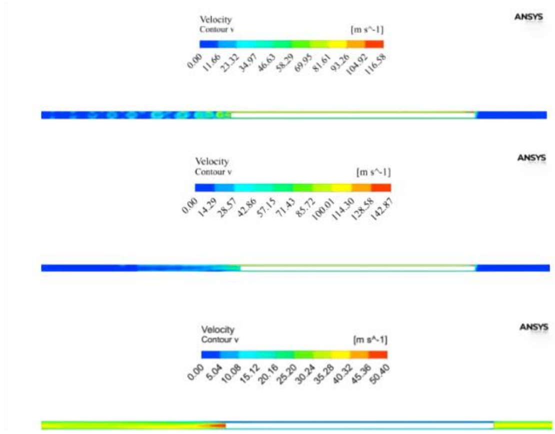

Fig. 10. Comparison of airflow velocity cloud image in the tunnel under different ventilation conditions.

When the train runs at 160km/h, the airflow velocity cloud image in the tunnel under downwind, upwind, and with no natural ventilation (from top to bottom) is compared. (see Fig. 10). When there is natural ventilation, the wind speed on both sides of the train body is higher, and the air velocity distribution in the tunnel is uneven. When the train is running downwind, the airflow at the car's rear is in a vortex shape, caused by the air in front of the car body, which can not be timely around the rear when the train is running fast. When driving against the wind, the natural wind accelerates the flow of air in front of the car body so that there is no vortex behind the car body, and the local airflow speed in the tunnel increases. When there is no natural ventilation, the wind speed on both sides of the train body is low, and the air velocity distribution in the tunnel is more uniform.

5 Conclusion

This paper establishes and verifies the calculation model of piston wind for trains running in a tunnel under low pressure. The following important conclusions are drawn:

(1) Different atmospheric pressure and tunnel wall temperature have little influence on the piston wind effect in the tunnel, so the impact of these two factors on the piston wind in the tunnel can be ignored in the study of the thermal environment in the tunnel and the ventilation design.

(2) With the train running in the tunnel at different speeds, the piston wind speed increases regularly and tends to be stable with the increased running time. Through fitting analysis, the piston wind speed variation function of EMU, passenger train, and cargo train in the high-altitude and high-rock temperature tunnel of the Sichuan-Tibet Railway is obtained, which provides a reference for thermal environment analysis.

(3) With the increase of train speed, the piston wind speed in the tunnel increases and gradually accelerates, the piston wind speed at the monitoring point drops sharply, and the influence range of the piston wind effect increases. When the piston wind speed tends to be stable, the piston wind speed increases by 7-8m/s for every 40km/h increase in train running speed. In addition, the piston wind speed reaches its maximum in the train wake.

(4) Natural ventilation significantly influences the change of airflow velocity in the tunnel. The natural wind direction has little influence on the average airflow velocity in the tunnel but dramatically affects the local airflow velocity. When there is no natural ventilation, the flow velocity in the tunnel is evenly distributed, while when there is natural ventilation, the flow velocity is unevenly distributed.

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