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Optimization Study on the Layout of Full Jet Ventilation Fans in Extra Long Highway Tunnels

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ABSTRACT: The ventilation problem of long tunnels has received widespread attention from scholars and affects the operational safety of the tunnel. Based on the Chunmushan extra-long highway tunnel, this paper uses ANSYS FLUENT software to simulate and analyze the influence of the installation angle of jet fans, the lateral spacing of jet fans, and the longitudinal spacing of jet fans on the flow field and pressure field in the tunnel, and the comprehensive influence coefficient of the fans It is determined that the optimal installation angle of the jet fan is 5°, the optimal horizontal spacing is 1.5D, and the optimal longitudinal spacing is 300m. The optimal fan layout scheme can save about 170 million yuan in mechanical and electrical costs compared with the original scheme for 20 years of operation.

Key words: Highway tunnel; Numerical simulation; Full jet ventilation; Fan layout

I. INTRODUCTION

The longitudinal ventilation method using axial jet fans is widely applied in the ventilation and smoke extraction of extra-long highway tunnels due to its advantages of low construction cost, simplicity of equipment, and ease of operation [1-2]. The operation of jet fans constitutes a significant portion of tunnel ventilation costs. In the long run, maximizing the pressure-boosting ventilation effect of jet fans and optimizing the utilization of jet fan pressure-boosting can greatly reduce the operational costs associated with longitudinal ventilation in extra-long tunnels. This leads to significant energy savings and emissions reduction.

Numerous scholars, both domestic and international, have conducted research on the installation of axial jet fans for tunnel longitudinal ventilation. Hu et al.[3] for instance, used CFD software to numerically simulate a highway tunnel's longitudinal jet ventilation system, analyzing its internal flow characteristics. The study recommended that jet fan outlets be inclined at a certain angle downward and that the longitudinal spacing of the fans should not be less than 150 meters. Li et al.[4] utilized ANSYS FLUENT computational fluid dynamics software to analyze changes in the velocity field inside the tunnel under the influence of full jet ventilation. They determined the optimal longitudinal installation distance for the jet fans. Wang et al.[5] also employed ANSYS FLUENT to identify the factors affecting the comprehensive fan performance coefficient K and its variations. Shi and Xia[6] used finite element numerical simulation to provide recommendations for the installation height of fans in highway tunnels and the optimal number of fan groups. Jung et al.[7], conducted a numerical analysis of air velocity changes within the tunnel resulting from the operation of jet fans. They adjusted the distance between the jet fans from 0.5D to 3.0D.

Currently, research on the installation of axial jet fans for tunnel longitudinal ventilation by scholars often focuses on individual factors, with limited consideration of the combined effects of multiple factors on the tunnel's flow field and pressure field. This paper, based on the Chunmushan Extra-Long Highway Tunnel, utilizes ANSYS FLUENT software to simulate and analyze the impact of jet fan installation angles, transverse spacing, and longitudinal spacing on the tunnel's flow field and pressure field. By assessing the comprehensive fan performance coefficient, the study aims to determine the optimal layout for fan installation.

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II. PROJECT OVERVIEW

The Chunmushan Tunnel, currently under construction, is a key and pivotal project for the Huaihua City (Zhijiang) to Tongren (Hunan-Guizhou Border) Expressway in Hunan Province. It is situated in the border area between Zhijiang County and Mayang County. The tunnel's entrance is located approximately 50 meters to the northwest of Yangjiazhai in Wulangxi Township, Zhijiang County, while the exit is around 380 meters to the northeast of Zhangmuao in Yaoshi Town, Mayang County. This tunnel is a separated extra-long tunnel designed for two lanes in each direction, with a standard design speed of 100 km/h. The tunnel spans from chainage ZK18+163 to ZK24+310 for the left tunnel (total length of 6,147 meters) and from K18+130 to K24+288 for the right tunnel (total length of 6,158 meters). For ventilation, the left tunnel employs a vertical shaft segmented ventilation method, along with connecting passages for segmented smoke extraction. The right tunnel employs a full axial jet ventilation system, also utilizing connecting passages for segmented smoke extraction. This design enables the ventilation and smoke extraction functions to be controlled by a single shaft for both tunnels. The maximum design wind speed for the left tunnel of Chunmushan is 6.1 m/s, while for the right tunnel, it is 5.1 m/s. The layout of the ventilation shafts is illustrated in Fig. 1.

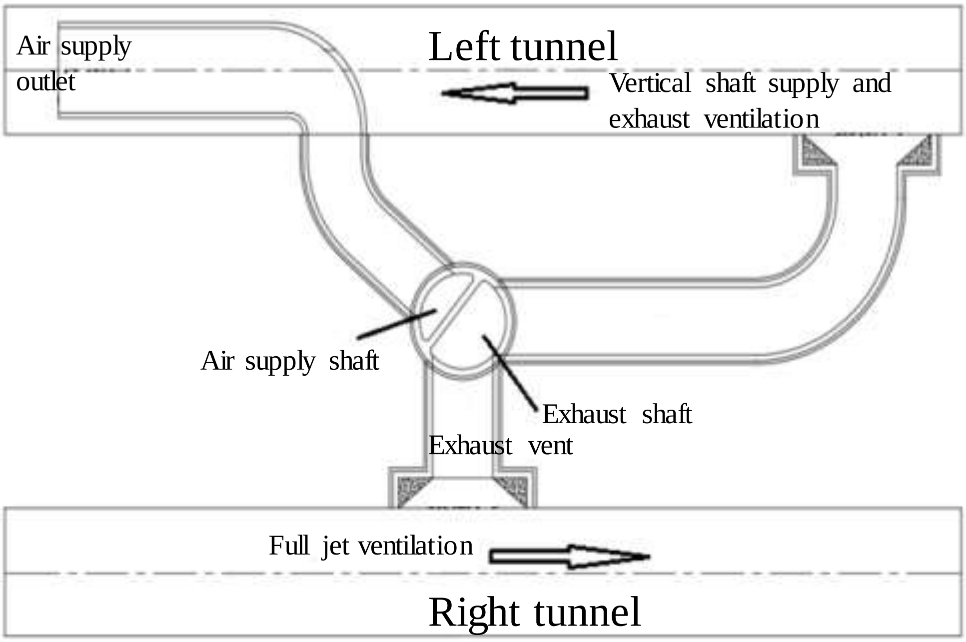

Fig. 1 Setting diagram of ventilation shaft

III. COMPREHENSIVE IMPACT COEFFICIENT OF FAN

Jet fans primarily play a significant role in the pressurization process. The efficiency of jet fans is measured by the comprehensive fan performance coefficient, which is the ratio of actual pressurization to theoretical pressurization. The calculation of the comprehensive fan performance coefficient[8-9] is as follows:

$$\Delta p=\frac{1}{2}\times\lambda\times\frac{L}{D_r}\times\rho\times V_j^2 \quad (1)$$

$$p_j=\Delta p-(p_1-p_2) \quad (2)$$

$$p_j^*=n\times\rho\times v_j^2\times\frac{A_j}{A_r}\times\frac{v_j-v_r}{v_j} \quad (3)$$

$$K=\frac{p_j}{p_j^*} \quad (4)$$

In which, p_j^* represents the theoretical pressurization value of a single jet fan, p_1,p_2 denote the static pressure values at the tunnel's entrance and exit, respectively, p_j signifies the actual pressurization value of the jet fans, n stands for the number of jet fans, K is the comprehensive fan performance coefficient.

From the formula, it is evident that the comprehensive fan performance coefficient is directly proportional to the pressure increment that jet fans actually provide to the tunnel. The actual pressurization from jet fans is dependent on factors such as the installation angle of the jet fans, the

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transverse spacing of the jet fans, and the longitudinal spacing of the jet fans. These factors influence the effectiveness of the jet fans in enhancing tunnel ventilation and pressure control.

IV. ESTABLISHMENT OF FLUENT VENTILATION MODEL

Chunmushan Tunnel's right lane, with a total length of approximately 6 kilometers, is an extra-long single-tube tunnel designed for one lane in each direction. It employs full axial jet longitudinal ventilation. According to regulatory requirements, two jet fans are recommended to be installed at the same cross-section, with a minimum net distance between fans of not less than one jet fan diameter. Additionally, the distance between jet fans and the tunnel's structural clearance should not be less than 15 cm. Given that the tunnel has a consistent narrow cross-sectional design, the uniform distribution of axial jet fans along the tunnel's longitudinal axis results in periodic variations in the airflow patterns along the tunnel's length. Each period corresponds to the range affected by each fan location. Therefore, to study the impact of jet fan layout parameters on the flow field and pressure field within each period, while minimizing computational load, this study selects a section 500 meters from the tunnel entrance as the calculation model. Two jet fans are placed at a distance of 150 meters from the entrance, with the fans positioned 15 cm below the tunnel's ceiling. Each jet fan has a diameter of 1 meter and a length of 1.5 meters, spaced apart at a distance equal to one jet fan diameter. The layout of jet fans in the cross-section is illustrated in Fig. 2. The computational model is created and meshed using ICEM CFD modeling software, resulting in a total of 1,037,503 grid cells. The model's tunnel entrance is defined as a velocity inlet boundary with an inlet velocity of 2.5 m/s. The exit boundary is set as a pressure outlet with a value equal to the ambient pressure, representing a free exit condition. The wall boundary conditions are specified as no-slip walls with a surface roughness of 0.05. The layout of the computational model and grid cells is shown in Fig. 3.

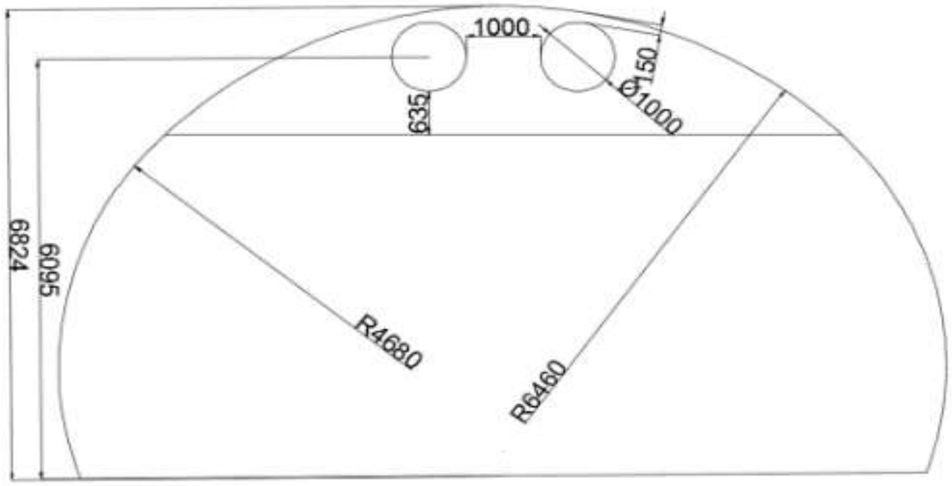

Fig. 2 Layout of jet fan

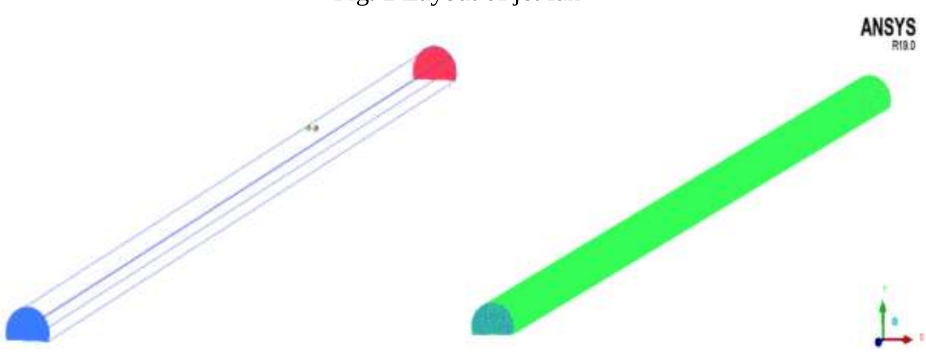

Fig. 3 Calculation model and grid division

The algorithm utilized in this study employs the velocity-pressure steady-state coupled calculation method under the SIMPLE algorithm. For modeling turbulence, the RNG k-ε turbulence model is chosen. During the calculation process, the governing equations solved include the continuity equation, momentum conservation equation, energy conservation equation, and turbulent kinetic energy equation[10-12].

V. RESEARCH ON OPTIMIZATION OF INSTALLATION ANGLE OF JET FAN

During the calculations, the jet fan installation angles are adjusted by altering the direction of the jet fan outlet flow velocity. The study of the optimal installation angle is conducted without considering the resistance from vehicular traffic inside the tunnel. When the jet fan angle is set to 0°, the variation of static pressure along the tunnel's longitudinal axis is depicted in Fig. 4, and the variation of flow velocity along the tunnel's longitudinal axis is shown in Fig. 5.

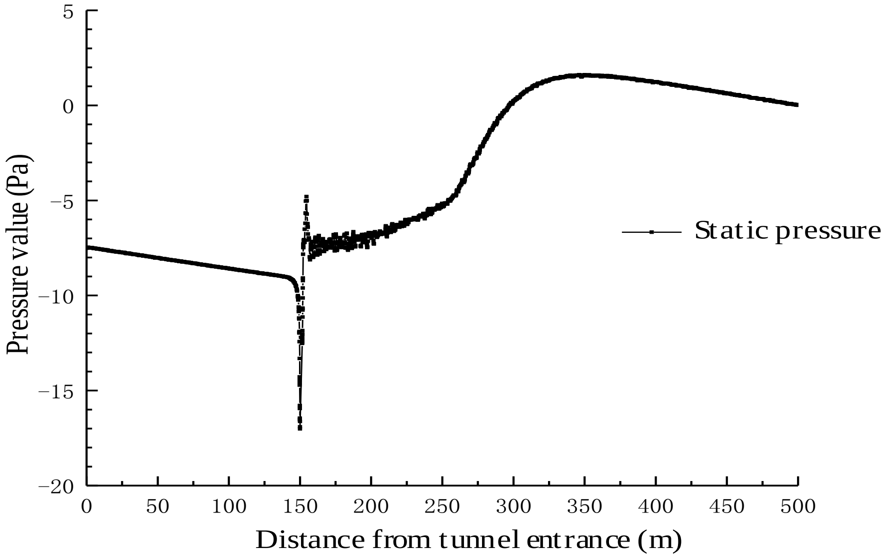

Fig. 4 Change of static pressure in the tunnel

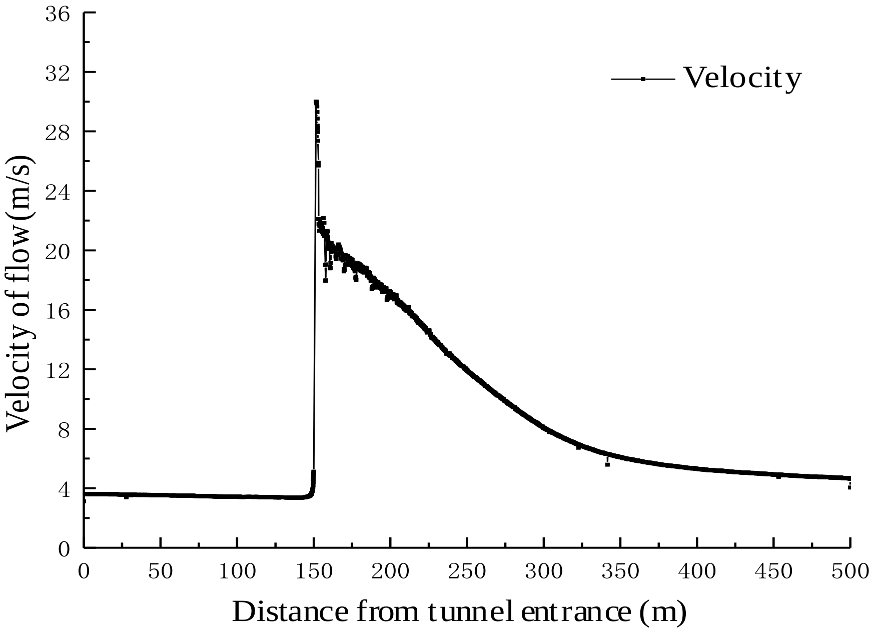

Fig. 5 Flow velocity variation diagram in the tunnel

Analysis of Fig. 4 and Fig. 5 reveals the following observations: Within a range of approximately 1 meter upstream of the jet fan, there is a sharp drop in static pressure, reaching a minimum value of -17 Pa. However, before the jet fan outlet, the tunnel's internal dynamic pressure and flow velocity remain relatively stable with minimal changes. The reasons for this behavior can be attributed to the following two factors:

Upstream Flow Velocity: The upstream flow velocity is primarily influenced by the pressure difference between the tunnel entrance (0 Pa) and the upstream. The drop in static pressure within the first meter is mainly due to the downstream wind pressure generated by the jet fan, which propels the movement of gases downstream. The continuous supply of gases from the upstream region drives the gases in the upstream direction. The abrupt drop within the first meter is caused by the substantial influx of gases from the jet fan.

Flow Velocity Variation: The flow velocity inside the tunnel experiences a momentary increase at the jet fan outlet but rapidly decreases shortly after. At a distance of 1.5 m from the fan outlet, it falls to 22 m/s. Afterward, there is a stable but relatively quick reduction in flow velocity within a 200-meter section from the fan outlet. Beyond this point, the velocity reduction occurs at a slower rate.

By adjusting the installation angle of the jet fans and conducting numerical calculations for tunnel ventilation, the study obtained various ventilation parameters for different installation angles, as shown in

Table 1.

Table 1 Ventilation Parameters in Tunnel at Installation Angle

Angle of installation	Static pressure of inlet (Pa)	Flow velocity inside the tunnel (m/s)	Pressure loss along the way (Pa)	Actual boosting of fan (Pa)	Theoretical boost value of fan (Pa)	Comprehensive impact coefficient of fan
0°	-7.58	5.06	8.50	16.08	23	0.70
3°	-8.17	5.17	8.87	17.04	23	0.74
4°	-8.85	5.25	9.16	18.01	23	0.78
5°	-9.25	5.35	9.51	18.76	23	0.82
6°	-9.10	5.28	9.26	18.36	23	0.79
7°	-9.02	5.09	8.61	17.63	23	0.77
8°	-8.71	4.98	8.24	16.95	23	0.74
10°	-8.54	4.88	7.91	16.45	23	0.71

Based on the numerical analysis results, the relationship between the comprehensive fan performance coefficient and the angle is depicted in Fig. 6.

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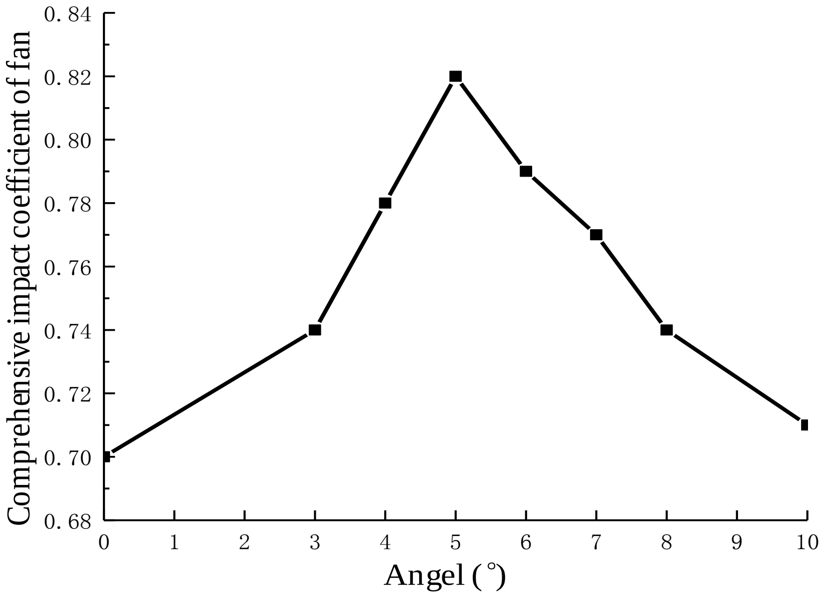

Fig. 6 Curve of comprehensive influence coefficient of fan changing with angle

The analysis reveals that when the installation angle of the jet fans is relatively small, the main jet of the jet fan is significantly restricted by the tunnel's ceiling. This results in a substantial amount of energy loss due to friction at the tunnel's upper region, which is not conducive to the efficient utilization of the jet fan. On the other hand, in the event of a fire inside the tunnel, the hot air generated by the fire, under the influence of buoyancy, tends to move upward. Even after reaching the tunnel's upper section, the smoke generated by the fire will still spread along the upper part of the tunnel. Based on the analysis, it is evident that excessively large jet fan installation angles are not advisable. If the angle is too large, the influence of the jet fan's main jet on the tunnel's upper region is reduced, which is not conducive to the expulsion of smoke in the event of a tunnel fire. Additionally, with a very large angle, the tunnel's bottom also experiences significant energy losses. As shown in Fig. 6, the comprehensive fan performance coefficient increases initially with the angle and then decreases. When the installation angle is 5°, the comprehensive fan performance coefficient reaches its maximum value of 0.82. Therefore, to fully utilize the ventilation function of the jet fans, maximize the ventilation efficiency, achieve energy savings, and reduce emissions, the jet fans in the Chunmushan Tunnel are installed with a 5° downward tilt in a horizontal plane.

VI. RESEARCH ON OPTIMIZATION OF HORIZONTAL SPACING OF JET FAN

In this section, based on the optimal installation angle determined in the previous section, the impact of the transverse spacing between jet fans on tunnel ventilation is further investigated using the FLUENT computational fluid dynamics software. The model setup is identical to that in the previous section, maintaining a jet fan installation angle of 5 degrees. The transverse spacing between the jet fans is varied to 1.2D, 1.5D, 1.7D, and 2D (where D represents the jet fan diameter, which is 1.0m in this study) for ventilation simulation calculations. The boundary conditions and computational methods remain consistent with those in the previous section, and vehicular traffic resistance inside the tunnel is not considered during the calculations.

The longitudinal velocity data along the tunnel's centerline is extracted for each transverse spacing, and the longitudinal velocity variation along the tunnel's centerline for each spacing is presented in Fig. 7.

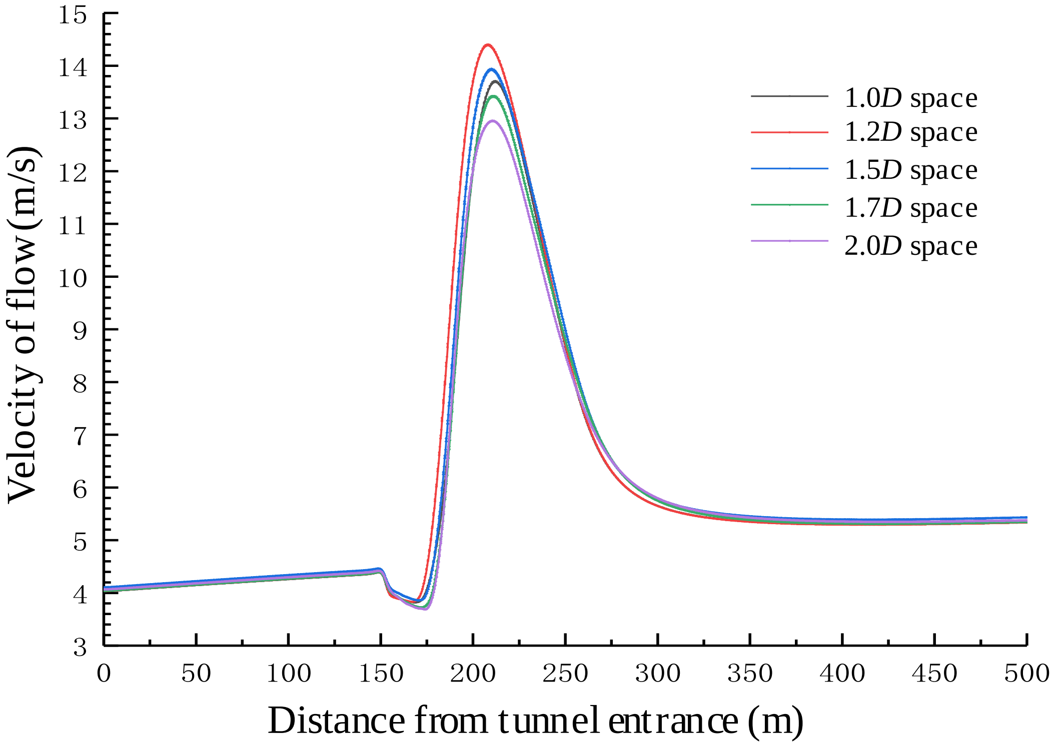

Fig. 7 Longitudinal variation of flow speed of tunnel center line under each spacing

From Fig. 7, it can be observed that the transverse spacing between the jet fans does not influence the longitudinal velocity variation within the tunnel. In the longitudinal direction, there is a segment of relatively lower velocity within approximately 25 m from the jet fan outlets, primarily due to the influence of the two jet flows. Subsequently, the velocity increases rapidly, reaching its maximum value at around 210 meters. When the spacing is 1.2D, the maximum velocity is 14.4 m/s, while it drops to 13 m/s when the spacing is 2.0 D. Afterward, the velocity decreases and stabilizes, with nearly identical velocities in the stable state. At the tunnel exit, the velocity is approximately 5.3 m/s. The maximum stable flow velocity occurs with a jet fan spacing of 1.5 D.

The static pressure data inside the tunnel is extracted for various transverse spacing conditions, and the variations in static pressure within the tunnel for different jet fan spacings are represented in Fig. 8.

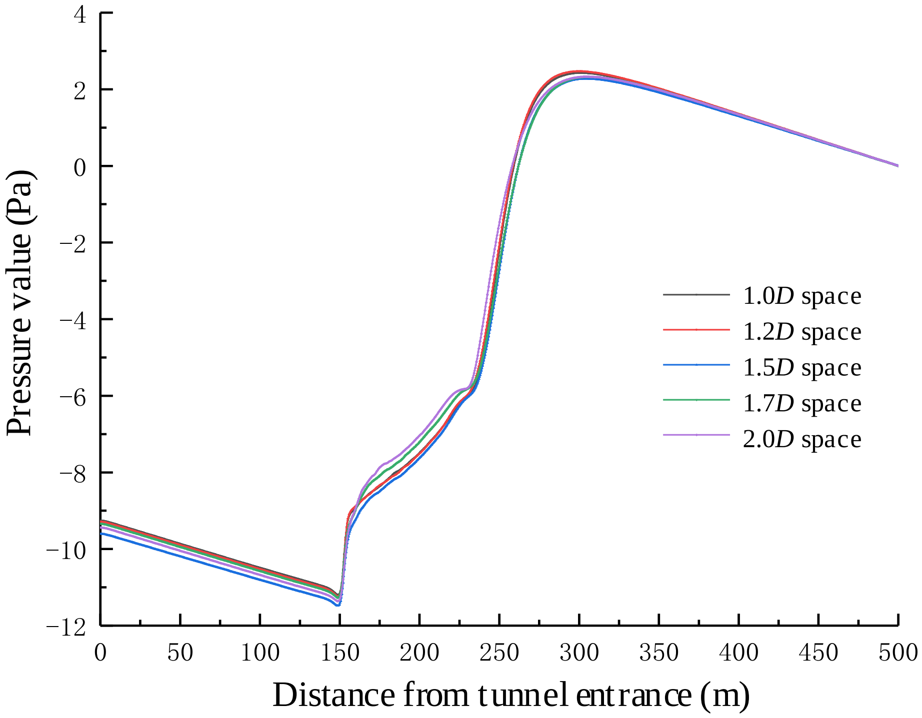

Fig. 8 Pressure variation diagram of tunnel

As shown in Fig. 8, the static pressure inside the tunnel continually decreases upstream of the jet fan and experiences a sharp increase at the jet fan outlet. It reaches its highest value around a distance of 300 m from the tunnel entrance, after which it gradually decreases. The variations in static pressure inside the tunnel are nearly identical for different jet fan spacings. When the jet fan spacing is 1.5D, the tunnel entrance static pressure reaches its lowest value of -9.61 Pa, while for a jet fan spacing of 1.0 D, the tunnel entrance static pressure reaches its highest value of -9.25 Pa.

Due to the minor differences in various parameters within the tunnel under different jet fan spacings, the selection is still based on the jet fan's comprehensive performance coefficient. The obtained ventilation parameters for different spacing conditions inside the tunnel are presented in

Table 2.

Table 2 Ventilation parameters in the tunnel under different installation spacing

Installation spacing	Static pressure of inlet (Pa)	Flow velocity inside the tunnel (m/s)	Pressure loss along the way (Pa)	Actual boosting fan (Pa)	Theoretical boost value of fan (Pa)	Comprehensive impact coefficient of fan
1.0D	-9.25	5.35	9.51	18.76	23	0.82
1.2D	-9.29	5.38	9.61	18.90	23	0.82
1.5D	-9.60	5.45	9.87	19.47	23	0.85
1.7D	-9.33	5.39	9.65	18.98	23	0.83
2.0D	-9.44	5.39	9.65	19.09	23	0.83

From

Table 2, it can be observed that the comprehensive fan performance coefficient increases initially with the jet fan spacing and then decreases. When the spacing is 1.5D, the comprehensive fan performance coefficient reaches its maximum value of 0.85. Therefore, to fully utilize the ventilation function of the jet fans, maximize the ventilation efficiency, achieve energy savings, and reduce

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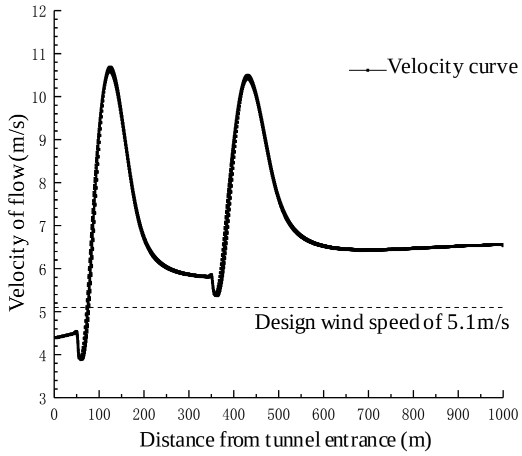
emissions, the transverse spacing between jet fans in the Chunmushan Tunnel is set at 1.5D, which corresponds to a net spacing of 1.5 m between the two jet fans.

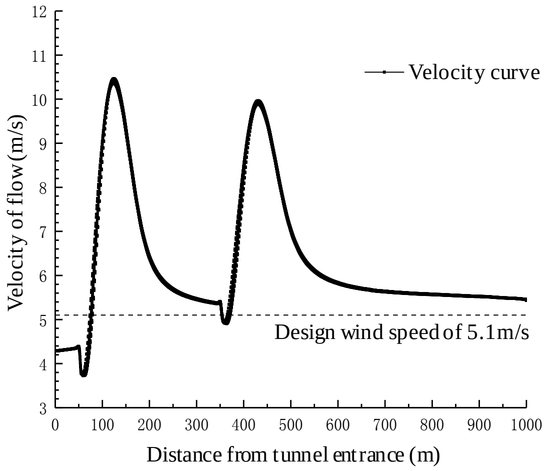
VII. RESEARCH ON OPTIMIZATION OF LONGITUDINAL SPACING OF JET FAN

When optimizing the longitudinal spacing of the jet fans, it's essential to consider the influence of natural ventilation. According to the "Highway Tunnel Design Ventilation Guidelines," the requirements for natural ventilation resistance are typically based on resistance, and natural wind speeds usually fall within the range of 2-3 m/s. Therefore, in this section, the impact of natural wind speeds at 0 m/s, 2 m/s, 2.5 m/s, and 3 m/s on the longitudinal spacing of the jet fans for full jet ventilation in the tunnel will be investigated. The longitudinal spacing of the jet fans will be set at 200 m, 300 m, 400 m, and 500 m, with a focus on providing guidance for the ventilation of the right-line Chunmushan Tunnel. The analysis will be conducted using 300 m as an example, and the same process applies to the other distances, which will not be redundantly explained.

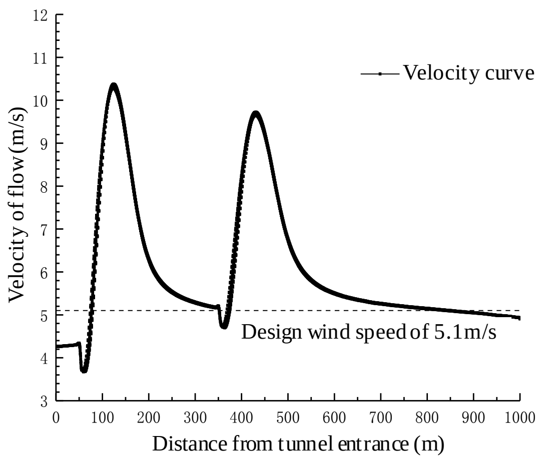
The computational model involves the placement of two sets of jet fans at distances of 50 m and 350 m from the tunnel entrance. The ventilation within the tunnel is analyzed for natural wind speeds of 0 m/s, 2 m/s, 2.5 m/s, and 3 m/s. The variations in flow velocity within the tunnel for a fan spacing of 300 meters under different natural wind speeds are presented in Fig. 9.



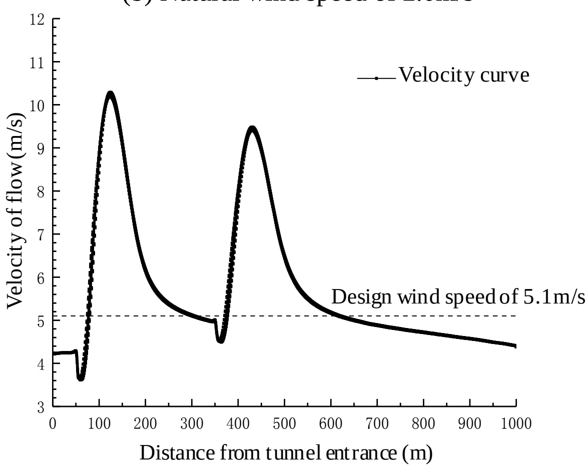
(a) Not considering natural wind speed



(b) Natural wind speed of 2.0m/s



(c) Natural wind speed of 2.5m/s



(d) Natural wind speed of 3.0m/s

Fig. 9 Flow speed change at fan distance of 300m

From Fig. 9, it can be observed that when the natural wind speed is 2.0 m/s, beyond a distance of 75 m from the tunnel entrance, except for some slight fluctuations in velocity near the second set of jet fans, the velocity remains higher than the design wind speed of 5.1 m/s. This suggests that for a natural wind speed of 2.0 m/s, a longitudinal spacing of 200 meters between the jet fans would meet the ventilation requirements for the Chunmushan Tunnel's right lane. When the natural wind speed is 2.5 m/s, beyond a distance of 80 m from the tunnel entrance, except for some velocity fluctuations between 355 m and 368 m, slightly below 5.1 m/s, the velocity between the two sets of fans remains higher than the design wind speed. However, after reaching a distance of 840 m from the tunnel entrance, the velocity falls below the design wind speed. This location is 490 m away from the second set of jet fans, indicating that placing a third set of jet fans before this point would satisfy the tunnel ventilation requirements. Therefore, with a natural wind speed of 2.5 m/s, a longitudinal spacing of 300 m between the jet fans would still meet the ventilation requirements for the Chunmushan Tunnel's right lane. When the natural wind speed is 3.0 m/s, there is a section between 300 m and 371 m where the velocity falls below 5.1 m/s. There is a significant stretch between the two sets of fans where the velocity remains lower than the design wind speed. Therefore, with a natural wind speed of 3.0 m/s, a longitudinal spacing of 300 meters between the jet fans does not meet the ventilation requirements for the Chunmushan Tunnel's right lane.

In conclusion, when the longitudinal spacing between the jet fans is set at 300 m and considering natural wind speeds in the range of 2.0 m/s to 2.5 m/s, the ventilation in the Chunmushan Tunnel's right lane can meet the design requirements. However, it is essential to base the design on the historical wind speed data for the Chunmushan Tunnel. Furthermore, the question of whether a longitudinal spacing of 300 m between the jet fans represents the most economical solution needs further investigation. It is necessary to conduct numerical analysis with larger spacing to determine the maximum spacing that meets the ventilation requirements.

After conducting calculations and analyses for various spacings, it has been determined that the optimal longitudinal spacing for the jet fans varies depending on the natural wind speed. When the natural wind speed is 2.0 m/s, the optimal longitudinal spacing for the jet fans is 400 m per set. When the natural wind speed is 2.5 m/s, the optimal spacing is 300 m per set. When the natural wind speed is 3.0 m/s, the optimal spacing is 200 m per set. Considering that the Chunmushan Tunnel experiences a natural wind speed of 2.5 m/s, the optimal configuration for the jet fans is to have a longitudinal spacing of 300 m per set, with each set consisting of two jet fans with a jet velocity of 30 m/s.

VIII. ECONOMIC CALCULATION OF FAN LAYOUT PLAN

Based on the calculations and analysis conducted, it has been determined that the optimal fan configuration for the Chunjushan Tunnel includes an installation angle of 5°, a lateral spacing of 1.5 times the fan diameter (1.5D), and a longitudinal spacing of 300 m per set. A comparison of the optimal fan arrangement with the original preliminary design is provided in

Table 3.

Table 3 Comparison of best plan and original plan

Plan	Installation angle	Horizontal spacing	Longitudinal spacing	Comprehensive influence coefficient	Number of fans
Original plan	0°	2 m	200 m	0.70	60
Optimal plan	5°	1.5 m	300 m	0.85	40

The motor power of the jet fan is 25 kW, and the electricity cost is calculated at 1.5 yuan per kilowatt-hour. The cost savings of the optimal fan arrangement compared to the original preliminary design plan over 20 years of operation can be calculated as follows:

$$(60-40)\times 25\times 24\times 365\times 20\times 1.5+40\times 25\times 24\times 365\times 20\times 1.5\times(0.85-0.7)=170{,}820{,}000 \quad (5)$$

After calculation, it is determined that the cost savings over 20 years of operation using the optimal fan arrangement is approximately 170 million yuan compared to the original design plan. The optimal fan arrangement significantly reduces the electrical operating costs.

IX. CONCLUSIONS

This study, based on the Chumushan Tunnel, optimizes the arrangement of jet fans for full longitudinal ventilation in the right lane. The primary conclusions obtained are as follows:

(1) Introduction of the fan's comprehensive impact coefficient to evaluate the effectiveness of jet fan ventilation. Simulations with different fan installation angles were conducted to analyze the variations in flow and pressure fields. It was concluded that the fan's comprehensive impact coefficient increases initially and then decreases with the angle of installation, and the optimal fan installation angle was determined to be 5°.

(2) With the fan installation angle set at 5°, simulations were performed with different transverse spacings to analyze the variations in flow and pressure fields. It was found that the fan's comprehensive impact coefficient increases initially and then decreases with an increase in transverse spacing, and the optimal fan installation spacing was determined to be 1.5 times the fan diameter, approximately 1.5 meters.

(3) Simulations were conducted to study the tunnel's ventilation under varying natural wind speeds and different longitudinal spacings between the jet fans. It was observed that the larger the natural wind speed, the smaller the distance influenced by the jet fans. To ensure the tunnel reaches its design wind speed (5.1 m/s) under the influence of actual natural wind resistance (2.5 m/s), the optimal configuration was determined to have fan installation angles of 5°, transverse installation spacing of 1.5D (1.5 m), and a longitudinal spacing of 300 m per group.

(4) Using the optimal configuration with a fan installation angle of 5°, transverse spacing of 1.5 m, and longitudinal spacing of 300 meters per group, it was estimated that this arrangement would save approximately 170 million yuan in electrical operating costs over 20 years compared to the original design plan, signifying significant cost savings.

X. ACKNOWLEDGEMENT

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