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Numerical Study on the Operational Ventilation Patterns of Alternative Jet Fans in Curved Tunnels

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Abstract: In tunnel operation ventilation systems, the arrangement of jet fans plays a decisive role in ensuring ventilation efficiency. Curved tunnels, due to their unique radius of curvature, exhibit significant differences in fan installation parameters and jet flow field distribution compared to traditional straight-line tunnels. In order to investigate the distinct characteristics, this research utilized computational fluid dynamics (CFD) simulation methods to analyze the ventilation performance of both an innovative, adjustable jet fan system and conventional jet fans within the context of curved tunnel configurations. The findings reveal that by adjusting the horizontal deflection angle of the novel jet fan, the flow field distribution can be effectively optimized, and the jet effect can be enhanced, thereby improving ventilation efficiency. Compared to traditional jet fans, the novel fan demonstrates a significantly greater capability in flow field optimization, especially when its horizontal deflection angle is adjusted, showing a trend where the jet effect initially increases and then decreases, with the longitudinal impact range being adjustable within a range of 5 m to 25 m.

Keywords: curved tunnels; ventilation optimization; numerical simulation; flow field characteristics; static pressure variation

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1. Introduction

In the past decade, with the ongoing development of the "Belt and Road" strategy, coupled with the swift establishment of the "Ten Vertical and Ten Horizontal" integrated transportation networks, the Chinese government has placed special emphasis on the development of transportation infrastructure in the central and western regions, aiming to precisely fill the gaps in the transportation network of these areas. Within the domain of tunnel engineering, the conceptualization and execution of ventilation systems are paramount for fostering a secure, hygienic, and pleasant ambiance for vehicular transit. Moreover, with the growing demand for urban transportation, the significance of research and application in this field has become increasingly prominent.

In a survey conducted by the World Road Association (PIARC) across 27 tunnel groups, it was found that over 70% of the tunnels have implemented longitudinal ventilation systems [1]. These systems are preferred due to their ease of management, installation, and lower operational costs. The operational foundation of longitudinal ventilation systems is predicated on the entrainment and pressure increment induced by jet fans. Consequently, optimizing the installation position of jet fans to enhance their pressure rise efficiency has garnered widespread attention among scholars.

For instance, Haiyan and colleagues [2] utilized CFD 2022R2 software to numerically simulate the parameters of jet fans in urban tunnel cross-sections. Their results indicated that the optimal ventilation effect is achieved when the ratio of fan diameter to transverse spacing is 1:2, and the air jet develops fully when the longitudinal spacing exceeds 150 m. Zhao et al. [3] explored the impact of fan longitudinal spacing, fan arrangement height, and fan transverse spacing on fan pressure rise using CFD software, thereby deriving the optimal layout in tunnel space. Chen Tao et al. [4] optimized the spread angle and pitch angle of jet fans using turbulent jet theory and Fluent 2019R3 software simulations. Their findings demonstrated that adjusting the inclination angle of the fan outlet can effectively increase the pressure rise coefficient. Cao et al. [5] investigated the impact of different jet fan arrangements on pressure rise efficiency, optimized the arrangement of fans, and established an expression for the pressure rise effect of jet fans. Yang et al. [6] utilized CFD to develop a 3D numerical model designed for the aerodynamic assessment of twin tunnels, subsequently performing a computational analysis to scrutinize the aerodynamic behavior within the ventilation flow field. They also delved into the influence of fan position and type on airflow structure, ultimately determining the best fan arrangement plan suitable for the site.

Despite the relative maturity of existing ventilation technologies for straight-line tunnels, the ventilation design for curved tunnels still faces numerous challenges. Firstly, traditional fan layout methods are primarily designed for straight-line tunnels and may not adapt well to the unique geometric characteristics of curved tunnels, leading to suboptimal ventilation performance. Secondly, the pressure increase efficiency of existing fans in curved tunnels is not ideal, which limits the overall performance of the ventilation system. Additionally, the uneven distribution of airflow within curved tunnels is a prominent issue that not only affects ventilation efficiency but may also pose potential threats to traffic safety. These limitations indicate that existing tunnel ventilation technologies and design methods require further optimization and improvement to meet the special needs of curved tunnels.

Regarding curved tunnels, several scholars have conducted research on fire control and fan setting parameters. In an effort to optimize the pressure augmentation capabilities of jet fans, Wang et al. [7] conducted a study to determine the most effective fan deflection angle within curved tunnel settings, ultimately discovering that a 3° deflection angle was optimal for achieving the best pressure enhancement. Ding et al. [8] employed CFD simulations to demonstrate that the pressure enhancement properties in small-radius curved tunnels are distinct from those observed in straight tunnels and that the lateral spacing of fans could be fine-tuned in accordance with the number of fans installed. Chen et al. [9] applied CFD software to evaluate the influence of diverse parameters on the airflow and pressure rise within curved tunnels. Their research offered guidelines for the strategic placement of fans in tunnels with radii measuring 65 m and 85 m, respectively. Xu et al. [10] constructed a full-scale tunnel model employing FLUENT software and determined that the airflow within curved tunnels exhibited asymmetry. They noted that tunnels with smaller radii necessitated a greater distance to facilitate uniform airflow distribution and to attain a more significant elevation in the pressure rise coefficient. Chen et al. [11] found that selecting an appropriate pitch angle for the jet fans could both amplify the pressure rise effect and diminish the wall shear force. Gao et al. [12] identified that the primary factors influencing the pressure-raising reduction coefficient (PC) are the jet angle and the vertical height of the jet fans. Li et al. [13] employed orthogonal testing methods to assess the influence on fan efficiency caused by multiple variables, including the transverse spacing, offset distance, and deflection angle of jet fans in tunnels that featured a variety of small radii. The findings indicated that the impact of each factor on the ventilation efficiency of fans is contingent upon the curvature radius of the tunnel; generally, a decrease in radius size corresponds to a degradation in ventilation performance. Research has consistently demonstrated that adjusting the outlet of jet fans at an angle towards the tunnel floor can lead to an enhancement in the pressure-raising coefficient (PC) efficiency of these fans.

Research data suggest that the operational expenses associated with road tunnels are largely influenced by ventilation and lighting, with ventilation costs being the most significant. Annually, these electricity expenses can amount to several million US dollars [14].

Accordingly, amidst the backdrop of global energy scarcity, the reduction in ventilation expenses has become particularly crucial. Chen et al. [4] have delved into determining the optimal pitch angles for jet fans in road tunnels and have examined the airflow development patterns within the context of curved road tunnels. Nevertheless, the enhancement of jet fan performance, especially in terms of pressure-raising capacity (PC) within the context of curved road tunnels, remains an area that requires additional investigative efforts.

The primary objective of this study is to explore the operational ventilation patterns of alternative jet fans in curved tunnels and to assess their optimization potential in terms of ventilation efficiency compared to traditional jet fans. Utilizing CFD numerical simulation technology, this research aims to compare and analyze the flow field characteristics and changes in cross-sectional average static pressure of traditional and alternative jet fans in curved tunnels. The study contributes to the understanding that by adjusting the horizontal deflection angle of alternative jet fans, the flow field distribution can be effectively optimized, enhancing the jet effect. Furthermore, a novel "banana-type" jet fan is proposed to further improve the performance of tunnel ventilation systems. The findings not only enrich the theoretical basis of tunnel ventilation design but also offer practical guidance for engineering applications, aiding in enhancing the performance of tunnel ventilation systems and ensuring a safe, healthy, and comfortable environment within a tunnel.

2. Numerical Simulation

2.1. Establishment of the Physical Model

In this study, based on the structural parameters of a specific curved tunnel, a simulation was conducted using the CFD software FLUENT. Notably, the numerical simulation employed ANSYS FLUENT 2020 R2, a widely recognized and advanced tool for simulating complex flow problems. This version of the software encompasses a variety of sophisticated physical models and solvers, enabling the precise simulation of the airflow distribution and ventilation efficiency within the tunnel. The model's computational length was set to 300 m to simulate the actual tunnel with a curvature radius of 700 m. Within the simulated tunnel, a set of two jet fans was installed to mimic the actual ventilation system. To ensure the accuracy of the simulation, the following steps were taken to precisely define the inlet and outlet wind speeds of each fan:

(1) Wind Speed Measurement: Prior to the simulation, high-precision anemometers were used to conduct field measurements of wind speed at various locations within the tunnel to obtain baseline data.

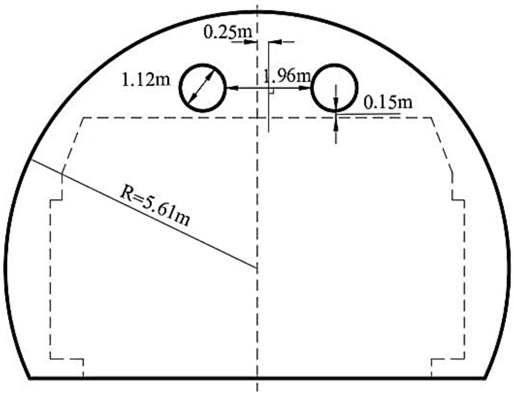
(2) Data Collection: Multiple wind speed sensors were installed at different locations within the tunnel to collect wind speed data continuously over a 24 h period, ensuring the representativeness of the data.

(3) Data Analysis: The collected data were subjected to statistical analysis to determine the average wind speed and fluctuation range at the inlet and outlet.

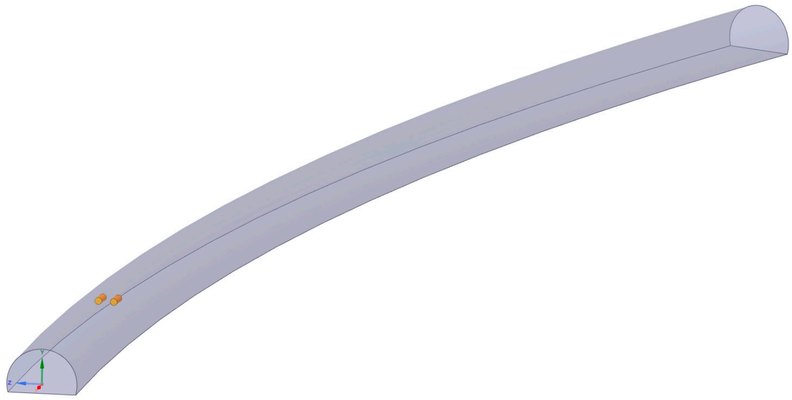
(4) Simulation Setup: In the CFD software, the wind speed boundary conditions at each fan inlet and outlet were set based on the results of field measurements and data analysis. Specifically, the inlet wind speed was set to 3 m/s, while the outlet wind speed was set according to the average value measured in the field, at 30 m/s, with a ±5% fluctuation range considered to simulate real-world conditions.

(5) Verification and Adjustment: After the initial simulation, the results were compared with actual measured data, and necessary adjustments were made to the wind speed settings to enhance the accuracy of the simulation.

Additionally, the 1120 model jet fan was simulated using a cylinder with a diameter of 1.12 m and a length of 3 m to capture its fluid dynamic characteristics in practical applications. The geometric model of the tunnel is detailed in Figure 1. Through this simulation approach, an in-depth analysis of the internal airflow distribution and ventilation efficiency within the tunnel can be conducted, providing a scientific basis for the design and optimization of the tunnel ventilation system.



(**a**) Cross-Section



(**b**) Three-Dimensional Tunnel Model

Figure 1. Geometric modeling of the tunnel.

2.2. Turbulence Model

In highway tunnels, airflow exhibits typical turbulent characteristics, and its complexity requires the use of an appropriate turbulence model for accurate simulation. Turbulence models are mainly divided into three categories: single-equation models, two-equation models, and zero-equation models. Among these, the two-equation model (k-ε model) is widely used due to its precision in simulating cylindrical jet flows, and its application is increasingly growing [15,16]. Therefore, this paper will focus on the two-equation model and provide a brief introduction to it.

The two-equation model offers a detailed depiction of turbulent flow by addressing the transport equations related to turbulent kinetic energy and the rate of its dissipation, thereby providing a more precise representation of energy distribution and the dissipative mechanisms inherent in turbulent flow phenomena. In CFD simulations for tunnel ventilation, selecting the appropriate turbulence model is crucial for predicting ventilation effects and optimizing design. The two-equation model employed in this paper combines the transport equations for turbulent kinetic energy (k) and its dissipation rate (ε), aiming to achieve an accurate prediction of the complex turbulent flow within the tunnel.

The turbulent kinetic energy transport equation is as follows [17]:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k \mu_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_i}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \quad (1)$$

The turbulent kinetic energy dissipation rate transport equation is as follows [18]:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon \mu_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_i}{\sigma_c}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_{1c} E\varepsilon - C_2\rho\frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} \quad (2)$$

In previous research, Chen et al. [18] validated the turbulence model used through full-scale experiments. As depicted in Figure 2, the discrepancy in velocity between the numerical simulation outcomes and the data obtained from full-scale experiments was maintained beneath the 10% threshold. This outcome signifies that the selected turbulence model for this investigation possesses a notably high level of precision and dependability when it comes to simulating air jet flows within the confines of highway tunnels. This high-precision simulation capability provides a solid foundation for the research presented in this paper, ensuring the validity of the simulation results and offering reliable data support for subsequent analysis and discussion.

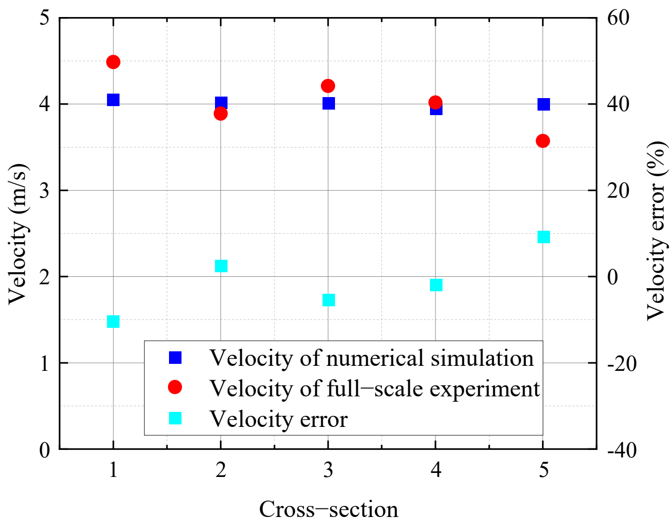


Figure 2. Comparative analysis of full-scale experimental data and computational simulation results [18].

2.3. Basic Assumptions

In conducting the simulation calculations for jet ventilation in highway tunnels, this study is based on the following fundamental assumptions:

(1) Incompressible Flow Assumption: The air is considered as the working medium in this study. Given that the airflow velocity is below a Mach number (Ma) of 0.3, the effects of air compressibility are considered negligible. Consequently, the airflow in this study is treated as incompressible [19], which simplifies the simulation process and enhances computational efficiency.

(2) Fluid Viscosity and Flow Regime: Although the viscosity of the fluid plays a significant role in actual flow and poses challenges for the research, this study particularly focuses on the frictional effects, leading to energy loss, during airflow. The jet produced by the jet fan involves both laminar and turbulent flow regimes, constituting a complex unsteady flow phenomenon [20].

(3) Boussinesq Assumption: In dealing with turbulent flow, this study employs the Boussinesq assumption, which permits considering only the changes in density when calculating buoyancy effects, while disregarding the temporal variations in the gas flow within the tunnel. This assumption aids in simplifying the calculations of the turbulence model while maintaining the accuracy of the simulation results.

2.4. Boundary Conditions

In accordance with the " *Guidelines for Design of Ventilation of Highway Tunnels*" [21], the boundary conditions for this study are set as follows:

(a) Inlet Boundary Conditions: At the tunnel inlet, a uniform velocity boundary condition of 4 m/s is applied to simulate the longitudinal ventilation environment.

(b) Outlet Boundary Conditions: The tunnel outlet is designated as a pressure outlet with a relative pressure set to 0 Pa, simulating equilibrium with the external atmospheric pressure.

(c) Wall Boundary Conditions: The walls and floor of the tunnel are assigned no-slip boundary conditions with a wall roughness of 0.002 m, representing typical smooth cement mortar surfaces.

These assumptions and boundary condition settings provide a solid foundation for the simulation, ensuring the scientific and practical nature of the simulation results, and offering accurate data support for subsequent analysis and design. The specific settings are illustrated in Table 1.

Table 1. Computational model boundary condition settings.

Model Position	Boundary Condition	Parameter
Tunnel Inlet	Velocity Inlet Boundary	3 m/s
Tunnel Outlet	Pressure Outlet Boundary	0 (relative to atmospheric pressure)
Fan Inlet	Velocity Inlet Boundary	−30 m/s
Fan Outlet	Velocity Inlet Boundary	30 m/s
Tunnel Floor and Ceiling	Wall Boundary	Average wall roughness height of 0.002 m Roughness constant of 0.5

2.5. Grid Independence Validation

In the process of numerical simulation, ensuring the quality of the grid is crucial as it directly affects the accuracy of the computational results. While a finer grid can provide higher computational accuracy, it also means that more grid cells are required, leading to increased computation time and resource consumption. Therefore, conducting a grid independence test is a key step in ensuring the accuracy of numerical simulation results. This testing process involves performing calculations with grids of different densities and comparing these results to verify the stability and reliability of the simulation solution. Utilizing this method, an optimal grid configuration plan can be determined that ensures the accuracy of the computational results while reducing computational resource consumption to a certain extent. The specific details of the grid settings are shown in Table 2.

Table 2. Mesh settings.

Operating Conditions	Tunnel Grid Size (m)	Jet Fan Grid Size (m)	Total Grid Count
1	0.48	0.12	416,437
2	0.40	0.10	661,561
3	0.32	0.08	957,859

To assess the impact of grid size, this study compared the lateral velocity distribution 30 m downstream of the jet fan, analyzing three grid configurations. From Figure 3, it can be observed that Grids 2 and 3 exhibited a high degree of consistency in capturing the velocity distribution, indicating that while Grid 1 showed similar trends, it lacked sufficient resolution to discern flow details, particularly at peak velocities.

The selection of Grid 2 as the final simulation parameter was a pragmatic decision. Although Grid 3 offered finer details, Grid 2 provided a satisfactory balance between detail and computational demand, making it a practical choice to achieve reliable simulation results without excessive resource consumption.

This approach ensures the reliability of the numerical simulation, laying a solid foundation for further analysis.

The computational model in this study employs unstructured mesh generation, with a mesh size of 0.4 m specified for the tunnel and 0.1 m for the jet fans. It should be clarified that while the mesh refinement accentuates the representation of these critical areas visually, it does not indicate the implementation of variable mesh sizing within the simulation. Designed to capture detailed flow characteristics within the tunnel, the mesh maintains uniformity across the simulation domain. A schematic representation of the mesh for the tunnel ventilation model is presented in Figure 4. The jet fans are simulated using cylindrical models with a diameter of 1.12 m and a length of 3 m.

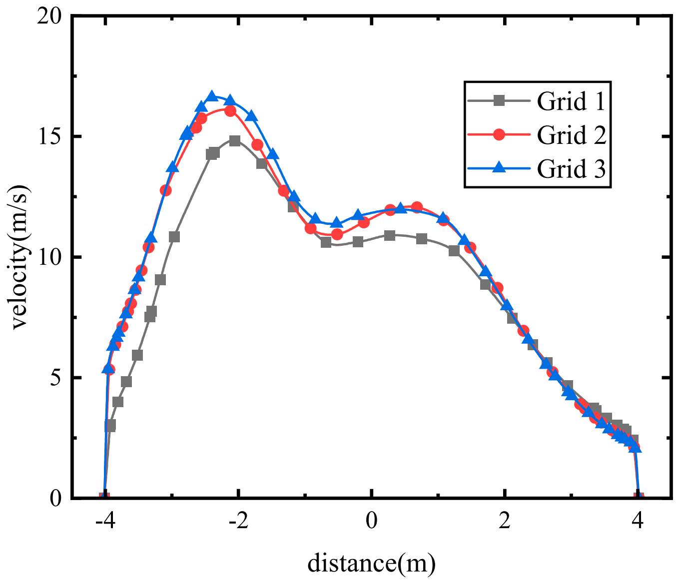


Figure 3. Lateral velocity distribution in the tunnel at 30 m downstream from the jet fan for different grid sizes.

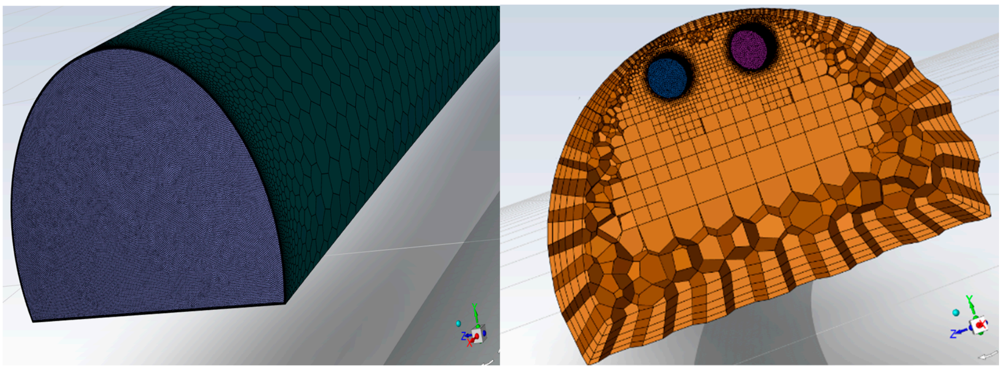


Figure 4. Schematic diagram of meshing at tunnel and fan.

2.6. Optimization of Jet Fan Model Layout in Curved Road Tunnels

In the study [7], it was discovered that deflecting the fan by 3° towards the convex wall of the tunnel maximizes the pressure rise coefficient on the ceiling and minimizes the wall shear stress. This finding is significant for optimizing the air distribution within the tunnel and reducing damage to the tunnel walls. Additionally, an innovative installation method for a new type of jet fan, referred to as the "banana-type" jet fan, has been proposed with the aim of further enhancing the performance of the tunnel ventilation system.

As depicted in Figure 5, the installation method of the new-type jet fan differs from traditional approaches, with its design taking into account the curvature of the tunnel and the aerodynamic characteristics of the airflow to achieve superior ventilation effects. The specific installation parameters and operating conditions are detailed in Table 3, which lists various parameter settings and the anticipated ventilation outcomes.

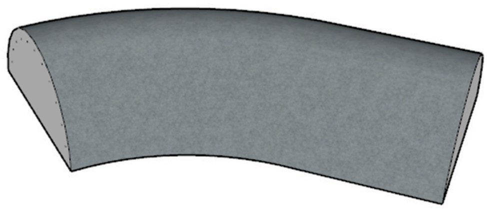


Figure 5. Schematic diagram of the "banana-type" jet fan.

Table 3. Installation parameters and operating conditions.

Operating Conditions	Horizontal Deflection Angle (°)	Transverse Offset (m)	Curvature Radius R (m)	Tunnel Length L (m)	Distance from Tunnel Inlet D (m)
1	0	0	700	300	50
2	0	0.25	700	300	50
3	2	0	700	300	50
4	4	0	700	300	50
5	6	0	700	300	50
6	8	0	700	300	50

3. Results Analysis

Performance of the Alternative Jet Fan

Figure 6 presents the velocity contour plots along the axis of the fan under different operating conditions, revealing the significant impact of fan layout and design on the flow field characteristics within the tunnel. In operating condition 1, when the jet fan is deflected inward by 0.25 m, which is the optimal distance, the velocity contour plot shows minimal change in the velocity across the fan axis. This indicates that the transverse offset has a relatively small effect on the jet performance at this offset, thereby validating this offset as a reasonable choice for fan placement.

Furthermore, when the traditional jet fan was replaced with the banana-type jet fan, it was observed that the jet effect initially increased and then decreased with the increase in the fan's horizontal deflection angle. This trend is attributed to the fact that when the fan is deflected towards the inner side, the high-speed jet avoids direct impact with the outer tunnel wall, effectively reducing the wall shear stress and thereby enhancing the pressure rise effect of the jet fan. This optimized fan configuration strategy not only improves ventilation efficiency but also helps to mitigate the adverse airflow effects that may arise due to the curved shape of the tunnel.

In spiral tunnels, careful design of the fan layout and adjustment of its parameters can effectively modify the longitudinal impact range of the fans, which is crucial for alleviating the ventilation challenges posed by the curved shape. The outcomes of this research offer substantial insights for the design of tunnel ventilation systems, with particular emphasis on the deployment of banana-type jet fans as a means to enhance the efficiency of ventilation. This research highlights the importance of adjusting the horizontal deflection angle of the fans to achieve the best ventilation effects.

Figure 7 provides a detailed depiction of the development of the jet flow within the tunnel under various operating conditions. Through comparative analysis, it can be observed that operating condition 1 and operating condition 2 exhibit a high degree of consistency in the development of the jet flow from 10 m to 90 m downstream of the fan. This phenomenon is in agreement with the results of the velocity contour plots shown in Figure 6, further substantiating the conclusion that the transverse offset has a minimal impact on the jet effect.

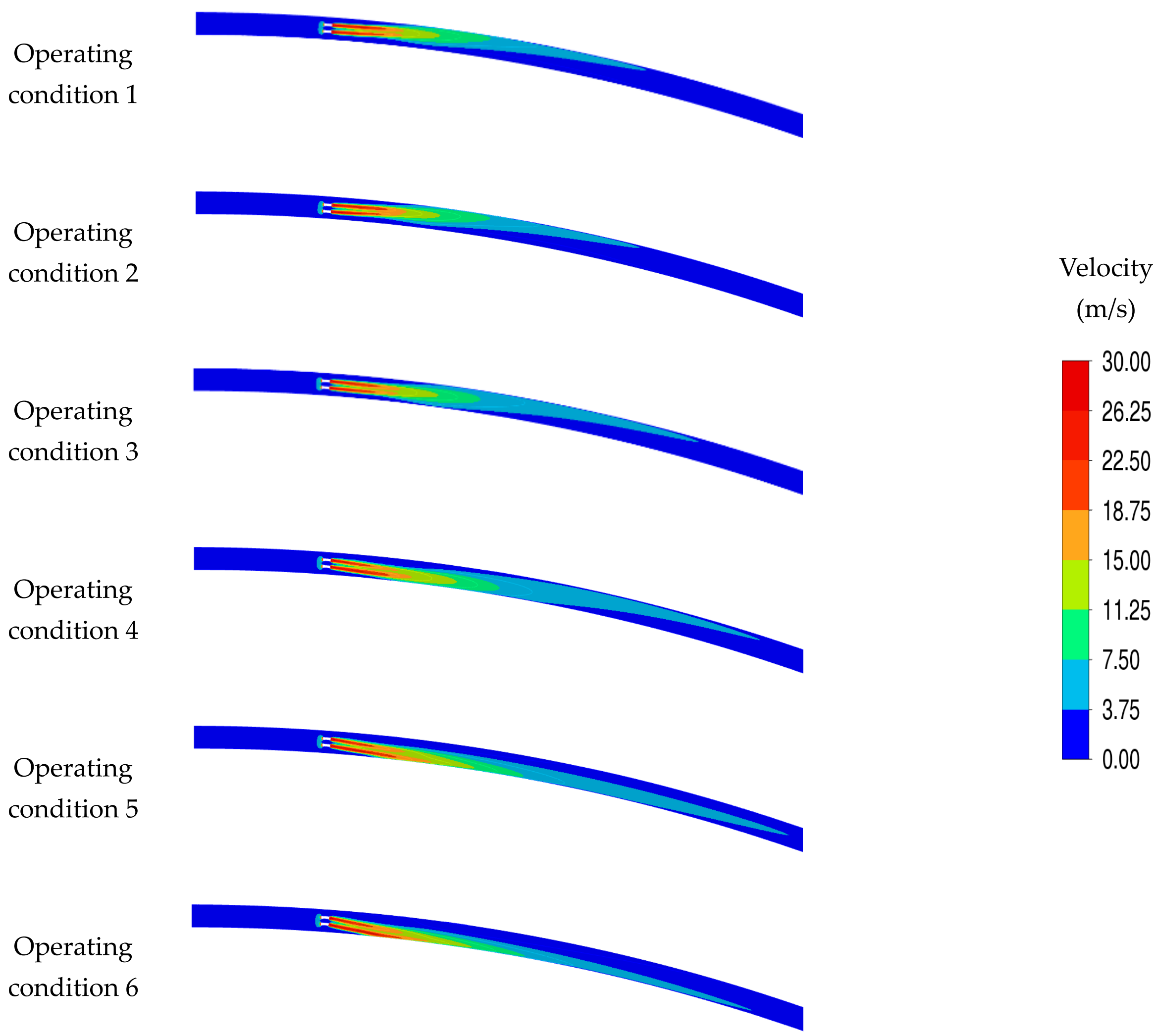


Figure 6. Contour of velocity variation along the axis profile of the fan under different operating conditions.

As the horizontal deflection angle of the alternative jet fan increases, there is a significant change in the direction and distribution of the jet flow. Specifically, the high-speed jet within the tunnel gradually shifts from the outer side to the inner side of the tunnel, with this trend being particularly evident at smaller deflection angles. This adjustment in the jet direction helps to optimize the airflow distribution within the tunnel, thereby enhancing the ventilation efficiency.

However, when the horizontal deflection angle continues to increase beyond a certain point, the jet effect begins to decline. This may be due to excessive deflection causing increased interaction between the jet and the tunnel walls, which in turn leads to greater energy loss and reduced penetration and coverage capabilities of the jet. Consequently, the ventilation effect of the jet flow within the tunnel exhibits a pattern of initial increase followed by a decrease, revealing the dual impact of the horizontal deflection angle on jet performance.

In summary, the results presented in Figure 7 emphasize the importance of considering various parameters, such as the positioning and deflection angles of the fans, when designing and optimizing tunnel ventilation systems to achieve optimal ventilation effects. By precisely controlling the horizontal deflection angle of the alternative jet fans, it is possible to optimize the airflow distribution within the tunnel to a certain extent, enhance the efficiency of jet utilization, and thereby mitigate the challenges associated with ventilating curved tunnels.

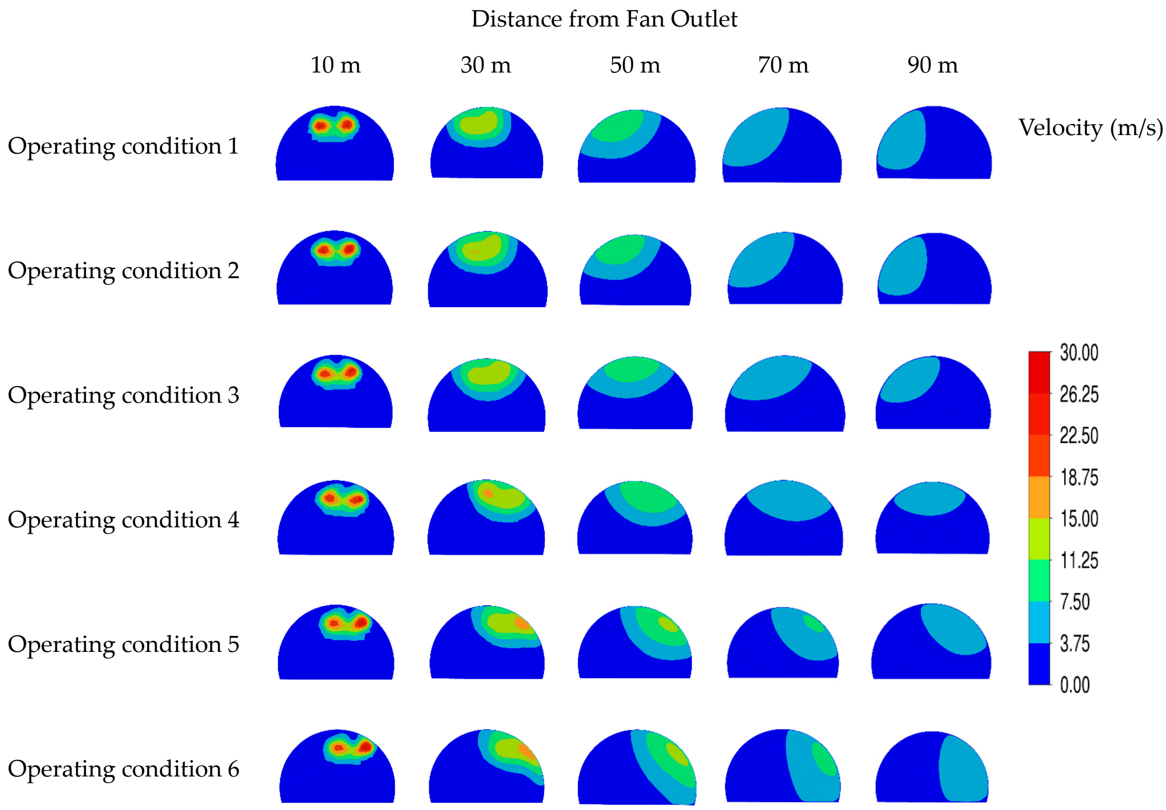


Figure 7. Development of tunnel jets under different operating conditions of wind turbines.

Figure 8 delineates the fluctuations in the average static pressure across the tunnel's cross-sectional area under varying operational parameters, offering a comprehensive understanding of the aerodynamic response of the airflow throughout the ventilation process facilitated by the jet fan. Within the sphere of the jet fan's influence, the airflow inside the tunnel experiences a pivotal phase of induced ventilation. In this phase, a diminishing trend in static pressure is observed as the airflow approaches the vicinity of the jet fan. This decrease is attributed to the induction effect of the jet fan, which accelerates the airflow, increases its kinetic energy, and consequently results in a relative reduction in pressure energy.

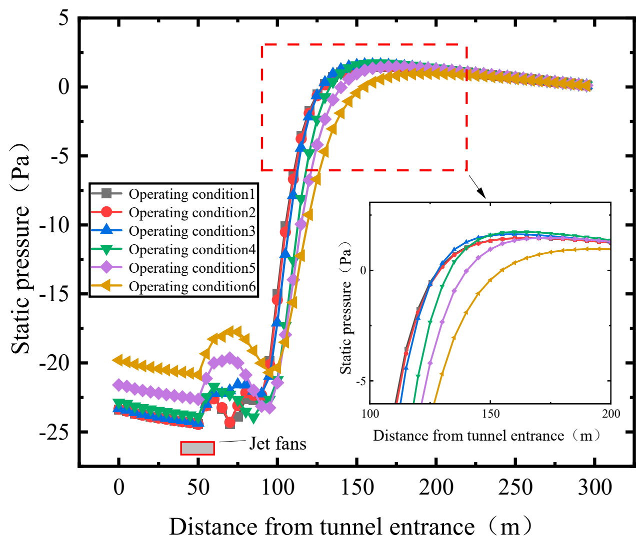


Figure 8. The average static pressure of the tunnel section along the tunnel under different operating conditions.

Upon the airflow's transit past the jet fan, the kinetic energy of the jet engages in a momentum transfer with the ambient airflow within the tunnel, a dynamic that results in a progressive augmentation of the static pressure within the tunnel confines. At the end of the induction ventilation section, the static pressure reaches its peak, indicating that the jet has been significantly enhanced within this zone. Notably, the average static pressure curves for operating condition 1 and operating condition 2 almost completely overlap, which is consistent with the observations from Figures 6 and 7. This confirms that merely altering the transverse offset of traditional jet fans has a limited effect on enhancing the pressure rise efficiency. In both of these operating conditions, the static pressure reaches its maximum value at 115 m downstream of the fan outlet, being 1.46 Pa and 1.43 Pa, respectively.

Furthermore, operating condition 3 and operating condition 4 reach their maximum static pressures at 110 m downstream of the fan outlet, namely 1.64 Pa and 1.74 Pa, respectively. Operating condition 5 shows that the static pressure reaches its maximum value of 0.97 Pa at 140 m downstream of the fan outlet. Under operating condition 6, where the horizontal deflection angle is set to the maximum (8°), the performance of the fan is not optimal. This phenomenon can be primarily attributed to several key factors: firstly, a larger deflection angle causes the high-speed jet to collide more readily with the tunnel walls, which not only reduces the effective range of the jet but can also lead to energy loss and decreased ventilation efficiency; secondly, an excessive deflection angle may cause the jet to be directed towards one side of the tunnel, resulting in uneven airflow distribution, which can create local low-pressure areas within the tunnel and affect the overall ventilation performance; finally, collisions with the tunnel walls lead to significant momentum loss of the jet, reducing its induction capacity in relation to the surrounding air and thus decreasing the air circulation efficiency within the tunnel. Therefore, while appropriate adjustment of the jet fan's deflection angle can optimize ventilation, an overly large deflection angle may have the opposite effect. The results of this study emphasize the need to carefully consider the deflection angle when designing jet fans to achieve optimal ventilation performance.

In summary, the results depicted in Figure 8 underscore the significance of alternative jet fans in the ventilation design of curved tunnels. By precisely controlling the horizontal deflection angle of the fans, it is not only possible to optimize the airflow distribution within the tunnel but also to significantly enhance the longitudinal impact range of the jet. This effectively addresses the challenges associated with ventilating curved tunnels.

4. Conclusions

The present study leveraged CFD numerical simulation technology to conduct a comprehensive analysis of the operational ventilation patterns of alternative jet fans within curved tunnels. Through meticulous investigation and comparison with existing technologies and previous research, the following conclusions have been drawn:

(1) Optimization of Fan Installation: The study revealed that the traditional method of adjusting the horizontal offset of jet fans results in limited improvements in pressure rise efficiency. In contrast, alternative jet fans, which allow for the adjustment of the horizontal deflection angle, showed significant potential in optimizing the flow field distribution and enhancing the jet effect. This finding underscores the importance of exploring new fan arrangement strategies for efficient ventilation in curved tunnels.

(2) Impact of Horizontal Deflection Angle: A key discovery was that the jet effect increases initially and then decreases with an increase in the horizontal deflection angle of the alternative jet fans. This finding indicates the existence of an optimal deflection angle for maximizing fan performance, which can be crucial for mitigating the adverse impact of curved tunnel shapes on ventilation.

(3) Practical Implications: The results of this study provide innovative ideas and practical solutions for the design and optimization of tunnel ventilation systems. By adjusting the horizontal deflection angle of alternative jet fans, it is possible to effectively extend the longitudinal impact range of the fans, thereby addressing the challenges associated with ventilating curved tunnels.

(4) Recommendations for Future Research: While this study has made significant strides in understanding the impact of alternative jet fans in curved tunnels, further research is recommended to validate these findings through experimental or field studies. Additionally, exploring the long-term performance and durability of these alternative jet fans under real-world operating conditions could be beneficial.

In summary, this study has demonstrated that with the proper configuration, alternative jet fans can substantially improve the ventilation efficiency in curved tunnels. The findings not only enrich the theoretical foundation of tunnel ventilation design but also offer feasible guidance for practical engineering applications, contributing to enhancing the performance of tunnel ventilation systems and ensuring a safer, healthier, and more comfortable environment within tunnels.

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