Comparative Study on the Efficiency of Ventilation Joints in Gas-Rich Shield Tunnels

Hailong Li, Qinghua Xiao *, Xiaofeng Xu

Sinohydro Engineering Bureau 3 Co.,Ltd. Xi'an, China

*xqhbp@swjtu.edu.cn

Abstract. In the construction of gas-rich tunnels, the design and performance of the ventilation system are critical to ensuring construction safety and operational efficiency. This study utilizes numerical simulation and comprehensive analysis to evaluate and compare the performance of straight joints and Y-joints, focusing on six key aspects: ventilation efficiency, system reliability, maintenance convenience, airflow stability, emergency response capability, and energy efficiency. Simulation results indicate that under specific conditions, Y-joints offer higher ventilation efficiency and better airflow capacity, making them suitable for scenarios requiring enhanced ventilation. However, straight joints exhibit advantages in terms of structural simplicity, ease of installation and maintenance, more stable airflow patterns, faster emergency switching, and lower energy consumption. The findings provide a scientific basis for selecting appropriate ventilation joint types in practical tunnel construction, supporting the optimization of ventilation system design and improving overall safety and cost-effectiveness.

Keywords: gas-rich shield tunnel; ventilation system; joint efficiency; numerical simulation; system reliability

1 Introduction

Gas is a common underground hazard that can accumulate during tunnel construction, potentially leading to serious safety incidents such as explosions and fires. Especially in shield tunneling through gas-rich formations, gas leakage and accumulation pose significant threats to both personnel safety and equipment integrity. Therefore, the safety of gas-rich tunnel construction has always been a focal point in engineering research and practical operations, attracting widespread attention in the fields of geotechnical engineering, construction safety, and disaster prevention and control [1–3]. Among the various safety measures, the ventilation system serves as a critical line of defense. It not only controls and dilutes harmful gas concentrations but also ensures the supply of fresh air to the working face, effectively reducing the risk of gas ignition or explosion, thereby playing a vital role in maintaining a safe and healthy underground working environment [4–5].

In practical engineering, the complexity of gas-rich tunnel environments presents significant challenges for ventilation system design and operation. On the one hand,

G. Zhao et al. (eds.), *Proceedings of the 2025 8th International Conference on Traffic Transportation and Civil Architecture (ICTTCA 2025)*, Atlantis Highlights in Engineering 39,
https://doi.org/10.2991/978-94-6463-793-9_84

sufficient ventilation must be ensured to maintain safe gas levels under dynamic excavation conditions; on the other hand, the system must also be energy-efficient, reliable, and easy to maintain. As a result, the design of tunnel ventilation systems must strike a comprehensive balance among ventilation efficiency, system stability, operational safety, energy consumption, and emergency responsiveness [6–7].

Ventilation joints, as indispensable transitional components that connect primary ventilation equipment (such as axial flow fans) with the tunnel ductwork, directly influence the performance and reliability of the entire ventilation system [8–9]. Among them, straight joints and Y-joints are the most commonly used connection structures. Straight joints offer simplicity and direct airflow paths, while Y-joints are often used to enable ventilation system branching or multi-point ventilation. Each type has distinct characteristics in terms of airflow organization, pressure loss, structural layout, maintenance convenience, and adaptability to construction changes. However, in current engineering practice, the selection of ventilation joint types is often based on empirical judgment or installation convenience, lacking systematic comparison and scientific basis under actual gas-rich tunneling conditions.

This study aims to investigate the performance differences between straight joints and Y-joints in gas-rich shield tunnel ventilation systems through numerical simulations and comprehensive analysis. The evaluation metrics include ventilation efficiency under varying airflow velocities, pressure loss characteristics, system stability, airflow distribution uniformity, ease of maintenance, emergency response capability, and overall energy consumption. By quantitatively analyzing the pros and cons of different joint types under representative working conditions, this research seeks to provide scientific and engineering guidance for optimizing tunnel ventilation system design. The findings are expected to contribute to enhancing construction safety, reducing operational risks, and improving the energy efficiency and cost-effectiveness of shield tunnel ventilation systems.

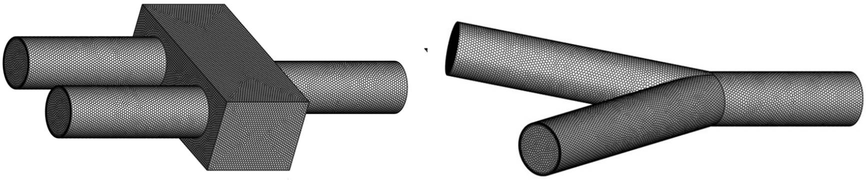
2 Project Overview

The Jiulong Reservoir Project is located in the Eastern New District of Chengdu and is included in both the 13th and 14th Five-Year Plans for national water conservancy development and safety assurance, as shown in Figure 1. The water-filling tunnel of the project adopts shield tunneling, with a total length of 7,330 m (from chainage 0+920.00 to 8+250.00). A circular, unpressurized tunnel with a 5.18 m excavation diameter is used, and construction is carried out via earth pressure balance shield tunneling, as shown in Figure 1. The total length of Class IV surrounding rock is 4,726.0 m (64.5%), and Class V surrounding rock (including overburden) totals 2,604.0 m (35.5%). The geological formation is mainly composed of silty mudstone interbedded with sandstone, siltstone, and clay, predominantly soft rock, with saturated uniaxial compressive strengths ranging from 7.6 to 43.8 MPa. The maximum gas emission far exceeds 0.5 m^3/min, classifying it as a high-gas, high-risk tunnel section.

Fig. 1. Construction Site

3 Numerical Model

To ensure the accuracy and reliability of the simulation results, a precise mathematical model was developed. The model incorporates fluid dynamics, heat transfer, and turbulence effects, and it replicates the physical geometry of the ventilation ducts and joints. Reasonable boundary conditions were set to simulate real working environments. A schematic of the ventilation joint model is shown in Figure 2.



(a) (b)

Fig. 2. The numerical model of different joints

Finite Element Method (FEM) and Finite Volume Method (FVM) were adopted in this study due to their robust capabilities in handling complex geometries, irregular boundaries, and varied boundary conditions, all while maintaining high computational accuracy and stability. These numerical methods are well-suited for modeling airflow behavior in shield tunnel environments with intricate ventilation layouts.

Mesh generation is a critical step in numerical simulation, as it directly impacts the accuracy, stability, and efficiency of the computation. In this study, a carefully designed meshing strategy was employed to ensure the reliability of simulation results, as shown in Figure 4. Particular emphasis was placed on key regions such as the ventilation joints, where complex flow patterns, turbulence, and pressure gradients are prominent. These areas were subjected to detailed local mesh refinement to accurately capture flow details and ensure the fidelity of the simulation. At the same time, to avoid numerical errors caused by abrupt changes in mesh size or uneven mesh distribution, a uniformly distributed mesh was applied throughout the overall computational domain. This approach not only enhances local resolution where needed but also maintains global stability and consistency across the simulation. The mesh design adhered to the principles of refinement in high-gradient regions and uniformity across the domain. This balanced strategy effectively improves the overall simulation quality, providing a solid foundation for the subsequent analysis of airflow behavior and ventilation performance. The specific mesh layout and refinement details are shown in Figure 2.

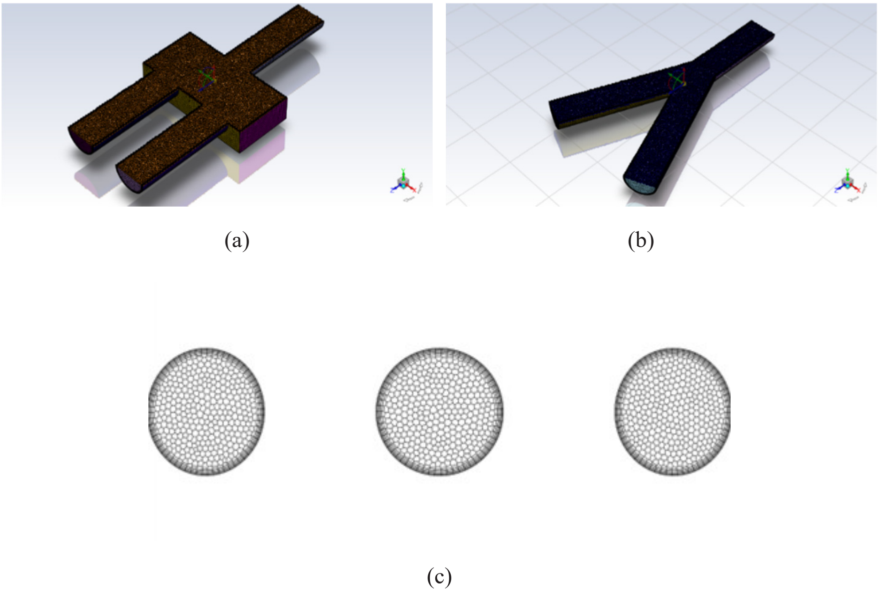
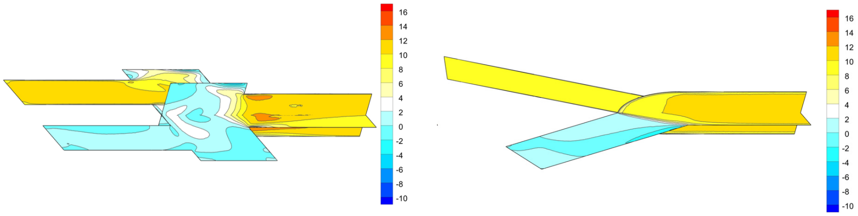


Fig. 3. Mesh Generation Schematic Diagram

The simulation scenarios were designed to reflect practical ventilation configurations, including both single-duct and dual-duct inlet arrangements. Inlet airflow velocities were set at 10 m/s, 15 m/s, and 20 m/s, representing common ventilation conditions in shield tunnel construction. The outlet airflow characteristics were then analyzed to evaluate the ventilation efficiency, pressure loss, and airflow distribution consistency of both straight and Y-joints under varying operational parameters. These analyses provide a quantitative basis for joint performance comparison and engineering decision-making.

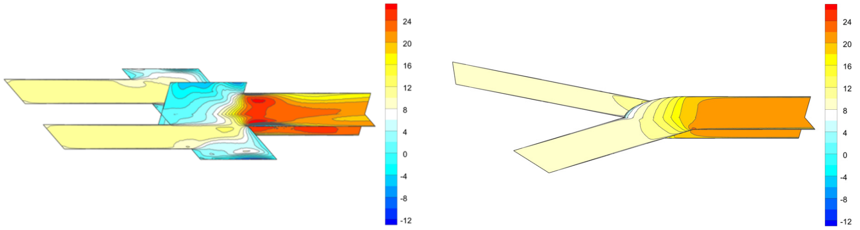
4 Results Analysis

Ventilation performance was evaluated by measuring outlet velocities. Figures 3 and 4 show the results for single and dual duct simulations, respectively. Table 1 summarizes the numerical results.



(a) (b)

Fig. 4. Analysis of Single-Duct Ventilation Simulation Results



(a) (b)

Fig. 5. Analysis of Double-Duct Ventilation Simulation Results

Table 1. Numerical Ventilation Results for Different Joint Types

Duct Configuration	Inlet Velocity (m/s)	Straight Joint Outlet (m/s)	Y-Joint Outlet (m/s)
Single	10	9.54	9.72
	15	13.95	14.25
	20	18.24	18.90
Double	10	19.10	19.25
	15	28.32	29.10
	20	37.51	38.86

The simulation results clearly indicate that Y-joints consistently exhibit higher outlet air velocities compared to straight joints across all tested inlet velocity conditions, including both single-duct and dual-duct configurations. This consistent performance advantage suggests that Y-joints possess superior ventilation efficiency, making them particularly suitable for scenarios where maximizing airflow is critical to maintaining safe gas concentrations and promoting effective air exchange. Notably, the performance disparity between the two joint types becomes increasingly pronounced as the inlet velocity rises, highlighting the growing influence of flow dynamics and momentum distribution at higher energy levels. For instance, under a 20 m/s inlet condition in a dual-duct configuration, the difference in outlet velocity reached up to 1.35 m/s, underscoring the Y-joint's enhanced flow capacity and its ability to reduce turbulence-induced energy loss.

However, it is important to place these findings within the broader context of tunnel ventilation system performance. While Y-joints demonstrate a measurable advantage in airflow output, the associated ventilation losses due to joint selection remain relatively minor in the context of the entire system. The localized differences in outlet velocity, although notable, do not significantly compromise the overall effectiveness, safety, or reliability of tunnel ventilation. Therefore, while Y-joints may offer technical benefits, their selection must be weighed against other critical engineering considerations, including structural complexity, installation and maintenance requirements, system adaptability during construction phases, emergency ventilation switching, and long-term energy consumption. A comprehensive evaluation framework must integrate both performance metrics and practical constraints to support informed engineering decision-making.

5 Conclusions

In gas-rich shield tunnel construction, dual-fan parallel systems (with one fan on standby) are commonly adopted to ensure ventilation reliability and operational safety. The selection between straight joints and Y-joints plays a vital role in overall system performance. Straight joints provide key advantages, particularly in emergency scenarios. Their ability to centralize airflow from multiple fans allows for rapid gas displacement, effectively reducing explosion risks. Structurally simpler, they are easier to maintain and less prone to failure—essential traits in hazardous environments. Additionally, straight joints maintain unidirectional airflow, improving gas flow stability and facilitating better monitoring and control of tunnel atmospheres.

From a system perspective, straight joints enhance emergency response by supporting quick activation of all available fans. This rapid deployment capability ensures strong ventilation when faced with sudden gas surges. Furthermore, in dual-fan systems, straight joints enable seamless switching between airflow paths, boosting overall system redundancy without compromising performance. Energy efficiency is another advantage, as straight joints reduce transmission losses and ensure more concentrated airflow delivery compared to the more dispersed patterns of Y-joints. Taken together, these features make straight joints a highly effective and reliable choice for ventilation system design in gas-rich shield tunnel construction.

References

1. Yan Q, Yang K, Wu W, et al. Prevention and control of gas hazards in a tunnel under construction: a case study[J]. Environmental Earth Sciences, 2020, 79: 1-17.

2. Zhang P, Lan H, Yu M. Reliability evaluation for ventilation system of gas tunnel based on Bayesian network[J]. Tunnelling and Underground Space Technology, 2021, 112: 103882.
3. Kang X B, Xu M, Luo S, et al. Study on formation mechanism of gas tunnel in non-coal strata[J]. Natural hazards, 2013, 66: 291-301.
4. Fang Y, Fan J, Kenneally B, et al. Air flow behavior and gas dispersion in the recirculation ventilation system of a twin-tunnel construction[J]. Tunnelling and underground space technology, 2016, 58: 30-39.
5. Zhang P, Lan H Q. Experimental study on dynamic exhaust law for ventilation system of gas tunnel[J]. Applied Sciences, 2023, 13(23): 12783.
6. Lu H, Huang K, Fu L, et al. Study on leakage and ventilation scheme of gas pipeline in tunnel[J]. Journal of Natural Gas Science and Engineering, 2018, 53: 347-358.
7. Colella F, Rein G, Borchiellini R, et al. Calculation and design of tunnel ventilation systems using a two-scale modelling approach[J]. Building and environment, 2009, 44(12): 2357-2367.
8. Suo L, Li S, Wu F. Influence of Ventilation Parameters on Gas Transportation Patterns in Long Highway Tunnels and Sustainable Development of Ventilation Systems[J]. Sustainability, 2025, 17(3): 1020.
9. Sánchez M N, Giancola E, Blanco E, et al. Experimental validation of a numerical model of a ventilated façade with horizontal and vertical open joints[J]. Energies, 2019, 13(1): 146.