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Experimental Study on Smoke Exhaust Characteristics during Emergency Stopping of a Burning Train in Subway Tunnels

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ABSTRACT: As urban subway systems have become the backbone of public transportation, fire safety in subway tunnels has attracted increasing attention. The piston wind generated by moving trains complicates smoke propagation and poses significant challenges to conventional smoke control strategies. This study combines scaled experiments and theoretical analysis to investigate the effects of mechanical ventilation systems on smoke propagation and smoke exhaust performance during the emergency stopping of a burning train in subway tunnels. The influences of fire source location and train speed on the performance of vertical shaft ventilation (VSV) and local semi-transverse ventilation (LSTV) are systematically evaluated. The results show that the optimal smoke exhaust performance is achieved when the train stops upstream of the ventilation shaft, with VSV reducing the peak downstream smoke temperature by approximately 70%. To address the limitations of VSV in ultra-long subway tunnels caused by shaft spacing and engineering constraints, a combined ventilation (CV) system integrating LSTV with longitudinal ventilation is proposed. The results demonstrate that the CV system establishes a stable airflow pattern within the tunnel and achieves nearly complete smoke removal within 98 s under different train operating speeds. Moreover, it reduces the dependence of smoke exhaust performance on the fire source location. The findings provide theoretical support and engineering guidance for the design and optimization of mechanical smoke exhaust systems in subway tunnels.

KEYWORDS: Subway tunnel; scaled-down experiments; piston wind; mechanical ventilation; burning train; smoke exhaust

1 Introduction

As global urbanization accelerates, metro systems have become critical transportation infrastructure, serving as an efficient, high-capacity public transit solution to alleviate surface traffic congestion. By the end of 2025, metro systems had been operational in over 200 cities worldwide, with China's subway network exceeding 10,000 km of operating mileage (representing approximately 40% of the global total) [1]. Fire safety is a critical aspect of tunnel disaster prevention. Due to the enclosed environment and the narrow, long space of tunnels, heat and smoke accumulate rapidly during a fire, making evacuation and rescue much more difficult compared to above-ground buildings [2]. Moreover, the ventilation conditions are poor. In the event of a fire, the smoke rapidly spreads along the longitudinal direction of the tunnel. Without effective ventilation, fire-induced smoke rapidly fills the tunnel space, causing a sharp decrease

in visibility. Consequently, the accumulation of high-temperature and toxic smoke severely degrades the thermal environment within the tunnel [3,4].

Tunnel fires can be mainly classified into stationary fire sources and mobile scenarios. Compared with stationary fires [5], mobile fires are more complex. Due to the significant obstruction caused by trains, a strong piston effect is more likely to occur [6–9], resulting in complex and highly variable smoke dispersion patterns. Chen et al. [10,11] experimentally compared the flame morphology, heating characteristics, and plume development of stationary and moving fires. Their results show that the deformation rate of moving fires is 15%–46% higher than that of stationary fires, indicating that wind tunnel tests have limitations in studying moving fires. The piston effect makes the smoke extraction process in dynamic fire scenarios more complex. Thus, the depth and refinement of related research still need to be further improved.

The harsh fire environment severely disrupts tunnel aerodynamic stability, significantly complicating smoke control operations. The most effective way to mitigate fire hazards is to design an appropriate smoke exhaust system to effectively control smoke propagation and mitigate heat accumulation within the tunnel. At present, the main mechanical ventilation methods include longitudinal ventilation, transverse ventilation, semi-transverse ventilation, and shaft ventilation. Different exhaust configurations can significantly alter the propagation paths and residence characteristics of smoke [12–16]. Shaft design plays a critical role in smoke control, and the combination of optimally arranged shafts with mechanical ventilation can significantly enhance smoke dispersion and exhaust efficiency [17–19]. After conducting a study on four smoke exhaust methods, Dong et al. [20] found that top smoke exhaust is the most effective, as it can slow down smoke spread within the tunnel. Sun et al. [21] investigated smoke dispersion and its interaction with internal tunnel structures using the $k-\epsilon$ turbulence model. As train speeds and tunnel lengths continue to increase, smoke exhaust strategies are becoming increasingly complex, and traditional methods may no longer meet current demands. There is a lack of in-depth research on the coupling between different ventilation modes and the piston effect, which is essential to address the rapid development of metro systems.

With the rapid development of computational fluid dynamics technology, numerical simulation, by leveraging the governing equations of fluid flow, has effectively addressed research problems under multi-parameter conditions to a certain extent. Through numerical simulations, Zhang et al. [22] and Wu et al. [23] demonstrated that both ambient wind speed and main tunnel airflow velocity have significant effects on shaft smoke exhaust behavior. Liu et al. [24] conducted numerical simulations and carried out comparative analyses to examine the influence of various factors on the spread of fire smoke under different ventilation methods. Yang et al. [25,26] used numerical simulation to study the effect of tunnel slope on the smoke exhaust performance of subway tunnels. Although numerical simulation methods have been widely applied in the study of smoke exhaust and ventilation in subway fires, due to the complex boundary conditions and uncertain factors present in actual engineering, the numerical calculation results often show significant differences from the actual conditions. Moreover, numerical simulations cannot fully replace experimental studies, as experimental data are essential for validation, making experimental research indispensable. Zhou et al. [27] employed numerical simulation and experimental research methods to conduct a systematic study on the fire dynamics characteristics of a semi-transverse ventilation rescue station. Liang et al. [28] and Qiu et al. [29] experimentally investigated smoke propagation and longitudinal temperature distribution under natural ventilation and varying tunnel slopes. Zhao et al. [30] and Liu et al. [31] quantified the effects of exhaust layout and flow rates on ventilation efficiency through scaled experiments. However, due to the combined effects of the tunnel's narrow and elongated characteristics, train operating conditions, and fire hazards, experimental studies on fires involving moving trains in tunnels remain relatively limited.

Therefore, conducting more in-depth experiments on smoke control for tunnel fires involving moving train fires in tunnels is highly necessary.

This paper systematically investigates the smoke dispersion characteristics during train emergency stopping in subway tunnel fire conditions. Through scaled-down experimental investigations, the effects of various mechanical ventilation modes on smoke dispersion and exhaust efficiency are systematically examined. The influence of various factors on the smoke exhaust performance of vertical shaft ventilation (VSV) and local semi-transverse ventilation (LSTV) is compared and analyzed. To overcome the limitations of these standalone systems, a novel combined ventilation (CV) strategy is proposed, which integrates LSTV with longitudinal ventilation. This study establishes a theoretical framework for moving fire prevention and control systems in subway tunnels. The findings provide significant guidance for optimizing mechanical smoke extraction and developing scientific emergency ventilation protocols in tunnel fire conditions.

2 Experimental Settings

2.1 Design Principles of the Scaled-Down Experimental Platform

Scale modeling represents a principal methodology for investigating smoke extraction dynamics in metro tunnel fire conditions. Based on the similarity theory [32], this study constructs a scaled tunnel model test platform. The premise of the similarity theory is geometric similarity. Based on geometric similarity, the similarity ratio between the prototype (denoted by p) and the model (denoted by m) is expressed as follows:

The corresponding linear length ratio can be expressed as:

$$\lambda_L = \frac{L_m}{L_p} \quad (1)$$

The ratio of the areas of the corresponding faces can be expressed as:

$$\lambda_A = \frac{A_m}{A_p} = \frac{L_m^2}{L_p^2} = \lambda_L^2 \quad (2)$$

The ratio of volumes can be expressed as:

$$\lambda_V = \frac{V_m}{V_p} = \frac{L_m^3}{L_p^3} = \lambda_L^3 \quad (3)$$

Based on geometric similarity, the motion similarity of the tunnel flow field follows the principle of Froude number similarity, which is expressed as follows:

$$Fr_m = \frac{V_m^2}{gL_m} = Fr_p = \frac{V_p^2}{gL_p} \quad (4)$$

According to the Froude number similarity principle, the similarity between the prototype (denoted by p) and the model (denoted by m) can be expressed as follows:

Speed ratio:

$$\lambda_\mu = \frac{v_m}{v_p} = \left(\frac{L_m}{L_p} \right)^{1/2} = \sqrt{\lambda_L} \quad (5)$$

Acceleration ratio:

$$\lambda_a = \frac{a_m}{a_p} = \frac{\lambda_V^2}{\lambda_L} = 1 \quad (6)$$

Mass flow rate ratio:

$$\lambda_M = \frac{M_m}{M_p} = \left(\frac{L_m}{L_p} \right)^{5/2} = \lambda_L^{5/2} \quad (7)$$

Ratio of fire source power:

$$\lambda_Q = \frac{Q_m}{Q_p} = \left(\frac{L_m}{L_p} \right)^{5/2} = \lambda_L^{5/2} \quad (8)$$

Temperature ratio:

$$\lambda_T = \frac{T_m}{T_p} \approx 1 \quad (9)$$

The HRR is determined as follows:

$$Q = \eta \cdot \dot{m} \cdot H_c \quad (10)$$

$$\dot{m} = \frac{\Delta W}{\Delta \tau} \quad (11)$$

where Q , η , $\dot{m}$, H_c , ΔW , $\Delta \tau$ represent the heat release rate, the combustion efficiency, the fuel mass loss rate, the heat of combustion of the fuel, the fuel mass consumed over a given time interval, and the time interval, respectively.

Calibration trials confirmed that each active burning compartment yields a nominal HRR of approximately 0.84 kW/compartment. This yields a quasi-steady model HRR of 10.08 kW. Applying the Froude power scaling ratio ($\lambda_Q = 1/1024$), this model fire corresponds to a full-scale prototype train fire of 10.3 MW, which complies closely with standard benchmark design fires for a single metro car specified in NFPA guidelines [33].

2.2 Description of the Experimental Platform

2.2.1 Reduced-Scale Tunnel Model

The experimental model is a 1:16 scale replica of the actual tunnel, including the standard section of the tunnel, the VSV section, LSTV section, and the train model. Fig. 1 shows the physical diagram. The tunnel is 40 m long, 0.3 m wide and 0.34 m high. According to the similarity theory, the corresponding full-scale tunnel would be 960 m long. The height of the VSV section is 1 m, and the cross-sectional dimensions are 0.24 m × 0.24 m. The LSTV section is arranged at the tunnel exit position. A partition is set on the top of the tunnel, and together with the partition, it forms an exhaust channel.

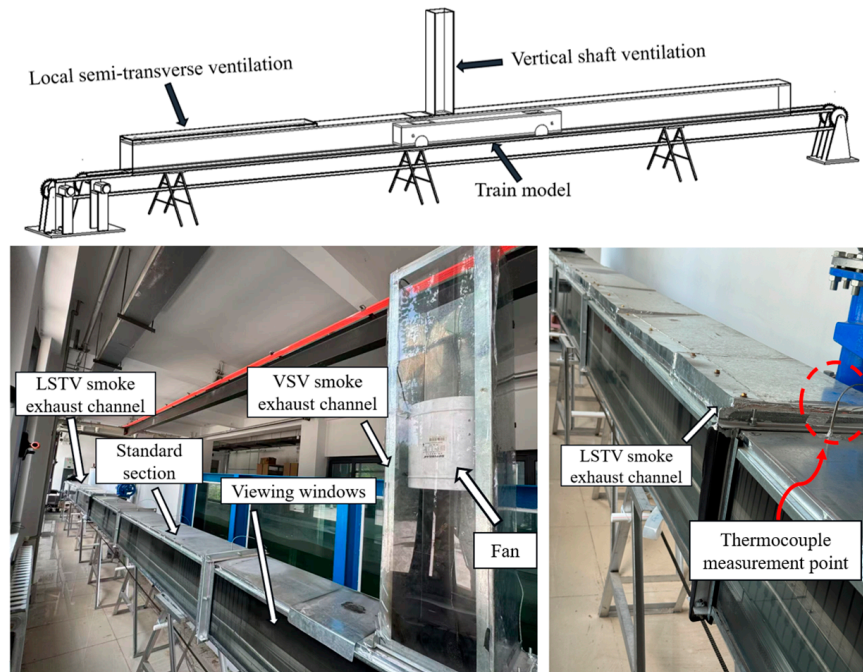


Figure 1: Physical diagram of the experimental platform.

A moving train model is arranged inside the tunnel experimental setup. The size of the train is $2\text{ m} \times 0.2\text{ m} \times 0.24\text{ m}$, as shown in the Fig. 2a. The blocking ratio of the train relative to the tunnel is approximately 0.47, which matches the realistic range commonly encountered in subway interval tunnels (typically 0.44–0.51). A 12-unit honeycomb combustion disc fueled by anhydrous ethanol is integrated into the rear of the train as the fire source. To facilitate smoke exhaust during fires, ventilators are installed in VSV and LSTV sections for mechanical smoke exhaust. As shown in Fig. 2b, the whole system realizes the integrated operation of precise power transmission and motion control through the coordinated work of various components. Through this control system, adjustments of train operating speeds can be achieved.

2.2.2 Test System and Equipment

The experimental acquisition system consists of the wind speed acquisition system and temperature acquisition system. In the wind speed acquisition system, a hot-wire anemometer (Fig. 3a) is employed to measure the wind speed inside the tunnel. It has a measurement range of 0.01–30 m/s, with an accuracy of $\pm 0.03\text{ m/s}$ or $\pm 4\%$. The temperature acquisition system uses Type K thermocouples with a diameter of 2 mm to measure the temperature variations beneath the tunnel ceiling. The thermocouples are installed at positions 1 cm above the tunnel roof. 18 measurement points are arranged along the roof centerline. The thermocouple has a measurement range of 0–1100°C, with an accuracy of $\pm 0.5^\circ\text{C}$. All thermocouples are connected to the data acquisition instrument (Fig. 3b), which displays the real-time temperature changes inside the tunnel. Anhydrous ethanol is used as the fire source (Due to laboratory facility constraints, this study has certain limitations in replicating absolute smoke concentration and visibility). The ethanol mass is precisely measured by an electronic balance (Fig. 3c) to ensure consistent combustion conditions across all experiments.

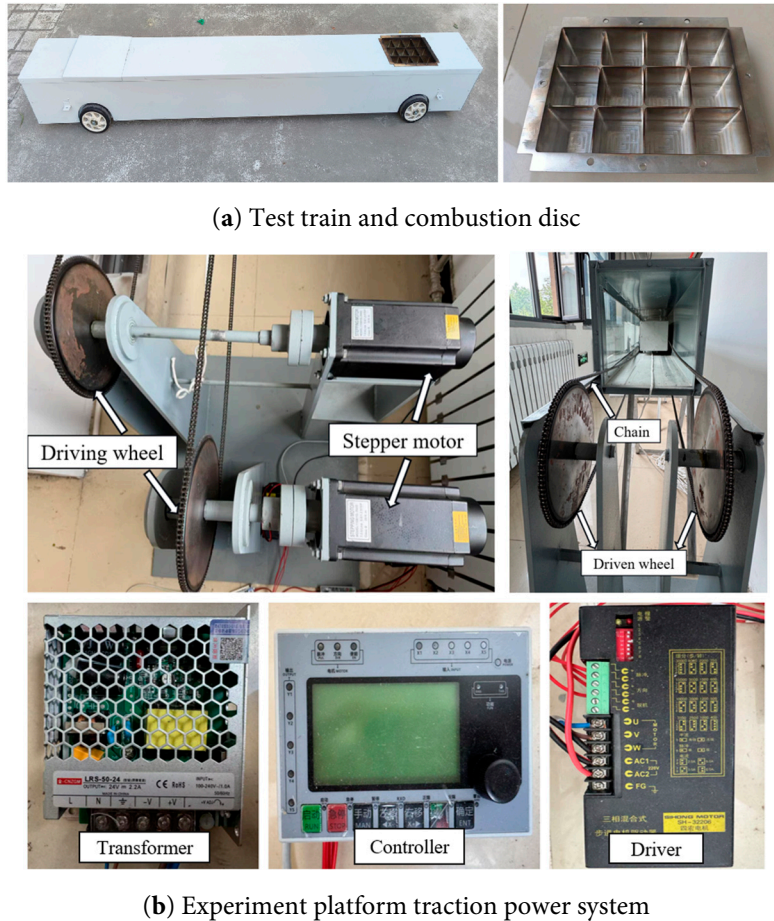


Figure 2: Schematic of the local motion system. (a) Test train and combustion disc; (b) Experiment platform traction power system.

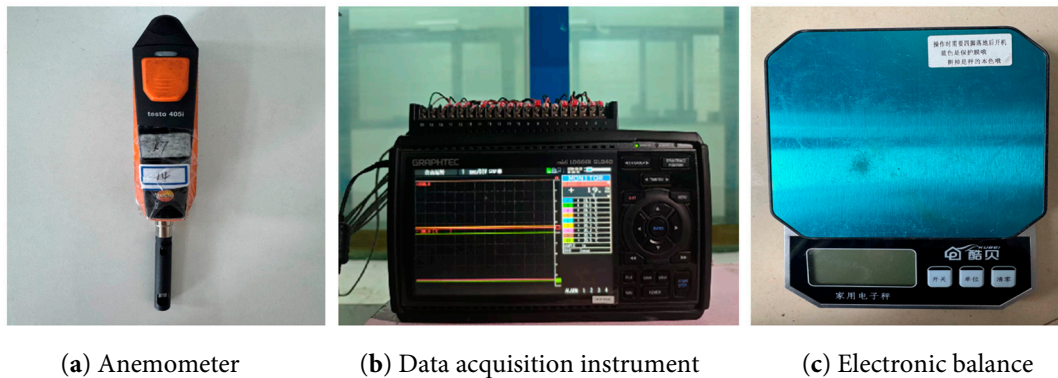


Figure 3: Experimental instrument diagram. (a) Anemometer; (b) Data acquisition instrument; (c) Electronic balance.

Temperature measurement points are arranged symmetrically at 1 m intervals centered on the fire source to comprehensively characterize the smoke temperature distribution, as shown in Fig. 4. The measurement points are designated as X, where X_0 represents the point directly above the fire source, X_1 to X_4 denote the upstream points in sequence, and X_{-1} to X_{-4} denote the downstream points (the personnel evacuation direction).

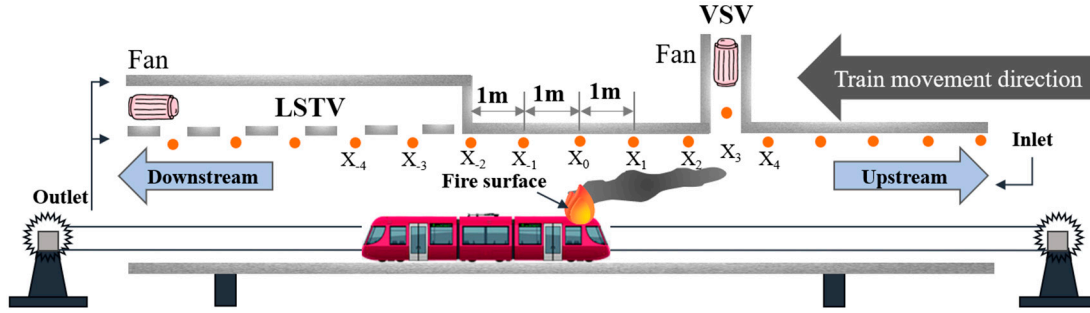


Figure 4: Schematic diagram of measurement points on the experimental platform.

2.3 Pre-Experiment and Experimental Conditions

Before the formal experiments, preliminary tests are conducted to verify the stability and reliability of the experimental system. Three independent repeated tests are performed under identical conditions, and the tunnel temperature field is simultaneously monitored to evaluate the repeatability of the experimental results. To quantitatively characterize the differences among the repeated tests, the Symmetric Mean Absolute Percentage Error (SMAPE) is introduced as an evaluation metric, as defined below:

$$SMAPE = \frac{1}{n} \times \sum_{i=1}^n \frac{|A_i - B_i|}{(|A_i| + |B_i|)/2} \times 100\% \quad (12)$$

where A_i and B_i denote the measured values of any two test runs at time step i , respectively.

Fig. 5 illustrates the temperature evolution at the upstream, fire center, and downstream locations across three independent repeated experiments ($n = 3$) under identical operating conditions is presented. Line types indicate continuous raw measurement data from individual tests, while discrete markers denote mean temperatures, with associated error bars illustrating the error margins. The temperature curves from independent tests converge consistently at all measurement locations. Based on Eq. (13), the average standard deviations for the upstream, fire center, and downstream locations throughout the entire testing period are 1.8°C , 4°C , and 2.2°C , respectively, with the maximum transient deviation remaining below 7°C across all measurement points. Furthermore, the maximum relative discrepancy among all repeated measurements is strictly bounded within 3%, satisfying the stringent acceptable error margins in tunnel fire experimental research. These results quantitatively confirm the stability and statistical reproducibility of the experimental system across all stages of heat source control and smoke propagation.

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}} \quad (13)$$

The experimental process is shown in Fig. 6. When the rear of the train caught fire and came to a slow stop, the piston wind caused the hot smoke to spread rapidly towards the front of the train, and the flames tilted significantly towards the front of the train. Then, as the piston wind weakened, the flame gradually assumed a vertical combustion state. When mechanical ventilation is activated, flames and hot smoke spread toward the rear of the train, keeping the front area smoke-free. At the same time, a blank control group is established with no mechanical ventilation to observe the free spread of smoke. The experimental conditions are summarized in Table 1.

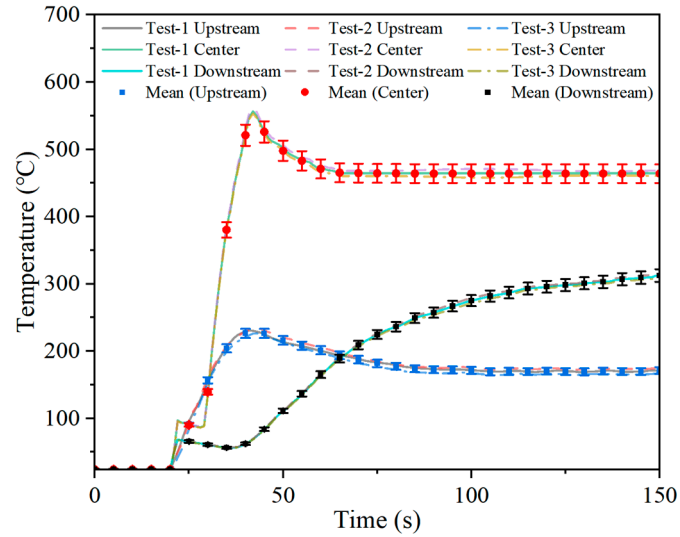


Figure 5: Statistical temperature profiles of the pre-experiments.

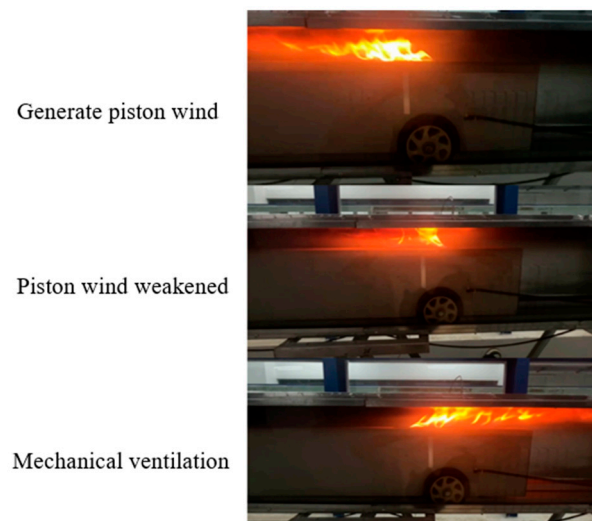


Figure 6: Experimental smoke spread diagram.

Table 1: A summary of the experimental conditions.

Ventilation Method	Train Speed (m/s)	Distance of the Fire Source
VSV (Supply air)	1.0	1, 2, 3 m upstream
VSV (Smoke exhaust)	1.0	1, 2, 3 m downstream
VSV (Supply air)	0.5, 1.0, 1.5	3 m upstream
LSTV (Smoke exhaust)	1.0	Beneath vents
LSTV (Supply air)	1.0	1, 2, 3 m upstream
LSTV (Supply air)	0.5, 1.0, 1.5	3 m upstream
CV (Supply air)	1.0	1, 2, 3 m upstream
CV (Supply air)	0.5, 1.0, 1.5	3 m upstream

Note: vertical shaft ventilation (VSV); combined ventilation (CV); LSTV (Local semi-transverse ventilation).

3 Results and Analysis

3.1 Vertical Shaft Ventilation (VSV) Characteristics

VSV is the most prevalent approach for tunnel ventilation and smoke extraction. Considering different train operating conditions, this study first investigates the smoke characteristics under the coupling effect of the piston effect induced by moving train and VSV smoke exhaust. The effects of varying fire source positions and train speeds relative to the shaft are examined. The relative position of the fire source and the shaft have a significant impact on the ventilation efficiency of the tunnel and the control effect of smoke. However, taking the case of a fire occurring at the rear of the train as an example, the smoke extraction performance of the shaft differs depending on whether the train is forced to stop upstream or downstream of the shaft. As shown in Fig. 7, two types of flue gas discharge conditions will be generated: negative pressure smoke exhaust by the fan and positive pressure air supply. The negative pressure smoke extraction mode creates a vertical negative pressure field through the fan, allowing the smoke to be rapidly discharged from the tunnel space through the vertical shaft structure, thereby reducing the smoke concentration gradient. This scenario applies to the case in which the train remains downstream of the VSV. The positive pressure air supply mode relies on vertical shafts to inject high-purity fresh air into the tunnel, driving smoke to move in a specific direction and controlling the spread of smoke. This positive pressure mode is applicable to conditions where the train is halted upstream of the VSV. Both modes of the smoke exhaust system can effectively prevent high-temperature smoke from spreading to the front of the train, thereby maintaining a lower temperature and smoke-free zone in the downstream area. The train speed is 1.0 m/s. Temperature measurement points are selected above the fire source, as well as upstream and downstream of the fire source for analysis.

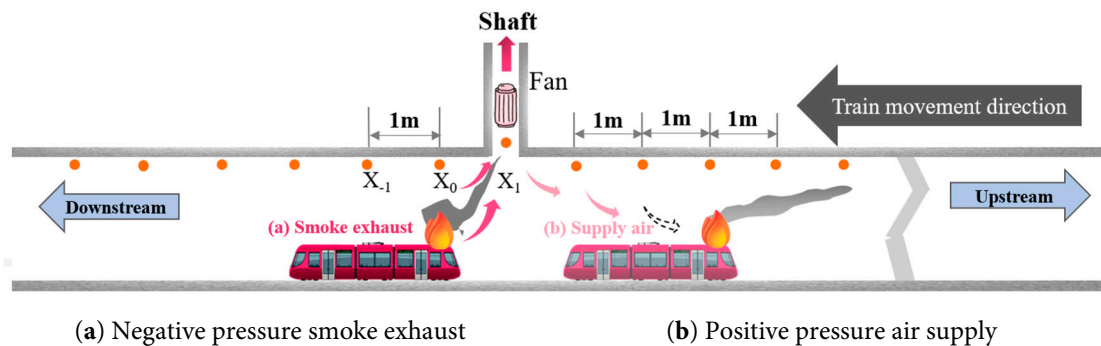


Figure 7: Train stops measurement point diagram under VSV. (a) Negative pressure smoke exhaust; (b) Positive pressure air supply.

3.1.1 The Influence of the Locations from the Fire Source

Since the train may be forced to stop at a random location during a fire incident, this study investigates the smoke exhaust characteristics when the train is parked at 1, 2, and 3 m upstream or downstream of the shaft, respectively. Fig. 8 presents the experimental process after the train stops and mechanical ventilation is activated. The flame inclination angle can serve as an important indicator for evaluating the effectiveness of mechanical ventilation. In the upstream region, the flame inclination angle is relatively larger, primarily because the fans supply air inward, allowing the ventilation airflow to act more directly, thereby producing a more pronounced ventilation effect. In contrast, in the downstream region, where the fans exhaust smoke outward, the influence of the airflow is weakened, resulting in a smaller flame inclination angle and a comparatively lower ventilation efficiency. Moreover, as the distance from the shaft increases, the

attenuation of airflow becomes more significant, leading to a gradual decline in the overall effectiveness of mechanical ventilation.

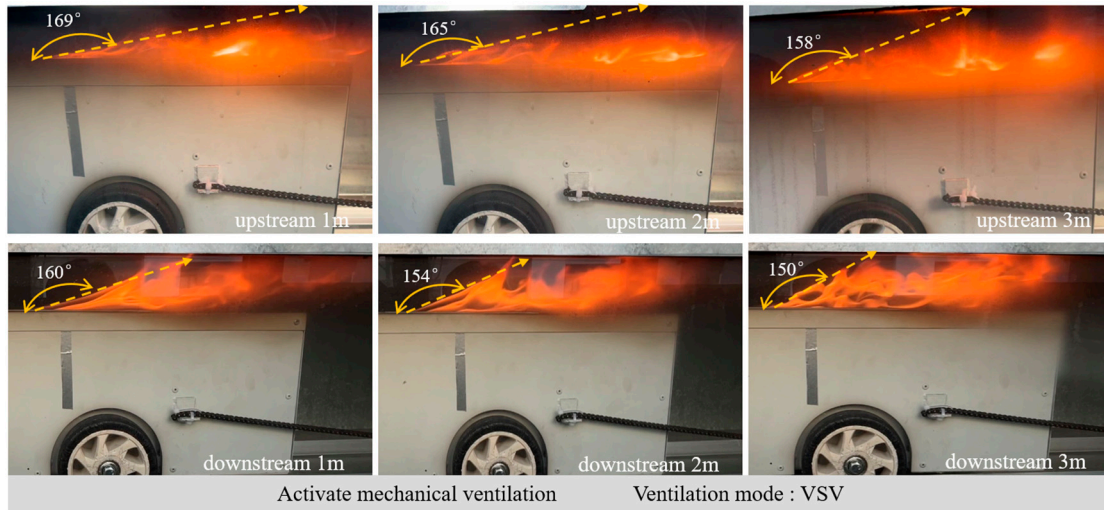


Figure 8: The experimental process at different fire source locations under VSV.

The temperature comparison results are shown in Fig. 9 where the train is forced to stop upstream and downstream of the VSV. The temperature above the fire source rises rapidly in both cases. In the downstream-stop case, as the distance between the train and the shaft increases from 1 m to 3 m, the peak smoke temperatures directly above the fire source are 404°C, 487°C, and 516°C, representing an approximate 30% reduction compared to natural ventilation (682°C). In the upstream-stop case, the corresponding maximum values are 236°C, 306°C, and 330°C, representing an approximate 60% reduction compared to natural ventilation. Compared to the downstream negative pressure exhaust, the upstream positive pressure supply reduces the smoke temperature directly above the fire source by an additional 40%. For downstream measurement points of the fire source, piston wind generated during operation drives smoke towards the downstream side. After the activation of negative pressure exhaust, the piston wind effect generated by the train gradually weakens, and most of the smoke is discharged through the shaft, with only a small portion spreading upstream. Under the condition where the train stops upstream of the shaft and positive pressure ventilation is applied, a small amount of smoke also backflows along the tunnel ceiling, with backflow durations at 1 m downstream of the fire source being 24 s, 27 s, and 30 s, respectively. Compared with downstream-stop, the smoke backflow times at 1 m downstream of the fire source (excluding the 1 m point from the shaft) are reduced by 14 s and 42 s when the train stops upstream of the shaft. These findings demonstrate that mechanical ventilation is more effective when the train is stopped upstream of the VSV. However, under both conditions, the effectiveness of ventilation decreases as the distance increases between the train and the shaft. When train operation is controllable, stopping the train upstream of the shaft is more favorable for smoke extraction and passenger evacuation.

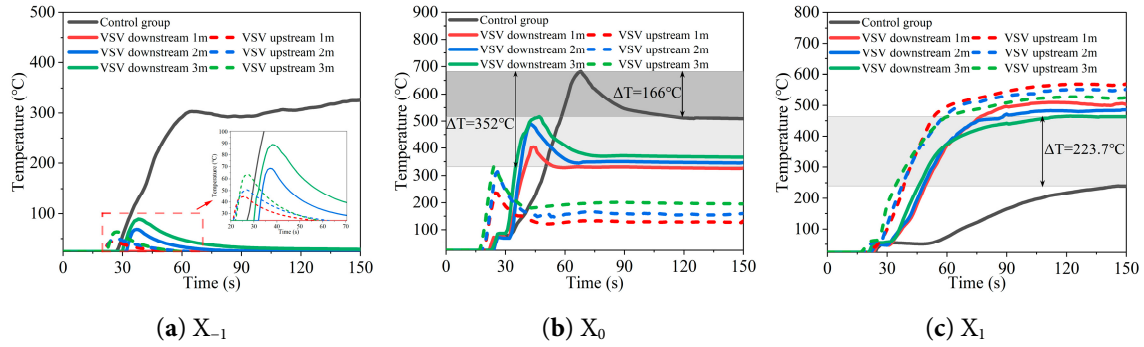


Figure 9: Temperature characteristics at different fire source locations under VSV. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

3.1.2 The Influence of Train Speeds

The varying speeds of the train will inevitably have a significant impact on the spread of smoke and the smoke exhaust through the shaft. Three train operating speeds (0.5, 1.0, and 1.5 m/s) are compared to analyze the smoke flow characteristics. When the train is stopped and mechanical ventilation is not activated, the flame characteristics are primarily governed by the piston wind, as shown in Fig. 10. With increasing train speed, the piston effect is gradually intensified, and the resulting airflow impingement causes the flame to exhibit more pronounced deflection, with the inclination angle increasing accordingly. This demonstrates that train speed is a critical factor affecting fire spread in tunnels, and that in the absence of mechanical ventilation, the piston effect plays a dominant role in determining the direction of flame propagation.

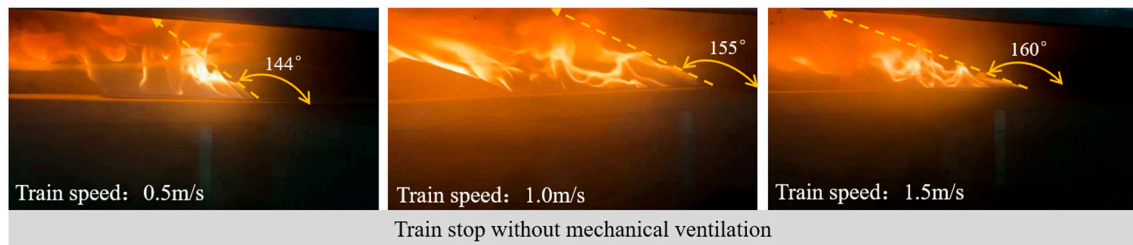


Figure 10: The experimental process at different train speeds.

Based on when the train stops 3 m downstream of the VSV, the temperature measurement points are selected above the fire source, upstream and downstream of the fire source. The temperature variation of the smoke directly above the fire source is relatively small (Fig. 11b). As the train speeds increases from 0.5 m/s to 1.5 m/s, the maximum smoke temperature above the fire source increases to 451°C, 516°C, and 534°C, respectively. Upstream of the fire source (Fig. 11c), the smoke temperature gradually increases and then stabilizes, eventually becoming uniform. At 1 m downstream of the fire source (Fig. 11a), the backflow durations of smoke are 57 s, 64 s, and 70 s, respectively. As the train speed increases, the piston effect is significantly enhanced, prolonging the residence time of hot smoke in the tunnel. This alters the transport and distribution of smoke and extends the duration of smoke backlayering at 1 m downstream of the fire source. Therefore, train speed mainly affects the transient smoke transport process and the duration of smoke back-layering, while its effect on the final steady-state smoke temperature established by the smoke exhaust system is relatively limited.

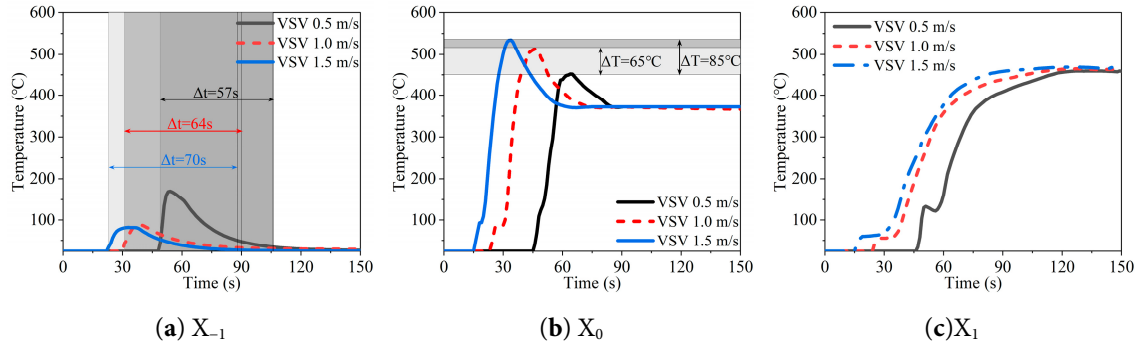


Figure 11: Temperature characteristics at different train speeds under VSV. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

3.2 Local Semi-Transverse Ventilation (LSTV) Characteristics

The semi-transverse ventilation system is also one of the common ventilation methods in tunnels. However, due to its greater construction difficulty and higher cost, it is not as widely applied as VSV. With the construction and development of ultra-long tunnels, this study integrates the characteristics of semi-transverse and longitudinal ventilation to establish the LSTV system and investigate its smoke exhaust performance. As shown in Fig. 12, the LSTV system implements a zoned-control strategy for creating independently regulated ventilation zones along the tunnel. With the fire source located within this zone, LSTV is activated in negative pressure. Conversely, if the fire source is positioned upstream of LSTV, the LSTV operates in positive pressure mode to maintain a clean air environment along evacuation routes. This section conducts a comparative analysis of the fire source distance, the number of air vents, and the train speeds.

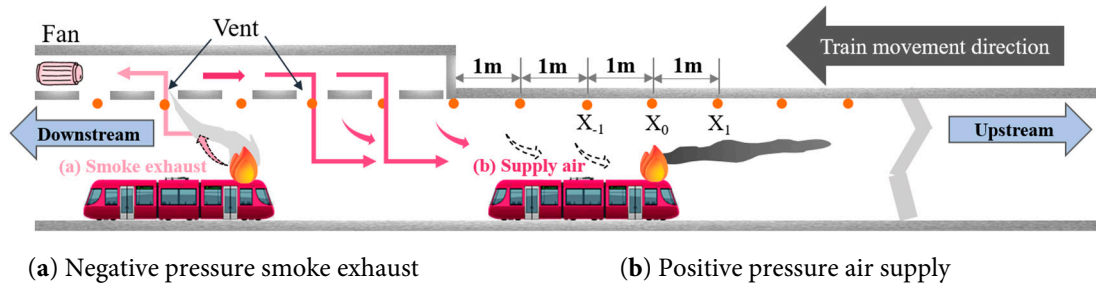


Figure 12: Train stops measurement point diagram under LSTV. (a) Negative pressure smoke exhaust; (b) Positive pressure air supply.

3.2.1 The Influence of the Locations from the Fire Source

Given the stochastic nature of emergency train stoppage during fire incidents, a comparative analysis is performed for four positioning scenarios: directly beneath the LSTV section, and 1 m, 2 m, 3 m upstream of LSTV section. As shown in Fig. 13, the experimental conditions of the train parked upstream and directly beneath the LSTV are compared. When the train is parked upstream, the positive pressure supply from the fan drives the smoke to spread toward the upstream direction. In contrast, when the train is parked directly beneath the LSTV, the negative pressure extraction induces a pronounced deflection of the flame. These results indicate that the parking position of the train has a significant impact on the smoke flow direction and flame characteristics, thereby affecting the overall smoke extraction performance.

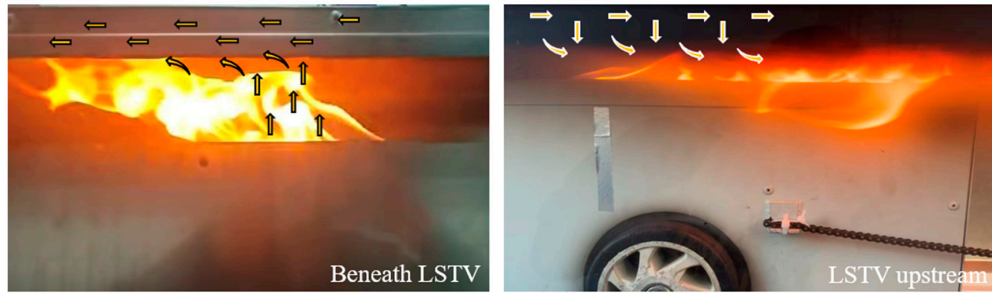


Figure 13: The experimental process at different fire source locations under LSTV.

At varying fire source distances, the maximum smoke temperature directly above the fire source (Fig. 14b) exhibits minimal variation, with the peak temperature stabilizing at approximately 550°C . The peak temperature in the blank control group is close to 700°C , representing a reduction of approximately 20%. For the upstream measurement point of the fire source (Fig. 14c), due to the action of the fan, the smoke is blown upstream. After a period of time, the temperature difference of the smoke does not increase significantly. When the fire source is located directly beneath the LSTV section, smoke is immediately exhausted through the vents, minimizing the overall smoke temperatures. The peak temperature reaches only about 90°C , representing a 70%–80% reduction compared to the upstream-stop scenario. For the downstream measurement points of the fire source (Fig. 14a), as the distance from the LSTV increases, the maximum smoke temperatures are 231°C , 257°C , and 302°C respectively. The lowest temperature, measured directly beneath the LSTV, is 127°C . Therefore, the smoke exhaust effect is best when the fire source is located directly below the LSTV. As the fire source moves farther away from the LSTV section, the maximum smoke temperature gradually increases, and the LSTV effect gradually decreases.

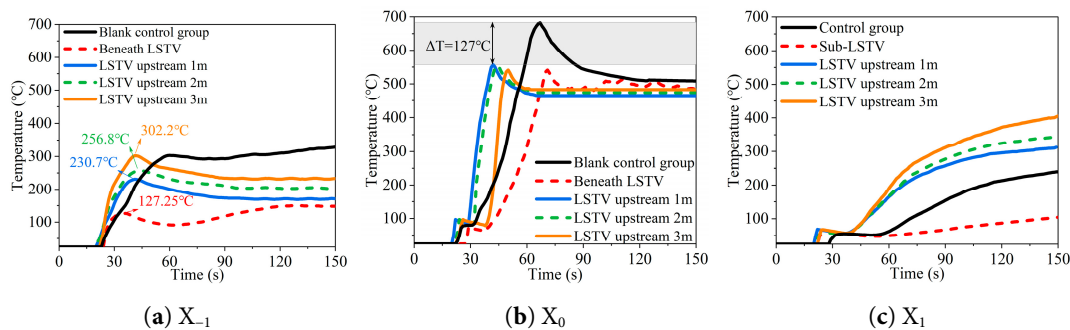


Figure 14: Temperature characteristics at different fire source locations under LSTV. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

3.2.2 The Influence of the Opening Method of Vents

When a moving train catches fire and is forced to stop directly below the LSTV section, the vent opening configuration significantly influences the smoke propagation dynamics. Therefore, based on the experimental setup, the smoke exhaust differences under three conditions are compared: all six vents open, three vents open with intervals, and three concentrated vents open (the three vents closely spaced above the fire source). The experimental process of adjusting the vents is illustrated in Fig. 15. Under the condition of constant fan power, reducing the number of open vents increases the exhaust velocity at each individual vent; however, the enlarged spacing between vents alters the flow distance of smoke. When three adjacent vents directly above the fire source are opened, the flame and high-temperature smoke can be discharged directly through the vents, resulting in the most concentrated exhaust path and relatively higher efficiency.

When three vents are opened at intervals, the presence of unopened sections above the fire source allows smoke to continue spreading along the tunnel, thereby increasing the propagation distance. When all six vents are fully opened, the exhaust flow is dispersed across multiple channels, thereby diluting the localized extraction intensity. Consequently, the smoke spreads further longitudinally, reducing the overall extraction efficiency. By comparison, concentrated activation of three vents results in the smallest smoke spread, followed by the alternating activation mode.

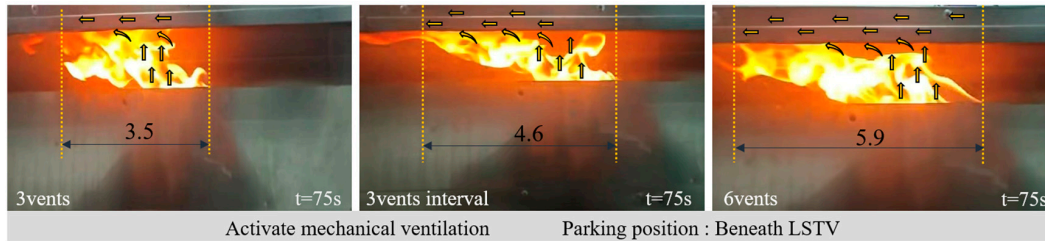


Figure 15: The experimental process of zoned-control.

The comparison of temperature characteristics under different opening method of the vents are shown in Fig. 16. The smoke temperature directly above the fire source (Fig. 16b) exhibited minimal variation across different opening conditions of the vents. The temperature attained approximately 490°C. With the fan activated, the majority of smoke is directly exhausted through the LSTV openings, resulting in relatively low temperature levels both upstream and downstream. The upstream smoke temperature (Fig. 16c) shows a gradually increasing trend and then stabilizes, eventually becoming consistent. The case with concentrated activation of three vents maintains a relatively low temperature of only about 40°C. For the downstream measurement point (Fig. 16a), the temperature remains lowest under the condition of concentrated activation of three vents, achieving near complete smoke extraction. This is because the vents are located above the fire source, and the number of opened vents is decreased, resulting in a significant increase in the smoke exhaust speed of each vent. After reaching the maximum temperature of 126°C, the smoke is almost completely exhausted from the tunnel after 31 s. It can be seen that the adjustment effect of the LSTV smoke exhaust vents near the fire source is the best. When all 6 vents opening are fully opened, the smoke discharge flow passes through the 6 openings, reducing the smoke discharge amount from each opening. Furthermore, the smoke needs to pass through each opening, leading to an increase in the length of smoke spread and a slow decrease in smoke temperature, which also affects personnel evacuation. As the fan continues to be turned on, the effect of opening 3 vents at intervals is slightly better than 6 vents. Therefore, when the moving train is forced to stop directly below the LSTV section, implementing zoned-control of vents with priority activation of those adjacent to the fire source significantly enhances smoke extraction efficacy.

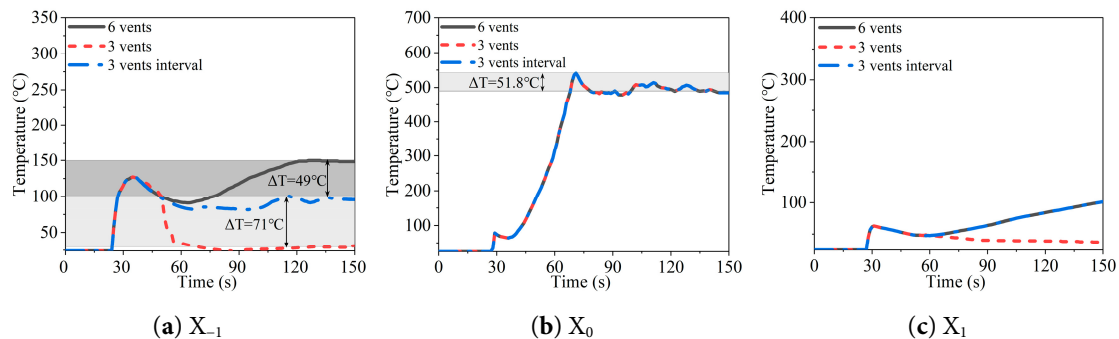


Figure 16: Temperature characteristics during the zoned-control of the vents. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

3.2.3 The Influence of Train Speeds

As train speed increases, the intensified piston wind significantly affects fire spread and mechanical smoke extraction. Therefore, for a train halted 2 m upstream of the LSTV section, the exhaust performance is evaluated across three speeds: 0.5, 1.0, and 1.5 m/s. The maximum value of smoke temperature directly above the fire source (Fig. 17b) exhibited minimal variation, while the smoke temperature stabilizes at approximately 480°C. After the fan is turned on, most of the smoke is blown upstream of the LSTV section. The upstream smoke temperature (Fig. 17c) shows a gradually increasing trend and then stabilizes, eventually becoming consistent. As the train speed increases from 0.5 m/s to 1.5 m/s, the peak smoke temperature downstream of the fire source (Fig. 17a) is 544°C, 302°C and 228°C, respectively. The time for the high-temperature smoke to reach the final stable smoke state is 86 s, 106 s, and 116 s. The decrease in maximum temperature with increasing train speed is mainly attributed to the enhanced piston wind, which promotes the longitudinal transport, entrainment, and dilution of the hot smoke. Meanwhile, the stronger longitudinal airflow alters the transient redistribution of smoke and prolongs the time required for the flow field to reach a steady state. Therefore, train speed mainly affects the transient smoke transport process and the time required to reach a steady state, while its effect on the final steady-state smoke temperature is relatively limited.

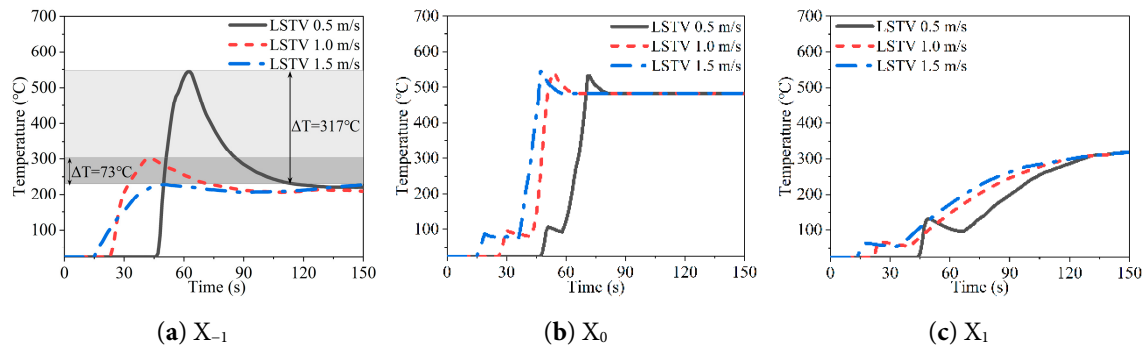


Figure 17: Temperature characteristics at different train speeds under LSTV. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

3.3 Comparison between VSV and LSTV

This section focuses on the differences in smoke exhaust performance between VSV and LSTV, when the train stops at 1, 2, and 3 m upstream of the VSV and LSTV section, with the power of the fans being the same. The comparison results are shown in Fig. 18. Under VSV, the temperature directly above the fire source decreases significantly, indicating a better smoke exhaust performance. Once the exhaust process stabilizes, as the distance from the fire source increases, the smoke temperature decreases by approximately 70% as the distance from the fire source increases. compared with LSTV. In addition, under VSV conditions, the hot smoke at a distance of 1 m downstream of the fire source (Fig. 18a) took approximately 30 s to be substantially exhausted from the tunnel, while the smoke temperature remained at a well-controlled low level with a peak of only 64°C. However, under LSTV, there is still hot smoke present within the tunnel. And the maximum smoke temperature under VSV is reduced by approximately 190–235°C compared with LSTV. At 1 m upstream of the fire source (Fig. 18c), a significant temperature rise is observed. Once the fan is activated, the hot smoke is primarily driven upstream. The higher the temperature, the greater the amount of hot smoke reaching this location. Compared with LSTV, the temperature under VSV is higher approximately 40%–80%. It can be seen that the VSV exhibits relatively better smoke exhaust performance at different fire source locations.

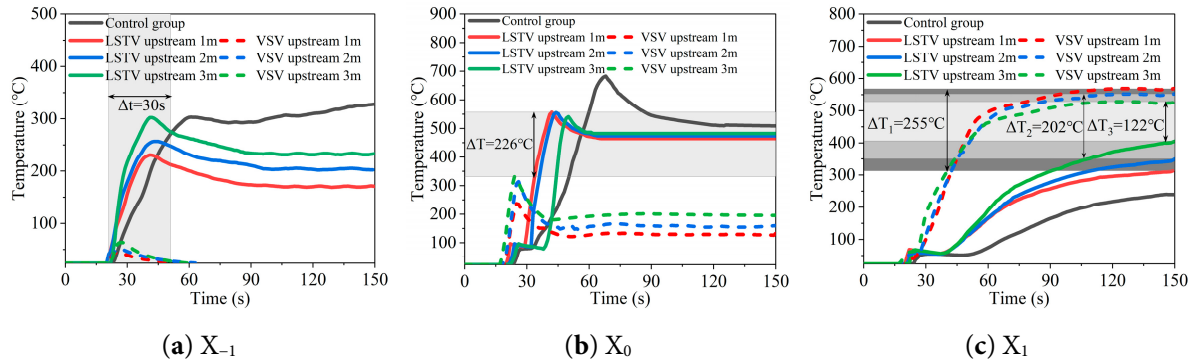


Figure 18: Temperature characteristics comparison of VSV and LSTV at different fire locations. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

The smoke exhaust effects of LSTV and VSV are further compared among different train speeds of 0.5 m/s, 1.0 m/s, and 1.5 m/s. The maximum value of the smoke temperature directly above the fire source (Fig. 19b) does not change significantly. However, once the fan is activated and the tunnel wind environment stabilizes, the smoke temperature under the LSTV reaches 483°C . In contrast, the smoke temperature under the VSV is maintained at 380°C , representing a reduction of approximately 20%. The temperature of the smoke at the upstream (Fig. 19c) gradually increases. After stabilization, the temperature of the smoke increased by approximately 160°C in LSTV. The VSV system reduces the maximum smoke temperature downstream by approximately 70% (Fig. 19a). Compared with LSTV, the time for the smoke temperature to reach its maximum value in VSV is reduced by 10 s, 14 s, and 15 s respectively. To sum up, the VSV demonstrates better performance compared to LSTV.

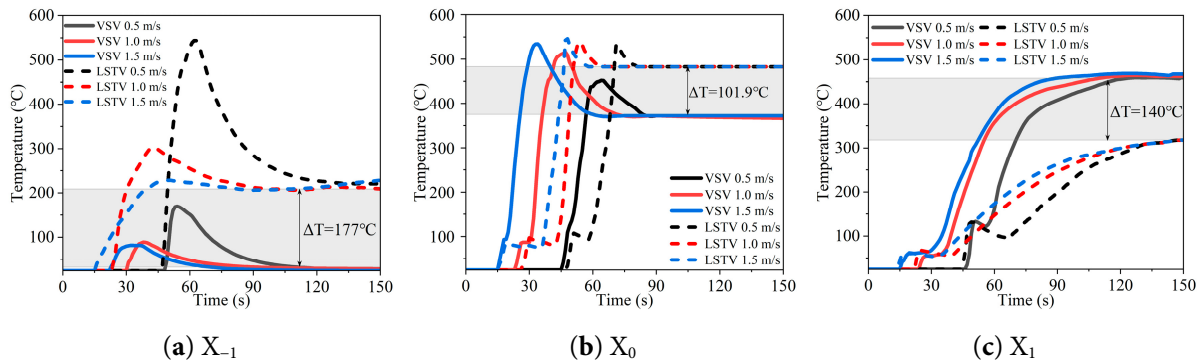


Figure 19: Temperature characteristics comparison of VSV and LSTV at different train speeds. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

3.4 Combined Ventilation (CV) Characteristics

With increasing tunnel length, ultra-long tunnels passing through mountainous regions or crossing seas may fail to satisfy the construction requirements for intermediate ventilation shafts. To fulfill tunnel ventilation and smoke extraction requirements, when the LSTV cannot effectively discharge the smoke in the tunnel, the longitudinal ventilation system is proposed to be combined, as shown in Fig. 20. A blank control group under natural ventilation is established for baseline comparison.

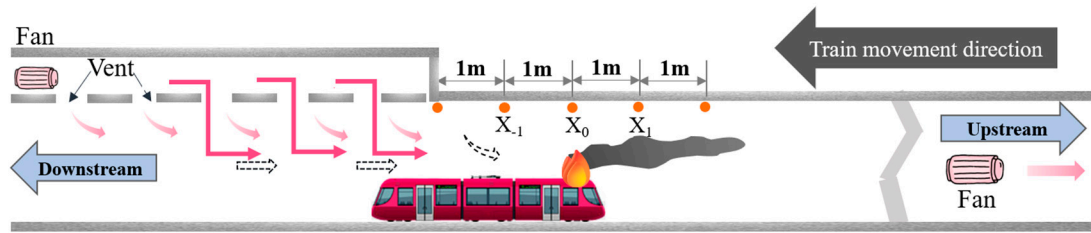


Figure 20: Train stops measurement point diagram under CV.

3.4.1 The Influence of the Locations from the Fire Source

The train stopping positions are identical to those in Section 3.2. At different fire source distances, the maximum value of smoke temperature directly above the fire source (Fig. 21b) is reduced by 30%–40% compared with the blank control group. Under the effect of CV, the temperature directly above the fire source decreases significantly after reaching the maximum value. The final stable temperature is approximately 260°C, indicating that the smoke exhaust effect of CV has been significantly improved. As the fan operates to blow the smoke upwards, the temperature at the measurement point gradually increases (Fig. 21c). The maximum smoke temperature is approximately 470°C. The maximum smoke temperature at the downstream measurement points of the fire source (Fig. 21a) is approximately 160°C, representing a significant reduction of about 50% compared with the blank control group. The duration of smoke backlayering at 1 m downstream of the fire source is 60 s, 67 s, and 75 s, respectively. With the addition of the longitudinal ventilation system and its coupling with the LSTV, a relatively stable relay airflow is formed throughout the tunnel. Therefore, it can be seen that the distance of the fire source in the CV has a relatively small impact on the change of smoke temperature. The CV has enhanced the stability of the smoke exhaust system.

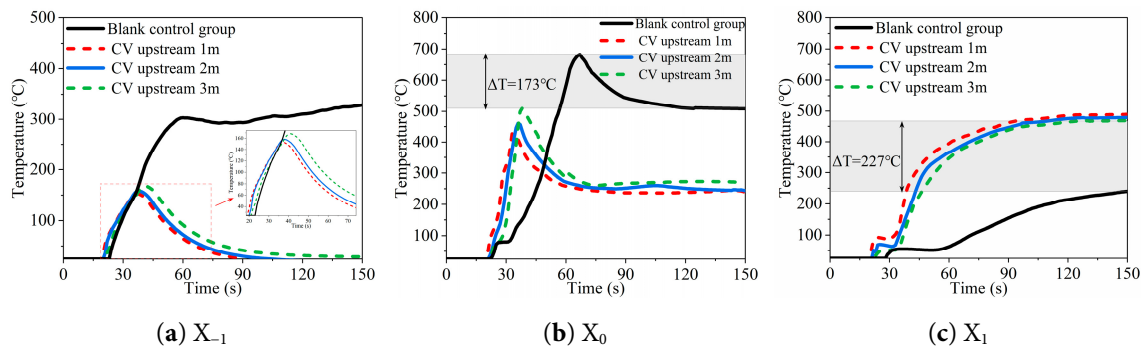


Figure 21: Temperature characteristics at different fire source locations under CV. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

3.4.2 The Influence of Train Speeds

In a similar way, the effects of different train speeds are analyzed. The maximum value of smoke temperature directly above the fire source (Fig. 22b) does not change significantly. However, as the fan is turned on, the wind environment inside the tunnel gradually stabilized, maintaining a constant smoke temperature of 295°C when opening CV. The upstream smoke temperature (Fig. 22c) gradually increases, and the final smoke temperature becomes consistent across different train speeds. At a distance of 1 m downstream of the fire source (Fig. 22a), the maximum smoke temperatures reached 198°C, 168°C, and 139°C respectively. The increase in train speed makes smoke more difficult to be expelled, resulting in longer residence time and greater heat accumulation at that location. Consequently, the duration of smoke backlayering is slightly extended, being 70 s, 93 s, and 103 s, respectively. These results indicate that train

speed mainly affects the transient smoke transport process and the duration of smoke back-layering, while its effect on the final steady-state smoke temperature under the CV system is relatively limited.

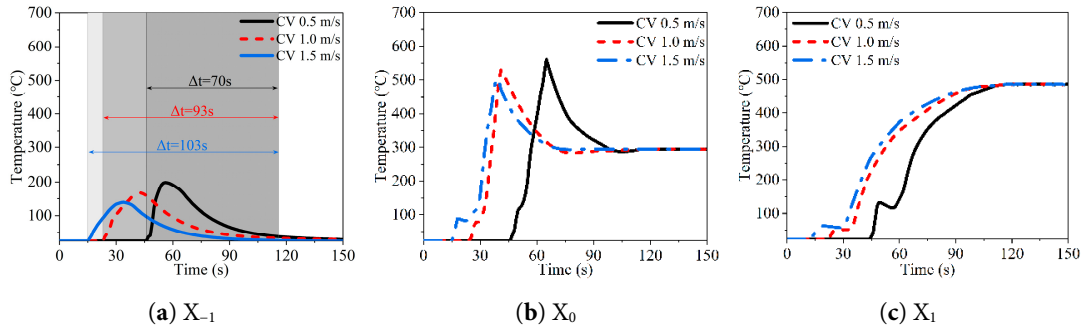


Figure 22: Temperature characteristics at different train speeds under CV. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

3.5 Comparison between CV and LSTV

In order to explore the coupling effect of the addition of longitudinal ventilation with the LSTV system, the smoke exhaust effects of the CV and LSTV are compared, and the results are shown in Figs. 23 and 24. Under different fire source locations, for the upstream area (Fig. 23c), the CV causes the smoke temperature to rise to a stable level, which is approximately 150°C higher than that of the LSTV. And the smoke temperatures at different distances tend to be consistent under CV. For the downstream area of the fire source (Fig. 23a), the maximum smoke temperature under the CV mode is approximately 40% lower than that under the LSTV. Furthermore, in the CV system, after 90 s of fan operation, the upstream temperature gradually returns to ambient temperature, and the ventilation and smoke exhaust effect is obviously better than that of the LSTV mode. Under the coupling of longitudinal ventilation and LSTV, the tunnel develops a relatively stable overall airflow that does not vary along the tunnel length. Therefore, the fire source location has a significantly smaller impact on the smoke exhaust performance of the CV system, which demonstrates higher smoke exhaust stability.

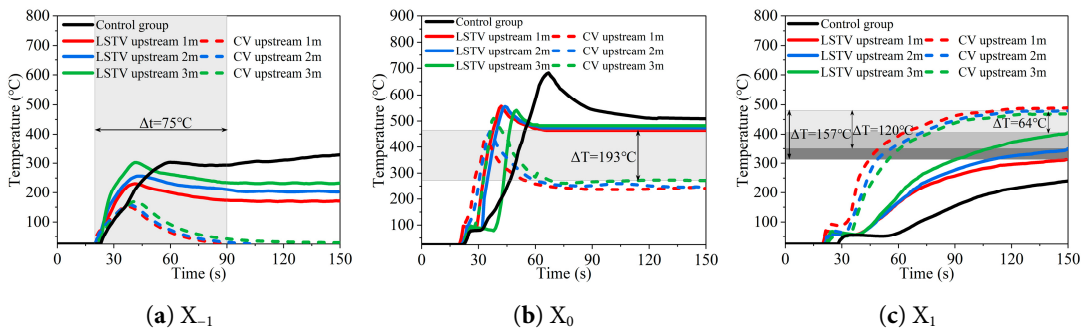


Figure 23: Temperature comparison of CV and LSTV at different fire source locations. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

Under the condition of different train speed, Fig. 24. indicates that train speed has little influence on the ultimate smoke extraction performance, as the final temperatures tend to stabilize. The CV system demonstrates superior performance. In the steady stage, smoke temperatures downstream and directly above the fire source decrease by approximately 40%, accompanied by a 60% increase upstream. On the other hand, train speed still affects the smoke extraction duration. Under the same conditions, the CV system requires only 98 s to achieve nearly complete smoke discharge, whereas approximately 220°C of high temperature smoke still remains under LSTV. Therefore, as the tunnels continue to expand in length, the

coupled zone ventilation smoke exhaust airflow organization mode that combines LSTV and longitudinal ventilation is expected to achieve efficient smoke exhaust in the tunnels, avoiding the construction of intermediate VSV. It is of great significance for the development and safety guarantee of ultra-long tunnels.

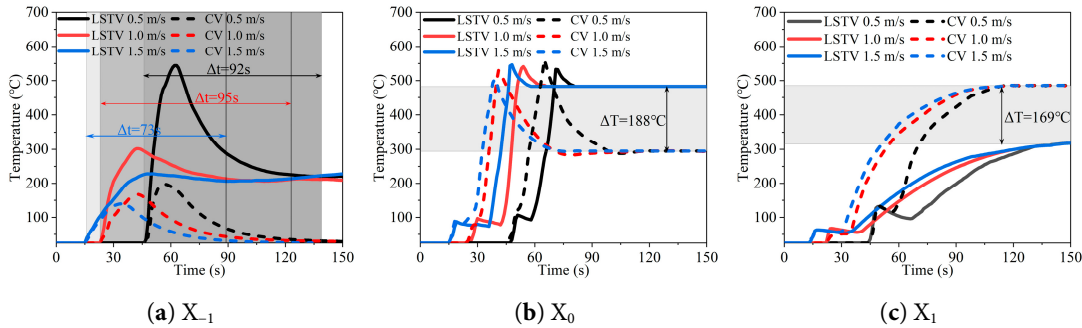


Figure 24: Temperature comparison of CV and LSTV at different train speeds. (a) X_{-1} ; (b) X_0 ; (c) X_1 .

4 Conclusions

Through a scaled-down tunnel model, the smoke effects of a moving train fire in a subway tunnel under different influencing factors are studied. The ventilation performance of VSV (Vertical shaft ventilation) and LSTV (Local semi-transverse ventilation) is comparatively analyzed. A combined ventilation (CV) strategy integrating LSTV and longitudinal ventilation is proposed, with experimental comparison conducted. This research provides the theoretical basis and valuable experimental data for the optimization of the ventilation and smoke control system in subway tunnels under the emergency stopping condition of a burning train. The main conclusions are summarized as follows:

1. For the VSV system, when the train stops upstream of the shaft, the peak smoke temperature directly above the fire source is reduced by approximately 40% relative to the downstream-stop scenarios. Furthermore, the duration of smoke backflow at 1 m downstream of the fire source is significantly shortened. When conditions permit, the burning train should be stopped upstream of the shaft to achieve optimal smoke extraction.
2. In the LSTV system, a fire positioned directly beneath the exhaust section results in minimum temperatures and optimal exhaust performance. Under zoned control, activating three vents directly above the fire minimizes downstream temperatures, achieving near-complete extraction within 31 s. For trains halted outside the LSTV section, exhaust efficiency degrades with increasing stopping distance. Additionally, higher train speeds prolong high-temperature smoke residence times, aggravating thermal hazards within the tunnel.
3. Comparative analysis reveals that across varying fire source locations and train speeds, VSV reduces downstream temperatures by approximately 60%–80% compared with LSTV, demonstrating superior performance. However, the smoke exhaust performance of both systems exhibits a declining trend with increasing train stopping distance.
4. Longitudinal ventilation is proposed to be combined with LSTV, forming the CV system. The smoke downstream temperature of CV is reduced by approximately 40%–60%, and the smoke exhaust performance is significantly improved compared with LSTV. The CV system established a relatively stable airflow within the tunnel, reducing the influence of fire source location and ensuring more stable exhaust performance. It can serve as a reference for designing safer and more efficient ventilation systems.

Across all mechanical ventilation schemes evaluated in this study, the experimental ventilation velocities (2–11 m/s) strictly comply with the GB 51298-2018 standard, ensuring practical engineering applicability.

Current findings validate significant thermal and aerodynamic improvements, establishing favorable conditions for evacuation processes. However, a comprehensive safety assessment requires further investigation into smoke toxicity, visibility, and occupant evacuation behavior. Detailed analyses of system energy efficiency and fan operating modes are not covered in this study. Future research will couple a smoke transport model with evacuation simulation and optimize fan operating modes, thereby developing a multi-objective framework balancing evacuation safety and energy efficiency.

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Ethics Approval: Not applicable. This study does not involve human or animal subjects.

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