

Experimental study on smoke propagation characteristics in dead-end tunnel networks during construction stage based on a small-scale model

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Received: March 12, 2026; Revised: September 7, 2026; Accepted: September 18, 2026

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Abstract: This study investigates smoke propagation in Dead-end tunnel networks during the construction phase using a 1:30 small-scale physical model based on the Tianshan Victory Tunnel. The model consists of two main tunnels, a central service tunnel, and two cross passages, with 62 temperature measurement points. Experiments were performed under various fire source locations, fire sizes, and ventilation conditions, focusing on three factors: longitudinal temperature decay, lateral diversion at cross passages, and smoke propagation time. Results show that temperature in the main tunnel exhibits an exponential decay along the tunnel's length, with higher temperatures near the fire source. Cross passages significantly alter smoke flow, causing lateral diversion at node locations. Mechanical ventilation was found to be more effective than natural ventilation in controlling smoke and temperature distribution. The study highlights how fire source location and ventilation mode influence smoke behavior and temperature attenuation. These findings provide experimental data for optimizing fire safety and ventilation strategies in ultra-long tunnels during the construction phase. The study emphasizes the importance of effective ventilation in controlling smoke and preventing excessive heat buildup, which can reduce fire risks and ensure the safety of

workers and tunnel users. The results also underscore the need for detailed modeling of smoke and fire behavior in the design and operation of multi-tunnel systems. This research contributes to fire safety science, offering practical insights into thermal dynamics and ventilation control in dead-end tunnel systems, and provides recommendations for improving fire prevention measures during tunnel construction and operation.

Keywords: Construction stage; Tunnel fire; Dead-end tunnel network; Small-scale model; Smoke propagation; Lateral diversion

1 Introduction

Tunnels, especially those with complex structures like the Tianshan Victory Tunnel, present significant fire safety challenges due to their confined space, limited egress, and complex ventilation systems. The interconnected configuration of multiple tunnels, including cross passages and service tunnels, makes it even more difficult to manage fire risks and ensure the safety of both construction workers and tunnel users. Therefore, understanding smoke propagation, temperature variation, and the role of ventilation in fire scenarios is crucial for designing effective fire safety protocols. This paper investigates these aspects in the dead-end Tunnel Group of the Tianshan Victory Tunnel using a small-scale physical model to simulate and analyze fire-induced behaviors and ventilation effects during the construction phase.

Several studies have explored smoke movement and temperature dynamics in tunnel fires, particularly in multi-branch and interconnected systems. Ji et al. (2016) conducted experimental studies on smoke movement in branched tunnel fires, providing foundational data on how smoke behaves in multi-branch tunnel systems. Following this, Tang et al. (2017) examined the effects of various ventilation modes, emphasizing the critical role of ventilation in controlling fire dynamics and smoke movement, and demonstrating that effective ventilation can significantly reduce fire hazards. Huang et al. (2017) extended this work with numerical simulations to explore smoke spread in multi-branch tunnel systems, offering crucial data for understanding the interaction between smoke and airflow in interconnected tunnel networks. Similarly, Zhang et al. (2018) and Wang et al. (2019) explored temperature decay and pressure redistribution in tunnel fires, showing how ventilation strategies can mitigate heat buildup and pressure imbalances in multi-tunnel systems.

The role of ventilation in tunnel fire safety has also been extensively studied. Li et al. (2019) investigated back-layering and critical velocity in tunnel fires under complex ventilation conditions, highlighting the importance of precise airflow control to prevent smoke buildup. Gao et al. (2022) further examined smoke migration in parallel tunnel systems, demonstrating how ventilation systems can be optimized to effectively control smoke spread. Zhou et al. (2020) and Li et al. (2020) studied smoke spread in cross-passage tunnel structures and multi-branch tunnel networks, respectively, emphasizing the importance of cross-passage design to enhance ventilation efficiency in fire scenarios. Wang et al. (2021) and Hu et al. (2021) focused on experimental analyses of ventilation strategies in twin-tunnel fires, showing how coordinated ventilation can improve smoke removal and stabilize the thermal field in interconnected tunnel systems.

Understanding the interaction between adjacent tunnels during a fire is also crucial for managing fire risks. Zhang et al. (2021) and Liu et al. (2022) studied the coupling behavior between tunnels during fires, demonstrating that tunnel geometry and the relative position of fire sources and cross passages significantly influence thermal and smoke behavior in interconnected systems. These

studies highlight the need for careful consideration of tunnel layout and ventilation systems to prevent thermal coupling and smoke accumulation. Recent research by Li et al. (2023) and Zhou et al. (2024) on coordinated ventilation strategies in multi-node tunnel fires showed how multi-tunnel ventilation can effectively suppress lateral smoke transfer and reduce inter-tunnel thermal redistribution.

Based on these findings, this paper focuses on the fire and ventilation challenges in the Tianshan Victory Tunnel's dead-end Tunnel Group. By using a 1:30 small-scale physical model of the tunnel system, this study investigates how fire source location, fire size, and ventilation modes affect smoke propagation, temperature decay, and inter-tunnel coupling. The study aims to optimize ventilation strategies to improve fire safety and minimize the risks associated with fire hazards in complex tunnel systems. The findings offer valuable insights for the design and operation of large-scale tunnel infrastructures during both construction and operational phases.

2 Experimental Setup and Similarity Theory

2.1 Model Configuration and Geometric Parameters

A 1:30 small-scale physical model was constructed based on the structural configuration of the Tianshan Victory Tunnel during the construction stage. The model consists of a right main tunnel, a left main tunnel, a central service tunnel, and two cross passages, forming a planar dead-end tunnel network. As shown in Figure 1, the right and left main tunnels were constructed using circular steel pipes with an inner diameter of 0.50 m, while the central service tunnel and cross passages used pipes with an inner diameter of 0.30 m. According to the 1:30 geometric scaling ratio, the equivalent prototype diameters are approximately 15 m for the main tunnels and 9 m for the service tunnel and cross passages. The diameter ratio between auxiliary and main tunnels is:

$$\beta = \frac{D_{aus}}{D_{main}} = 0.6 \quad (2 - 1)$$

The cross-sectional area of the auxiliary tunnel is approximately 36% of that of the main tunnel, indicating significant lateral diversion capacity. The total longitudinal length of the model is approximately 5.8 m, corresponding to 174 m at prototype scale. The fire source was positioned at different locations within the right main tunnel. The model represents a dead-end configuration, with only one end connected to the external environment, consistent with construction-stage ventilation conditions. A total of 62 temperature sensors were installed at a uniform height along the tunnel centerline. Sensors were distributed longitudinally along the three tunnels, with additional transverse measurement points arranged at the two cross-passage locations to capture smoke diversion characteristics.

2.2 Similarity Theory and Scaling Laws

To ensure that the small-scale experiments accurately reproduced the thermal and flow characteristics of the full-scale tunnel fires, the Froude similarity criterion was adopted. This assumes that smoke motion is governed by the balance between inertial and buoyant forces; maintaining an equal Froude number between the model and the prototype yields dynamically similar behavior.

(1) Geometric and Froude Similarity

For the prototype tunnel ($H_p = 6.0$ m) and the model tunnel ($H_m = 0.50$ m), the length scale ratio is:

$$\lambda_l = \frac{H_m}{H_p} = \frac{1}{30} \approx 0.0833 \quad (2-2)$$

The Froude number is defined as:

$$Fr = \frac{u}{\sqrt{gH}} \quad (2-3)$$

Setting $Fr_m = Fr_p$ gives the velocity scale:

$$\lambda_u = \sqrt{\lambda_l} = \sqrt{\frac{1}{30}} \approx 0.182 \quad (2-4)$$

(2) Time Scale

Since $t \sim L / U$, the time scale ratio is:

$$\lambda_t = \frac{\lambda_l}{\lambda_u} = \sqrt{\lambda_l} \approx 0.182 \quad (2-5)$$

(3) Heat Release Rate Scale

According to Froude scaling, the heat release rate (HRR) follows:

$$\lambda_q = \frac{H_m^{\frac{5}{2}}}{H_p} \quad (2-6)$$

(4) Temperature Scale

When ambient conditions and fuel are consistent, and heat losses are negligible, the non-dimensional excess temperature remains constant:

$$\lambda \Delta T = \frac{\Delta T_m}{\Delta T_p} \approx 1.0 \quad (2-7)$$

Table 1 summarizes the Froude similarity scaling relationships between the full-scale and small-scale experiments, using proper subscript notation for clarity.

Table 1 Froude similarity scaling relationships between the full-scale and small-scale experiments,

Physical Quantity	Symbol	Model / Prototype Ratio
Length	λ_l	1:30
Velocity	λ_u	0.182
Time	λ_t	0.182
Heat Release Rate	λ_q	2.6×10^{-3}

In the small-scale experimental study, five sizes of square methanol pool fires were used to simulate different fire intensities under controlled conditions. The pool pans had side lengths of 5 cm, 8 cm, 10 cm, 12 cm, and 15 cm, corresponding to increasing heat release rates (HRRs). As shown in Table 2, methanol was selected as the fuel because of its clean combustion, stable burning

behavior, and well-characterized thermal properties, ensuring comparability between repeated tests. Each pan was placed at different fire source locations along the tunnel floor to investigate the influence of fire position on the smoke flow and the exhaust performance of the vertical shaft. Moreover, experiments were conducted under different ventilation modes — including natural ventilation and forced exhaust through the shaft — to study the interaction between fire-induced buoyant flow and ventilation effects.



Figure 1 Small-Scaled Model

Table 2 Comparison between small-scale and full-scale equivalent fire powers for different methanol pool sizes

Pan side (cm)	Area (m ²)	Model HRR (kW)	Full-scale equiv. HRR (MW)
5	0.0025	1.3	0.624
8	0.0064	3.2	1.596
10	0.01	5.0	2.494
12	0.0144	7.2	3.592
15	0.0225	11.2	5.612

2.3 Instrumentation and Temperature Measurement System

A total of 62 temperature measurement points were installed throughout the tunnel network to capture the spatial and temporal evolution of smoke propagation during the fire experiments. As shown in Figure 2, all sensors were arranged at a uniform elevation corresponding to the tunnel centerline height, ensuring consistency in longitudinal temperature comparison and eliminating vertical stratification effects. The measurement system was designed to simultaneously monitor longitudinal temperature attenuation in the main tunnels as well as lateral smoke diversion effects induced by the cross passages.

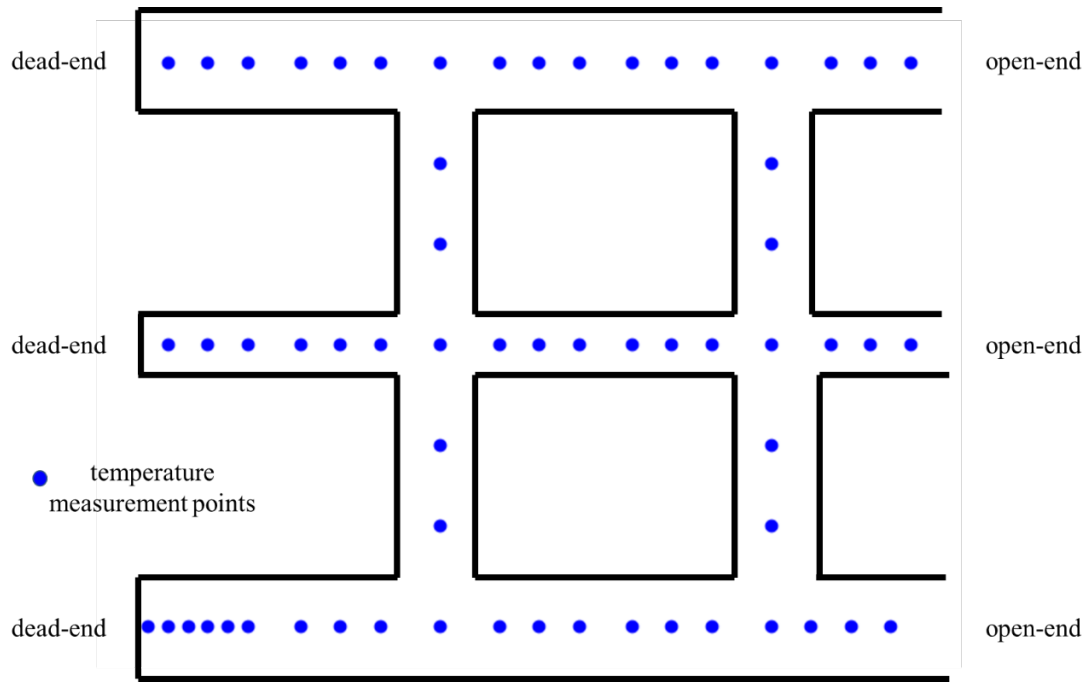


Figure 2 Schematic of Measurement Point Arrangement

Along the right main tunnel ($y=0$ cm), 20 thermocouples were installed at different longitudinal positions to characterize the temperature decay behavior downstream of the fire source. In the central service tunnel ($y=140$ cm) and the left main tunnel ($y=280$ cm), 17 measurement points were distributed along each tunnel axis to capture inter-tunnel coupling and smoke transmission behavior. Additional transverse measurement points were arranged at the two cross-passage locations ($x \approx 225$ cm and $x \approx 475$ cm) across the three tunnels. This configuration allowed detailed observation of lateral smoke diversion, pressure redistribution, and coupled flow interaction between adjacent tunnels at node positions. As shown in Figure 3.

Table 3 Coordinates of Temperature Measurement Points

Point ID	x (cm)	y (cm)	Point ID	x (cm)	y (cm)
1	5	0	32	400	140
2	20	0	33	430	140
3	35	0	34	475	140
4	50	0	35	520	140
5	65	0	36	550	140
6	80	0	37	580	140
7	120	0	38	20	280
8	150	0	39	50	280
9	180	0	40	80	280
10	225	0	41	120	280
11	270	0	42	150	280
12	300	0	43	180	280
13	330	0	44	225	280
14	370	0	45	270	280
15	400	0	46	300	280
16	430	0	47	330	280

17	475	0	48	370	280
18	505	0	49	400	280
19	535	0	50	430	280
20	565	0	51	475	280
21	20	140	52	520	280
22	50	140	53	550	280
23	80	140	54	580	280
24	120	140	55	225	50
25	150	140	56	225	90
26	180	140	57	225	190
27	225	140	58	225	230
28	270	140	59	475	50
29	300	140	60	475	90
30	330	140	61	475	190
31	370	140	62	475	230

All temperature measurements were conducted using armored K-type thermocouples. These sensors were selected due to their high-temperature resistance, mechanical durability, and rapid response capability under fire conditions. The thermocouples were equipped with stainless-steel protective sheaths to ensure structural integrity during high-temperature exposure and turbulent smoke flow. The measurement range of the thermocouples was $-50\text{ }^{\circ}\text{C}$ to $1100\text{ }^{\circ}\text{C}$, with an accuracy of $\pm 1.5\text{ }^{\circ}\text{C}$ or $\pm 0.4\%$ of the measured value (whichever was greater). The response time under airflow conditions was less than 1 s, which was sufficient to capture the transient temperature evolution during the 15-minute experimental period.

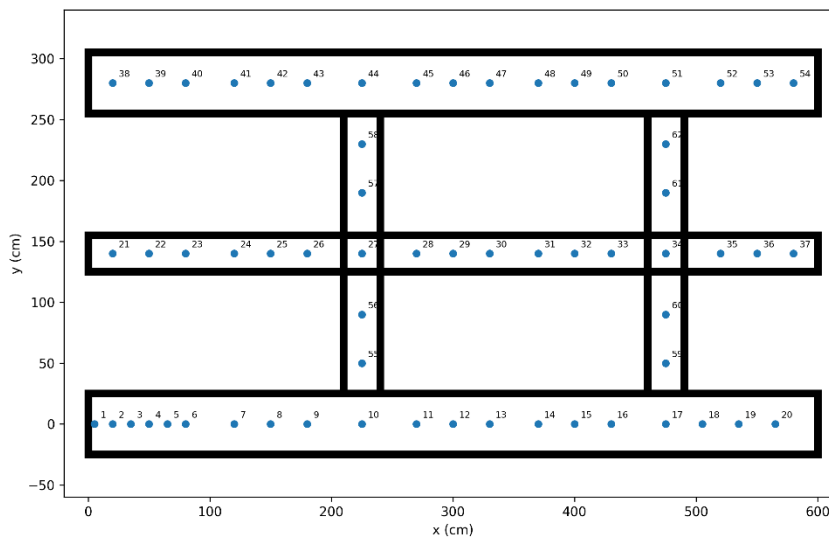


Figure 3 Detailed Map of Measurement Point Locations

To minimize disturbance to the flow field, all thermocouples were installed flush with the inner wall of the tunnel pipes while ensuring direct exposure to the main smoke stream. The sensor placement avoided direct flame impingement to prevent localized overheating and measurement distortion. Temperature data were recorded continuously during each experimental run, and only the 15-minute period following ignition was used for subsequent analysis to ensure consistency among different test cases.

2.4 Experimental Program

A series of fire experiments were conducted over multiple test days under different fire source and ventilation conditions. Each experimental case was uniquely defined by the ignition time, fire source location, fuel pan size, and ventilation mode, as specified in the experimental schedule. The ignition time of each test was recorded with second-level precision to ensure accurate synchronization between the temperature data and the fire initiation moment. For each case, only the 15-minute period following ignition was considered for analysis, as the combustion process was generally completed within this duration. The fire source was positioned at designated locations within the right main tunnel to investigate the influence of longitudinal position on smoke propagation characteristics. Different fuel pan diameters were used to represent varying fire sizes, thereby allowing comparison of temperature distribution and smoke spreading behavior under different heat release conditions. The variation in fuel pan size resulted in different effective fire intensities while maintaining geometric similarity under the Froude scaling principle. Two ventilation conditions were considered in the experimental program: natural ventilation and mechanical ventilation. Under natural ventilation conditions, no fans were operated, and smoke movement was driven solely by buoyancy-induced flow and pressure redistribution within the tunnel network. Under mechanical ventilation conditions, axial fans were activated to introduce longitudinal airflow, simulating forced ventilation during construction. The comparison between natural and mechanical ventilation scenarios enabled evaluation of ventilation control effectiveness, particularly in terms of longitudinal temperature attenuation and lateral smoke diversion at cross passages.

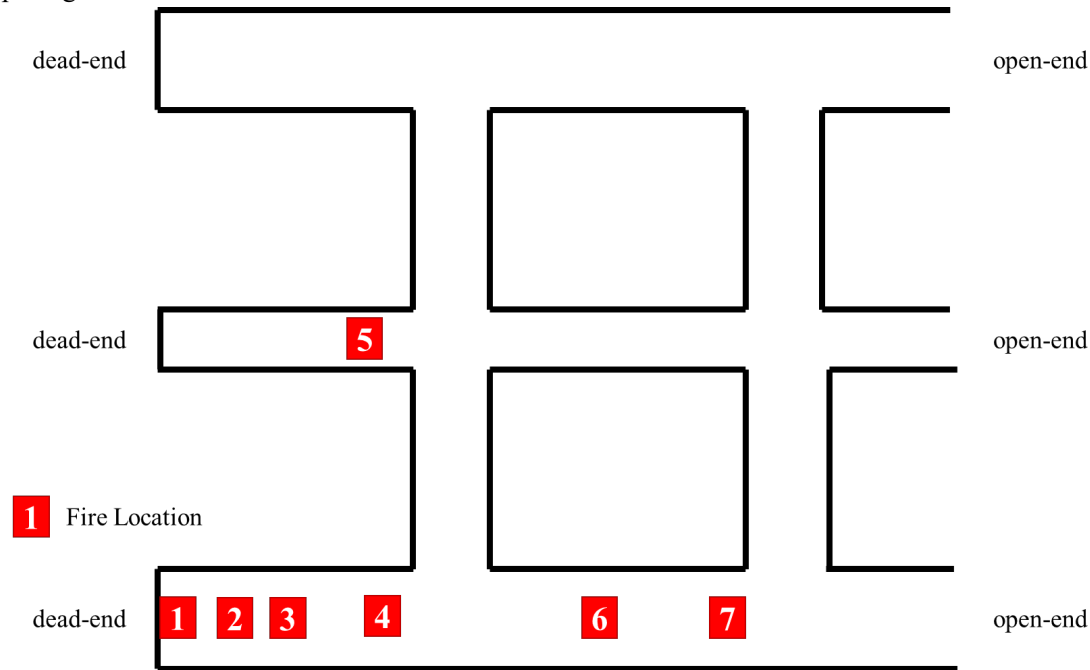


Figure 4 Schematic of Fire Source Locations

Table 4 Experimental Conditions Table

Case Range	Controlled Variable	Fixed Parameters	Research Purpose
Case 1–7	Fire size variation	Location 1	Effect of fire intensity at fixed location

Case 8–12	Fire size variation	Location 2	Effect of fire intensity at fixed location
Case 13–17	Fire size variation	Location 3	Effect of fire intensity at fixed location
Case 18–23	Fire size variation	Location 4	Effect of fire intensity at fixed location
Case 24–27	Fire size variation	Location 5	Effect of fire intensity at fixed location
Case 28–32	Fire size variation	Location 6	Effect of fire intensity at fixed location
Case 33–35	Fire size variation	Location 7	Effect of fire intensity at fixed location
Case 36–70	Ventilation variation	Fire size = 10 cm (Locations 2 & 3)	Influence of ventilation condition
Case 71–72	Large fire comparison	Fire size = 15 cm	High-intensity fire validation
Case 73	Repeatability test	Fire size = 10 cm, Location 2	Experimental consistency check

Across the entire experimental campaign, multiple tests were conducted each day, resulting in a comprehensive matrix of cases covering different fire locations, fire sizes, and ventilation configurations. This systematic design allowed investigation of individual parameter effects as well as their coupled influence on smoke propagation in the dead-end tunnel network. The structured experimental program provides a robust dataset for analyzing longitudinal temperature decay, cross-passage diversion behavior, and ventilation performance during the construction stage.

3 Data Processing and Characteristic Parameter Definition

3.1 Data Preprocessing and Quality Control

The temperature data collected during each experimental run were recorded with second-level resolution. To ensure consistency among different test cases, only the 900 s period following ignition was extracted for analysis. The ignition moment, recorded with second-level precision in the experimental schedule, was defined as the reference time ($t = 0$ s). All temperature records were temporally realigned according to this reference to ensure direct comparability across cases. Prior to analysis, the raw data were subjected to a systematic preprocessing procedure. During several experimental runs, certain thermocouples produced abnormal readings of 1999.9 °C. This value does not represent a physical temperature but indicates sensor malfunction. These abnormal values were corrected using spatial interpolation along the same tunnel axis. When the temperature at measurement point i was identified as invalid at a given time step, it was replaced by the average of its two adjacent valid points:

$$T_i(t) = \frac{T_{i-1}(t) + T_{i+1}(t)}{2} \quad (3 - 1)$$

After preprocessing, each test case consisted of 62 valid temperature time histories. To eliminate the influence of ambient temperature variations, all analyses were conducted using temperature rise rather than absolute temperature. The temperature rise at each location was defined

as:

$$\Delta T(x, t) = T(x, t) - T_0 \quad (3 - 2)$$

where T_0 represents the initial ambient temperature calculated as the average temperature during the 60 s period before ignition. This normalization ensures that differences among cases reflect fire-induced thermal effects rather than environmental fluctuations.

Through the above procedures, the dataset was standardized, corrected, and normalized, providing a reliable basis for subsequent quantitative analysis.

3.2 Definition of Research Variables and Analytical Parameters

To systematically investigate smoke propagation behavior in the dead-end tunnel network, the experimental data were analyzed from both spatial and temporal perspectives. The study focuses on four primary aspects: longitudinal temperature attenuation, smoke propagation dynamics, fire intensity effects, and lateral diversion between tunnels.

First, to characterize the peak thermal impact at different locations, the maximum temperature rise during the 900 s analysis window was defined as:

$$\Delta T_{max}(x) = \max_{0 < t < 900s} \Delta T(x, t) \quad (3 - 3)$$

This parameter is used to evaluate the spatial distribution of fire-induced thermal influence and to compare different fire sizes and ventilation conditions.

Second, the longitudinal temperature attenuation along the main tunnel was quantified using an exponential decay model:

$$\Delta T(x) = \Delta T_0 \exp(-kx) \quad (3 - 4)$$

where k is the longitudinal decay coefficient obtained through least-squares fitting. The coefficient k reflects the rate of thermal attenuation along the tunnel and serves as a key indicator of ventilation effectiveness.

Third, to describe smoke propagation dynamics, the smoke arrival time at each measurement point was defined as the time when the temperature rise first exceeded 1 °C:

$$t_a(x) = \min\{t | \Delta T(x, t) > 1^\circ\text{C}\} \quad (3 - 5)$$

A threshold of 1 °C was selected because the small-scale experimental model exhibits relatively moderate temperature elevations compared to full-scale tunnel fires. A lower threshold allows accurate identification of the initial smoke front arrival while minimizing the influence of minor background fluctuations. This definition provides a more sensitive indicator of smoke propagation speed and flow redistribution at node locations.

Finally, to quantify the coupling effect between adjacent tunnels at cross passages, a lateral diversion ratio was introduced:

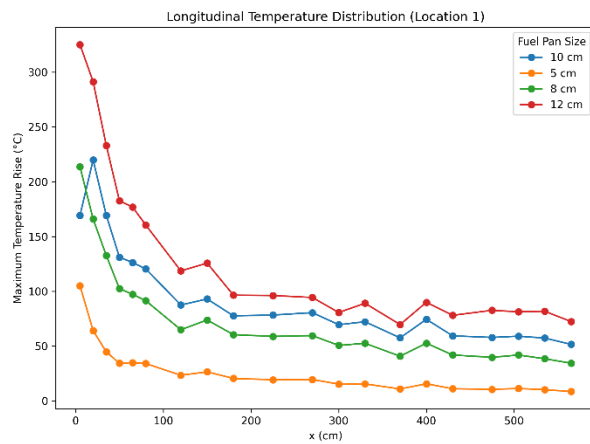
$$\eta = \frac{\Delta T_{central}}{\Delta T_{main}} \quad (3 - 6)$$

Where $\Delta T_{central}$ and ΔT_{main} correspond to temperature rise values at matching longitudinal positions in the central and main tunnels. This parameter allows evaluation of how effectively smoke is redistributed through cross passages under different fire and ventilation conditions. Together, these parameters form a comprehensive analytical framework for investigating thermal attenuation, propagation dynamics, and inter-tunnel coupling behavior in the dead-end tunnel system.

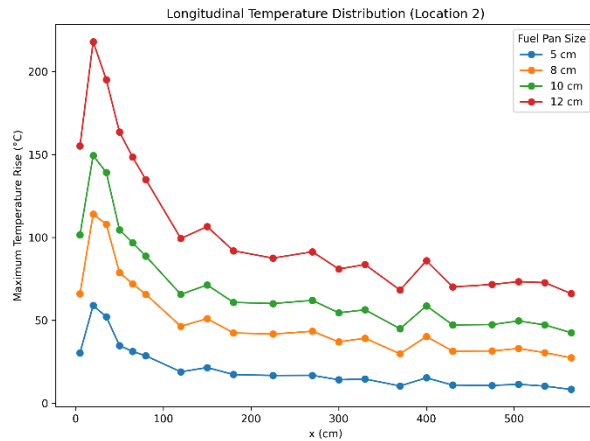
4. Analysis and Discussion

4.1 Effect of Fire Location on Longitudinal Temperature Distribution under Natural Ventilation

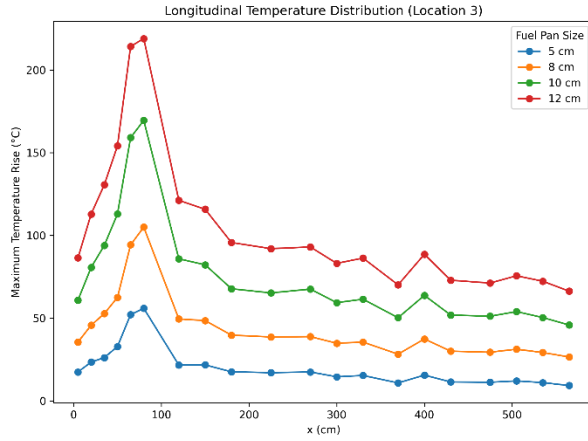
Figures 5-(a) to (c) present the longitudinal distributions of maximum temperature rise along the right main tunnel for three fire source locations under natural ventilation. The fire source is progressively positioned farther away from the dead-end side from Location 1 to Location 3. This spatial shift significantly influences the thermal attenuation pattern along the tunnel.



(a) Location 1 (X=5cm)



(b) Location 2 (X=35cm)



(c) Location 3 ($X=75\text{cm}$)

Figure 5 Temperature Rise Variation in a Single dead-End Tunnel

For Location 1, where the fire is closest to the dead-end boundary, the temperature rise near the ignition region is relatively high and exhibits a pronounced downstream decay trend. The confined geometry near the dead-end restricts longitudinal smoke outflow, leading to local accumulation of high-temperature gases. As a result, the initial temperature peak is more concentrated, and the subsequent attenuation along the tunnel axis follows a relatively steep exponential decay pattern. When the fire source moves to Location 2, farther from the dead-end side, the longitudinal temperature distribution becomes smoother. The confinement effect weakens, and smoke is able to redistribute more evenly along the tunnel. Although the peak temperature near the source still increases with fuel pan size, the overall decay gradient decreases slightly compared with Location 1, indicating enhanced longitudinal dispersion of thermal energy. For Location 3, which is the farthest from the dead-end boundary, the temperature profile shows an even more gradual attenuation. In this configuration, the available upstream volume between the fire source and the dead-end allows partial smoke accumulation before redistribution. Meanwhile, the downstream region experiences reduced confinement effects. Consequently, the longitudinal decay coefficient is smaller, and the temperature rise distribution becomes more spatially uniform. In addition to the general exponential attenuation trend, noticeable local temperature fluctuations are observed at positions corresponding to the cross passages. At these junctions, part of the hot smoke is laterally diverted into the central service tunnel, causing a redistribution of mass and energy within the network. This diversion alters the local longitudinal flow rate in the main tunnel, leading to slight deviations from the ideal exponential decay curve. The fluctuation is particularly evident downstream of the first cross passage, where a temporary reduction in temperature gradient can be identified. This phenomenon demonstrates that node-induced coupling plays a measurable role in modifying longitudinal thermal behavior, even under natural ventilation conditions.

Overall, as the fire source moves progressively away from the dead-end side, the confinement-induced temperature concentration decreases, and the longitudinal temperature field becomes more evenly distributed. However, cross-passage-induced lateral diversion introduces localized perturbations in the decay pattern, highlighting the coupled nature of smoke propagation in Dead-end tunnel systems.

4.2 Influence of Fire Source Location on Inter-Tunnel Thermal Interaction

4.2.1 Thermal Interaction When Fire Is Located in the Main Tunnel

Figure 6 present the longitudinal temperature rise distributions at 600 s after ignition for fire locations 1–4, 6, and 7, where the fire source is positioned within the right main tunnel. In all six cases, the thermal response of the three tunnels exhibits a clear hierarchical structure: the right main tunnel experiences the highest temperature rise, followed by the central service tunnel, while the left main tunnel shows comparatively weaker thermal response.



Figure 6 Temperature Comparison of Three Tunnels

For Location 1, where the fire is closest to the dead-end boundary of the right main tunnel, the

temperature rise is strongly concentrated near the ignition region. The confinement imposed by the dead-end condition limits longitudinal smoke escape, resulting in higher local accumulation of hot gases. The central tunnel exhibits only moderate temperature increase near the nearest cross passage, indicating limited lateral smoke diversion at this stage. The left main tunnel remains weakly affected. As the fire source moves downstream to Locations 2 and 3, the temperature distribution in the right main tunnel becomes more spatially extended. The reduction in upstream confinement allows smoke to develop a more stable longitudinal flow structure before interacting with the cross passages. Consequently, the temperature rise within the central tunnel becomes more pronounced. The curves show a clear temperature peak near the cross-passage region, confirming enhanced lateral mass and energy transfer. This indicates that the node coupling effect strengthens when the fire is positioned closer to the cross passages. For Locations 4 and 6, the fire source is located further downstream within the main tunnel network. In these cases, the temperature rise in the right main tunnel shows a smoother longitudinal attenuation profile. The central tunnel experiences a noticeable but more distributed temperature increase, suggesting that the smoke entering the cross passage has already undergone partial cooling and mixing. Compared with Locations 2–3, the peak temperature in the central tunnel slightly decreases, while the affected longitudinal region expands. This reflects a balance between energy dissipation and enhanced flow redistribution. At Location 7, where the fire source is positioned near the far end of the main tunnel system, the thermal influence on the central tunnel becomes relatively weaker again. The smoke flow primarily propagates longitudinally within the right main tunnel, while lateral diversion is reduced due to the increased distance between the fire source and the nearest cross passage. The left main tunnel remains only marginally influenced throughout the process, indicating that cross-tunnel transmission under natural ventilation is strongly controlled by node proximity.

Overall, when the fire is located in the main tunnel, the temperature response in the three tunnels follows a consistent mechanism: The right main tunnel dominates the thermal field. The central tunnel temperature is governed by lateral diversion intensity at cross passages. The opposite main tunnel shows delayed and attenuated response. The strength of inter-tunnel coupling is therefore primarily controlled by the relative position of the fire source with respect to the cross passages rather than by longitudinal distance alone.

4.2.2 Thermal Characteristics When Fire Is Located in the Central Service Tunnel

Location 5 represents a fundamentally different configuration, as the fire source is positioned inside the central service tunnel rather than in the main tunnel. This change alters the primary smoke propagation pathway and significantly modifies the inter-tunnel coupling behavior.

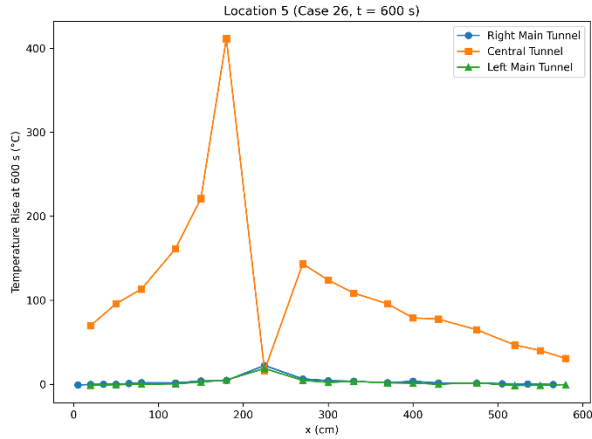


Figure 7 Special Case of Fire Source Located in the Service Tunnel

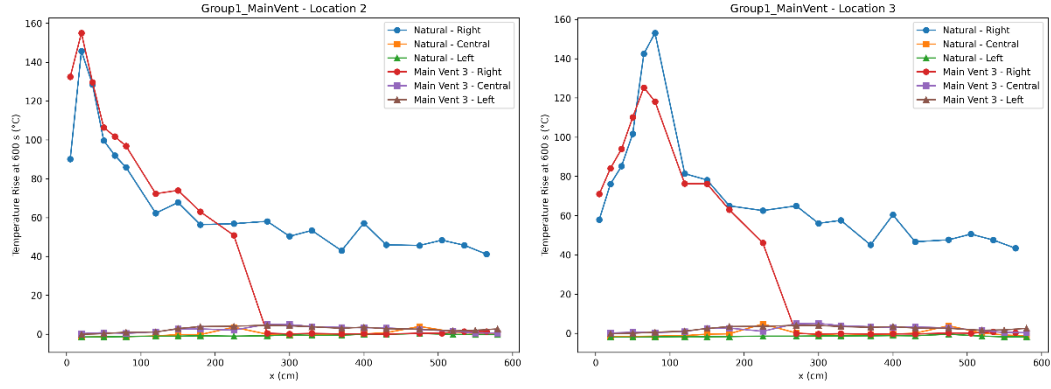
Unlike the previous cases, the central tunnel now exhibits the highest temperature rise, with the thermal peak concentrated near the ignition region. Due to the smaller diameter of the central tunnel and its dead-end configuration, smoke accumulation becomes more intense, resulting in a steeper local temperature gradient compared with the main-tunnel fire cases. The right and left main tunnels display asymmetric thermal responses. Smoke enters the adjacent main tunnels through the cross passages, producing localized temperature increases near the node regions. However, the magnitude of temperature rise in the main tunnels is substantially lower than that observed when the fire originates within the main tunnel itself. This indicates that the lateral transfer of hot gases from a smaller-diameter auxiliary tunnel is less efficient in driving large-scale longitudinal propagation within the main tunnels. Additionally, the temperature curves in the main tunnels show distinct local peaks near the cross-passage positions, followed by rapid attenuation away from the junctions. This pattern confirms that, when the fire is located in the central tunnel, the cross passages act as discrete injection points rather than as continuous coupling channels.

In summary, Location 5 demonstrates a reversed thermal hierarchy compared with the main-tunnel fire scenarios. The central tunnel dominates the thermal field, while the main tunnels behave as secondary receiving channels. This highlights the strong influence of tunnel hierarchy and geometric scale on smoke propagation patterns in Dead-end tunnel systems.

4.3 Influence of Ventilation Modes on System Thermal Stability

4.3.1 Natural Ventilation vs Main Tunnel Ventilation

Under natural ventilation, the temperature distribution along the right main tunnel is governed primarily by buoyancy-driven flow. The temperature peak remains concentrated near the fire source region, and the longitudinal attenuation is relatively smooth. The central tunnel exhibits a moderate temperature rise near the cross-passage region, reflecting lateral smoke diversion induced by pressure redistribution. The left main tunnel shows limited thermal response, indicating weak cross-tunnel transmission under purely buoyant conditions.



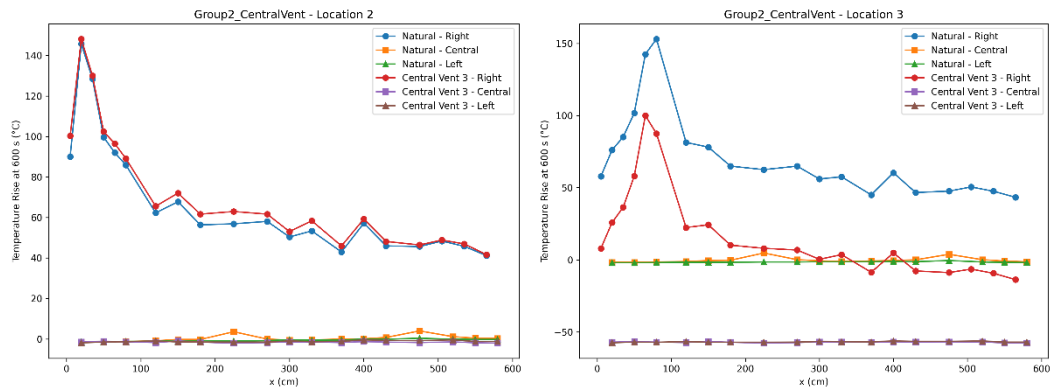
(a) Location 2

(b) Location 3

Figure 8 Natural Ventilation vs Main Tunnel Ventilation

When main tunnel ventilation (Level 3) is applied, the longitudinal thermal structure changes significantly. The temperature peak in the right main tunnel shifts downstream due to enhanced convective transport, while the upstream temperature rise decreases as fresh air entrainment increases. The longitudinal temperature gradient becomes steeper, demonstrating stronger directional flow dominance. Meanwhile, the temperature rise in the central tunnel decreases compared to the natural ventilation case. This indicates that forced longitudinal airflow suppresses lateral smoke diversion through the cross passage by stabilizing the pressure gradient along the main tunnel. The left main tunnel remains weakly affected, confirming that main-tunnel-focused ventilation primarily enhances longitudinal exhaust efficiency rather than promoting inter-tunnel coupling. Overall, main tunnel ventilation improves smoke removal in the fire tunnel but reduces the degree of inter-tunnel thermal interaction.

4.3.2 Effect of Central Tunnel Ventilation (Locations 2 and 3)



(a) Location 2

(b) Location 3

Figure 9 Effect of Central Tunnel Ventilation

Central tunnel ventilation produces a different response mechanism. For both Locations 2 and 3, the temperature within the central tunnel decreases noticeably compared to natural ventilation, confirming that forced airflow effectively mitigates smoke accumulation in the auxiliary tunnel. At Location 2, where node interaction is strongest, central ventilation reduces the temperature peak near the cross passage but does not significantly modify the temperature distribution in the right

main tunnel. This indicates that regulating airflow in the auxiliary tunnel has limited influence on the dominant longitudinal convection in the fire tunnel. At Location 3, the impact becomes even more localized. Since the fire source is positioned farther from the node, the central tunnel receives less smoke intrusion under natural ventilation. Consequently, the relative improvement due to central ventilation is smaller than at Location 2. In summary, central tunnel ventilation acts mainly as a local mitigation strategy, protecting the auxiliary tunnel while exerting limited control over system-wide smoke propagation.

4.3.3 Effect of Combined Ventilation (Locations 2 and 3)

When both the main and central tunnels are ventilated simultaneously, the thermal field exhibits the most stable and uniform distribution among all ventilation configurations. For both Locations 2 and 3, the longitudinal temperature gradient in the right main tunnel becomes steeper, and the upstream temperature accumulation is significantly reduced.

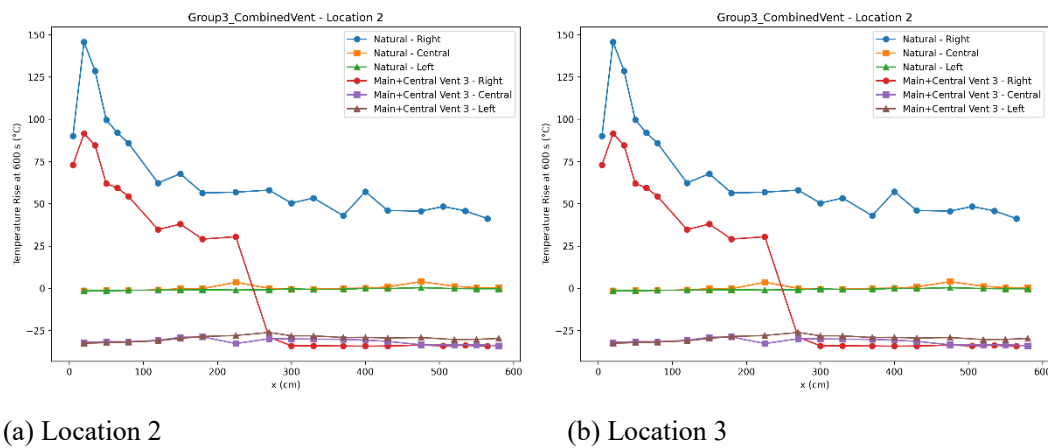


Figure 10 Effect of Combined Ventilation

At Location 2, combined ventilation effectively suppresses lateral smoke exchange at the cross passage. The temperature profiles in the central tunnel become smoother, and localized peaks near node regions diminish. This indicates that coordinated ventilation establishes a more stable pressure field across the tunnel network. At Location 3, the stabilization effect remains evident, although the magnitude of change is slightly smaller compared to Location 2. Since inter-tunnel interaction is inherently weaker at Location 3, the incremental benefit of combined ventilation is less dramatic. Overall, combined ventilation provides the most balanced control strategy, simultaneously enhancing longitudinal smoke removal and minimizing inter-tunnel thermal coupling. The effectiveness of this strategy is particularly significant when the fire source is located near structural nodes.

4.3.4 Summary of Ventilation Effects on Thermal Stability

The comparative analysis of ventilation modes at fire Locations 2 and 3 demonstrates that ventilation configuration fundamentally regulates the balance between longitudinal convection and lateral smoke diversion in the dead-end tunnel system. Main tunnel ventilation primarily enhances axial smoke transport. By strengthening longitudinal momentum, it reduces upstream temperature accumulation and shifts the thermal peak downstream. This mode significantly suppresses inter-tunnel thermal coupling when the fire source is located near structural nodes (Location 2), while the influence becomes less pronounced as the fire moves further from the cross passage (Location 3).

Central tunnel ventilation, in contrast, mainly mitigates thermal accumulation within the auxiliary tunnel. Although it effectively reduces temperature rise in the central tunnel, its influence on the dominant longitudinal propagation in the fire tunnel is limited. The system-wide stabilization effect is therefore moderate and localized.

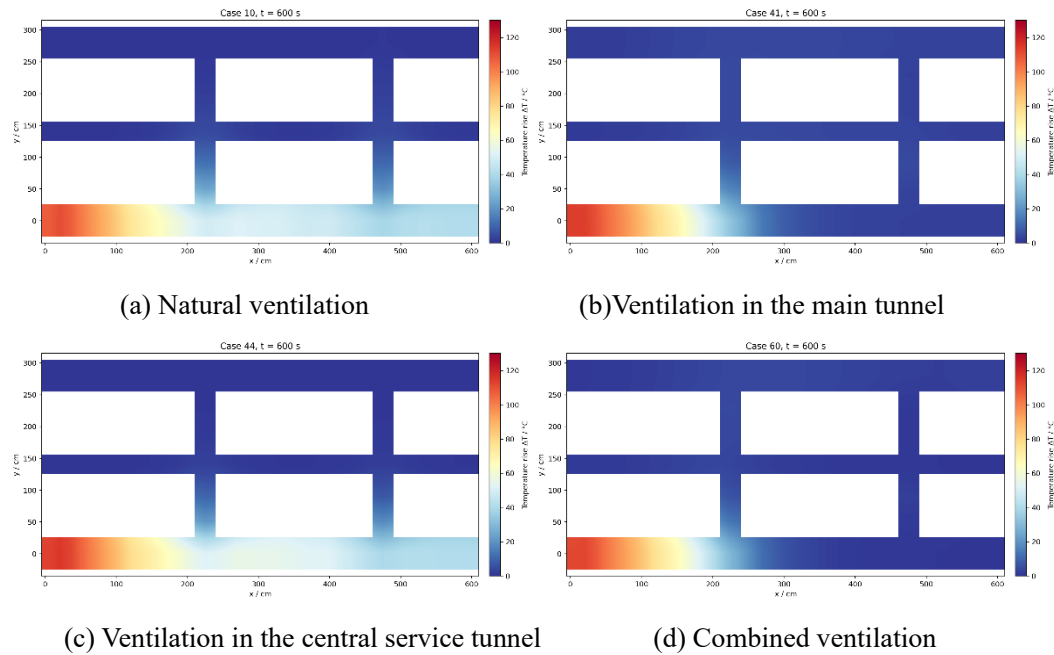
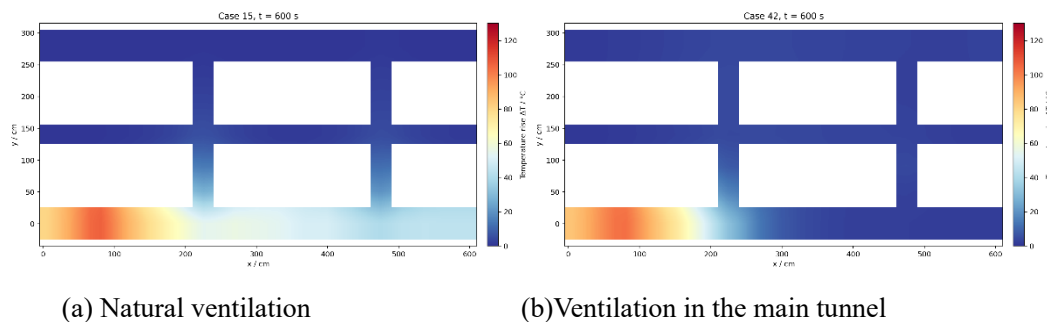


Figure 11 Fire Location 2

Figure 11&12 compares the planar temperature-rise fields at $t=600$ s for fire Locations 2 and 3 under natural ventilation, main-tunnel Level-5 ventilation, central-tunnel Level-5 ventilation, and combined Level-5 ventilation. Under natural ventilation, both fire locations produce the highest temperature rise in the right main tunnel, with the thermal field gradually attenuating in the downstream direction. The central service tunnel and the opposite main tunnel remain relatively weakly heated, although localized temperature increases can be observed near the cross-passage connections. Compared with Location 3, the Location 2 configuration produces a more pronounced thermal response around the first cross-passage, indicating that the shorter distance between the fire source and the structural node enhances lateral smoke diversion and inter-tunnel thermal interaction.



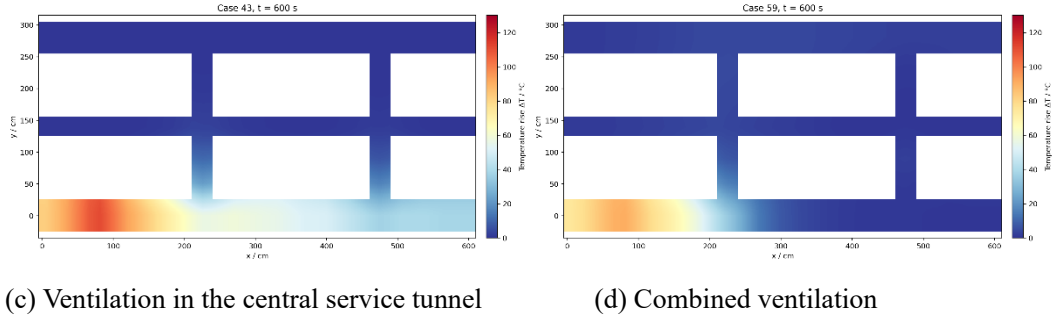


Figure 12 Fire Location 3

The ventilation cases demonstrate that the thermal field is strongly dependent on the ventilation arrangement. Main-tunnel Level-5 ventilation mainly promotes longitudinal transport and reduces thermal accumulation in the fire tunnel, while its influence on the central service tunnel is comparatively limited. Central-tunnel Level-5 ventilation produces a more localized reduction in the auxiliary tunnel and cross-passage regions, but does not substantially alter the dominant temperature distribution in the fire tunnel. The combined Level-5 ventilation configuration provides the most balanced thermal response: it simultaneously suppresses high-temperature accumulation in the fire tunnel and reduces the temperature rise transmitted through the cross passages. This stabilizing effect is more evident for Location 2, where the fire source is closer to the coupling node, whereas the differences among ventilation modes become less pronounced for Location 3. Overall, the heatmaps confirm that effective smoke-control performance depends not only on the ventilation intensity but also on the coordination between longitudinal exhaust and cross-passage pressure redistribution.

Table 5 Summary of Ventilation Modes

Ventilation Mode	Effect on Fire Tunnel (Right)	Effect on Central Tunnel	Inter-Tunnel Coupling	Sensitivity to Fire Location
Natural Ventilation	Smooth decay; dominated	longitudinal buoyancy-temperature near cross passage	Noticeable rise 2; moderate Location 3	High dependence at on node proximity
Main Tunnel Vent	Enhanced transport; upstream accumulation	downstream reduced smoke intrusion	Reduced lateral smoke intrusion	Significantly weakened at Location 2
Central Tunnel Vent	Minor change in main tunnel profile	Effective reduction of auxiliary tunnel temperature	Slight reduction; mostly local effect	Less sensitive to location shift
Combined Vent	Strong exhaust; gradient	longitudinal stabilized temperature profile	Uniform and suppressed temperature profile	Most effectively suppressed
				Stronger improvement at Location 2

Combined ventilation exhibits the most balanced performance. By simultaneously regulating longitudinal flow and cross-passage pressure gradients, it minimizes localized temperature peaks and reduces lateral fluctuation. The stabilization effect is particularly significant at Location 2, where node interaction is strongest. When the fire is positioned further away (Location 3), the relative improvement decreases but remains observable. Overall, ventilation efficiency and system stability are strongly dependent on the relative position of the fire source to the cross-passage nodes.

Coordinated ventilation strategies provide the most effective means of controlling thermal redistribution in multi-tunnel systems.

4.4 Quantitative Evaluation of Lateral Smoke Diversion

4.4.1 Definition of the Lateral Smoke Diversion Ratio

To quantitatively characterize the inter-tunnel thermal interaction in the dead-end tunnel system, a lateral smoke diversion ratio is introduced. This parameter represents the proportion of thermal energy redistributed from the fire tunnel into adjacent tunnels through cross passages.

At a given time t , the lateral diversion ratio toward the central tunnel is defined as:

$$\eta_c(t) = \frac{\int_0^L \Delta T_c(x, t) dx}{\int_0^L \Delta T_r(x, t) dx} \quad (4 - 1)$$

this study, the diversion ratios are evaluated at $t=600$ s, corresponding to the quasi-stable stage of fire development indicates stronger lateral smoke transfer and more intense inter-tunnel coupling, whereas a lower value implies dominant longitudinal transport and reduced cross-passage interaction.

4.4.2 Diversion Ratio under Different Ventilation Modes

The diversion ratios were calculated for fire Locations 2 and 3 under different ventilation configurations, including: Natural ventilation Main tunnel ventilation , Central tunnel ventilation , Combined ventilation. Under natural ventilation, the diversion ratio reaches its highest value at Location 2. Because the fire source is positioned close to the cross passage, buoyancy-driven pressure redistribution promotes strong lateral smoke transfer into the central tunnel. At Location 3, the diversion ratio decreases due to increased longitudinal transport distance and thermal attenuation before reaching the node.

The imposed longitudinal airflow stabilizes axial pressure gradients and reduces the pressure difference across the cross passage, thereby suppressing lateral inflow. This suppression effect is particularly evident at Location 2, where natural coupling is strongest.

Table 6 Parameter Comparison

Ventilation Mode	Case ID	η_c (Central Tunnel)	η_l (Opposite Tunnel)
Natural Ventilation	10	0.00743	0.00027
Main Vent	40	0.03991	0.04498
Central Vent	45	0.02313	0.00223
Main + Central Vent	56	0.00925	0.00047

Under central tunnel ventilation, the diversion ratio also decreases, but the reduction is moderate. While forced airflow in the central tunnel limits smoke accumulation, it does not fundamentally alter the dominant longitudinal convection in the fire tunnel. Combined ventilation yields the lowest diversion ratio among all configurations. By simultaneously enhancing longitudinal exhaust and regulating cross-passage pressure balance, it minimizes inter-tunnel thermal redistribution. The

reduction effect is more pronounced at Location 2 than at Location 3, confirming that ventilation efficiency depends strongly on node proximity.

4.4.3 Comparative Discussion and Mechanistic Interpretation

The calculated diversion ratios at Fire Location 2 reveal distinct and non-intuitive differences among ventilation modes. In contrast, central tunnel ventilation effectively suppresses lateral diversion. By actively extracting airflow within the auxiliary tunnel, this configuration reduces the pressure-driven inflow from the fire tunnel, thereby mitigating cross-passage exchange. Although this mode has limited influence on the dominant longitudinal transport in the fire tunnel, it successfully protects the auxiliary tunnel from thermal intrusion. The combined ventilation mode exhibits the most stable behavior, with diversion ratios approaching zero. Simultaneous regulation of axial and lateral pressure gradients minimizes cross-node imbalance and prevents uncontrolled smoke redistribution. This coordinated control strategy achieves both enhanced longitudinal exhaust efficiency and effective suppression of inter-tunnel coupling. These findings demonstrate that lateral smoke diversion is not monotonically reduced by increasing ventilation intensity. Instead, the redistribution of thermal energy depends critically on how ventilation modifies the pressure balance within the dead-end system. Mechanical ventilation confined to a single tunnel may amplify cross-node exchange, whereas coordinated multi-tunnel ventilation provides the most effective stabilization.

From a fire safety perspective, the diversion ratio serves as a quantitative indicator of inter-tunnel coupling strength. The results suggest that ventilation strategies should be designed based on node proximity and pressure coordination rather than relying solely on longitudinal exhaust capacity.

5 Conclusions

This study experimentally investigated the thermal behavior of a dead-end tunnel system based on a 1:30 scaled physical model of the Tianshan Victory Tunnel. A total of 62 temperature measurement points were arranged across three parallel tunnels connected by cross passages. A series of small-scale fire experiments were conducted under varying fire source locations and ventilation configurations. The temperature evolution at 600 s after ignition was analyzed, and a lateral smoke diversion ratio was introduced to quantitatively evaluate inter-tunnel thermal coupling. Based on the experimental results and quantitative analysis, the following conclusions can be drawn:

(1) Fire location relative to cross passages governs inter-tunnel thermal coupling. When the fire source is positioned near a cross passage, lateral smoke diversion significantly increases, resulting in stronger thermal interaction between tunnels. As the fire source moves away from node regions, longitudinal attenuation becomes dominant and inter-tunnel coupling weakens. Therefore, node proximity rather than absolute longitudinal distance is the primary geometric factor controlling smoke redistribution.

(2) Single-tunnel mechanical ventilation may intensify lateral smoke diversion under certain conditions. Main tunnel ventilation enhances longitudinal airflow but can increase cross-passage pressure differences, thereby amplifying lateral smoke transfer into adjacent tunnels. This finding indicates that increasing ventilation intensity in a single tunnel does not necessarily suppress inter-tunnel coupling and may unintentionally aggravate thermal redistribution when the fire is located

near structural nodes.

(3) Coordinated multi-tunnel ventilation effectively suppresses inter-tunnel coupling and stabilizes the thermal field. Simultaneous regulation of airflow in both the main and auxiliary tunnels significantly reduces the lateral smoke diversion ratio. Combined ventilation establishes a more balanced pressure distribution across the network and minimizes localized temperature peaks. This strategy provides the most effective control of smoke propagation in complex multi-branch tunnel systems.

Overall, the introduction of the lateral smoke diversion ratio provides a quantitative framework for evaluating inter-tunnel thermal interaction. The findings offer mechanistic insight and practical guidance for ventilation design and fire safety control in large-scale, dead-end tunnel infrastructures.

Acknowledgements

This work is supported by Beijing Natural Science Foundation (L259032) and National Natural Science Foundation of China (52374210), and the beneficiary are Chang Liu, Rongliang Pan, Junfeng Chen, Huihang Cheng, Wenshan Yang.

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