engineering proceedings

MDPI

Proceeding Paper

Study on Synergistic Smoke Control Using Opposite Jet in the Main Tunnel and Point Smoke Extraction in the Branch Tunnel of an Inclined T-Shaped Tunnel †

Fang Liu [1,2], Jianing Wang [1], Miaocheng Weng [1,2,*] and Kaiwen Ling [1]

[1] School of Civil Engineering, Chongqing University, Chongqing 400045, China; fangliu@cqu.edu.cn (F.L.); wjianing0222@126.com (J.W.); kwling1999@163.com (K.L.)
[2] Key Laboratory of New Technology for Construction of Cities in Mountain Area of Ministry of Education, Chongqing 400045, China
* Correspondence: mcweng@126.com
† Presented at the 7th International Conference on Civil, Architecture and Disaster Prevention and Control, Dali, China, 30 January–1 February 2026.

Abstract

The complex structure of inclined T-shaped tunnels significantly increases the difficulty of smoke exhaust and rescue operations. This study aimed to investigate the effects of fire source location, bifurcation angle, and opposite jet velocity on smoke control in the opposite jet side. Meanwhile, the smoke flow characteristics were examined during synergistic operation. The results show that the smoke spread length on the opposite jet side approaches a minimum when the opposite jet velocity reaches 1.5 m/s. A smaller bifurcation angle results in a longer smoke spread length. The smoke propagation length downstream of the bifurcation zone is independent of the fire source location. Under synergistic smoke control, optimal extraction performance is achieved when exhaust vent is positioned near the bifurcation zone of the branch tunnel. A prediction model is proposed between the branch tunnel ceiling temperature decay patterns and the exhaust volume during synergistic smoke control in inclined T-shaped tunnels, ensuring both economic efficiency and safety in real-world applications.

Keywords: inclined T-shaped branch tunnel; smoke control; opposite jet smoke exhaust system; point smoke extraction

1. Introduction

The branch tunnel is a key part of urban traffic link tunnels (UTLTs) [1]. Due to the greater possibility of fire at the tunnel bifurcation, it is easy for the smoke to spread into the connected tunnel [2]. In recent decades, smoke control in tunnel fires has attracted strong attention from scholars [3–5].

Xiao et al. [6] found that the smoke spread distance was influenced by the coupling effect of the heat release rate, opposite jet velocity and the fire source location. Hou et al. [7] investigated the mechanism of smoke plug-holing phenomena under synergistic operation between a centralized smoke exhaust and opposite jet system, identifying critical thresholds for the Froude number and exhaust rate coefficient. Chen et al. [8] discovered that the stability of fire smoke stratification is inversely proportional to the magnitude of the upstream–downstream velocity difference. The above research indicates that the opposite jet system can effectively control smoke spread in single-bore tunnels. However, when the

Check for updates

Academic Editor: Mohamed Abdelkader Ismail

Published: 2 September 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

opposite jet system is used in the main tunnel, the smoke will inevitably invade the branch tunnel [9]. Therefore, it is imperative to investigate the smoke diffusion characteristics and smoke exhaust strategy in the branch tunnel when the main tunnel is using the opposite jet system.

In this study, the influence of different fire source locations on smoke spread was examined through numerical simulations, bifurcation angles, and opposite jet velocities. In addition, under the precondition of ensuring a safe evacuation environment in the main tunnel, it focused on the smoke exhaust effectiveness of different smoke exhaust schemes and exhaust volumes in the branch tunnel in the most dangerous scenario. Finally, a predictive model for the ceiling temperature decay pattern in the branch tunnel under different exhaust volumes was developed.

2. Numerical Simulation

2.1. Model Design and Measurement Point Layout

In the FDS model, the main tunnel had the dimensions of 110 m × 10 m × 5 m (L × W × H). The branch tunnel had dimensions of 40 m × 7 m × 5 m (L × W × H). The fire source size was 1.5 m × 1.5 m. The arrangement of thermocouples, fire source location and exhaust vent is shown in Figure 1. Near the fire source, the thermocouples were arranged at an interval of 1 m, while in the remaining sections, the interval was 2 m. Each exhaust vent size was 1.6 m × 1.6 m. All thermocouples were positioned 0.2 m below the ceiling.

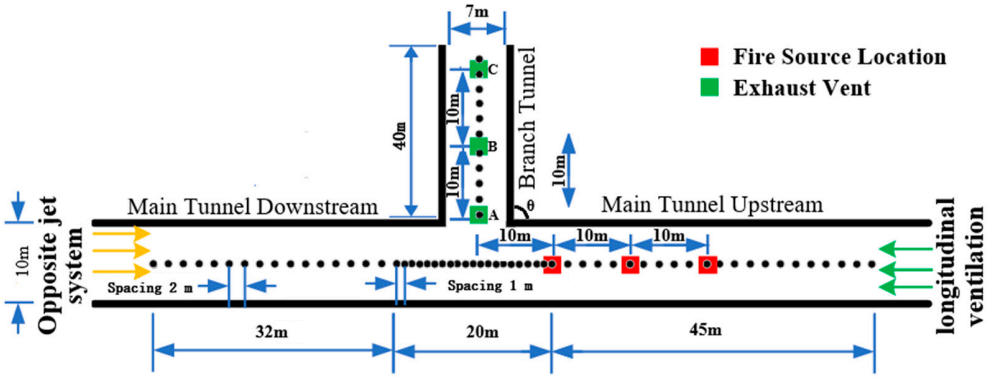

Figure 1. Schematic diagram of thermocouple, fire source, and exhaust vent locations.

2.2. Experimental Condition Settings

As UTLTs primarily accommodate cars, the heat release rate was selected as 5.0 MW The upstream air velocity was determined to be 2 m/s based on the prediction model established by Weng et al. [10]. The test conditions are summarized in Table 1.

Table 1. Simulation conditions for opposite jet smoke exhaust system.

Case	Upstream Velocity (m/s)	Opposite Jet Velocity u_x (m/s)	Bifurcation Angle θ (°)	Fire Source Offset from Center X (m)
A1–15	2	1, 1.5, 2, 3, 4	90°	10, 20, 30
A16–30	2	1, 1.5, 2, 3, 4	60°	10, 20, 30
A31–45	2	1, 1.5, 2, 3, 4	30°	10, 20, 30

Table 2 shows the simulation conditions for adding point smoke extraction in the branch tunnel. The exhaust volume was calculated as 20 m^3/s with the formula developed by Heskestad [11].

Table 2. Simulation conditions for point smoke extraction in the branch tunnel.

Case	Exhaust Volume V (m^3/s)	Branch Tunnel Point Smoke Extraction Schemes
B1	20	Only open vent P1
B2		Only open vent P2
B3		Only open vent P3
B4		Open all vents P1, P2, P3
B5	10, 12, 14, 16, 18	Most effective exhaust case (Only open vent P1)

3. Results and Analysis

3.1. Analysis of Smoke Spread Length on the Opposite Jet Side

Figure 2 shows the length of smoke spread on the opposite jet side under different opposite jet velocities. As the opposite jet velocity exceeds 1.5 m/s, the smoke spread length tends to be stable. When the fire source location and opposite jet velocity are fixed, the smoke spread length decreases as the bifurcation angle increases. This is due to the fact that the increased angle lowers flow resistance, diverting more smoke into the branch tunnel. Additionally, the smoke spread length decreases as distance from fire source to bifurcation decreases, meaning more hot smoke invokes the branch tunnel.

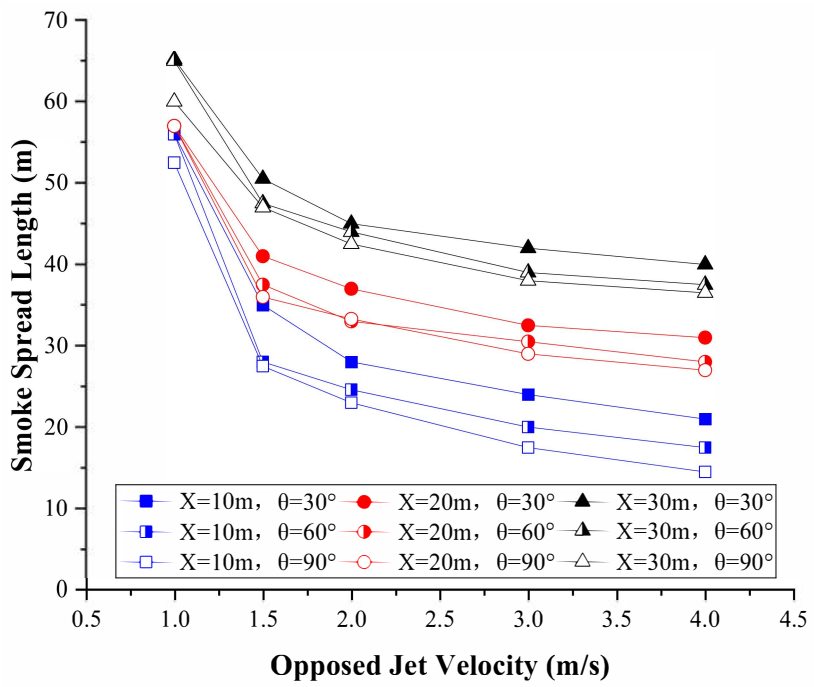

Figure 2. Smoke spread length on the opposite jet side under different opposite jet velocities.

3.2. Analysis of Smoke Flow in the Branch Tunnel

From Section 3.1, the most dangerous scenario for the branch tunnel is the fire scenario with $\theta = 90°$, $u_x = 1.5$ m/s, and $X = 10$ m. Therefore, the branch tunnel point smoke extraction schemes will be applied under this fire scenario. Figure 3 shows the ceiling temperature distribution of the branch tunnel. When only vent P2 or P3 opens, the temperature before the exhaust vent is similar to the case without exhaust, while the temperature downstream of the vent decreases significantly. When only vent P1 or all vents open, the temperature decreases significantly. Compared to opening all vents, the smoke extraction effect is better when only vent P1 opens. This is because the smoke and cold air are not fully mixed at the branch tunnel entrance, exhibiting stability. Therefore, the P1 exhaust vent can effectively remove hot smoke.

https://doi.org/10.3390/engproc2026146021

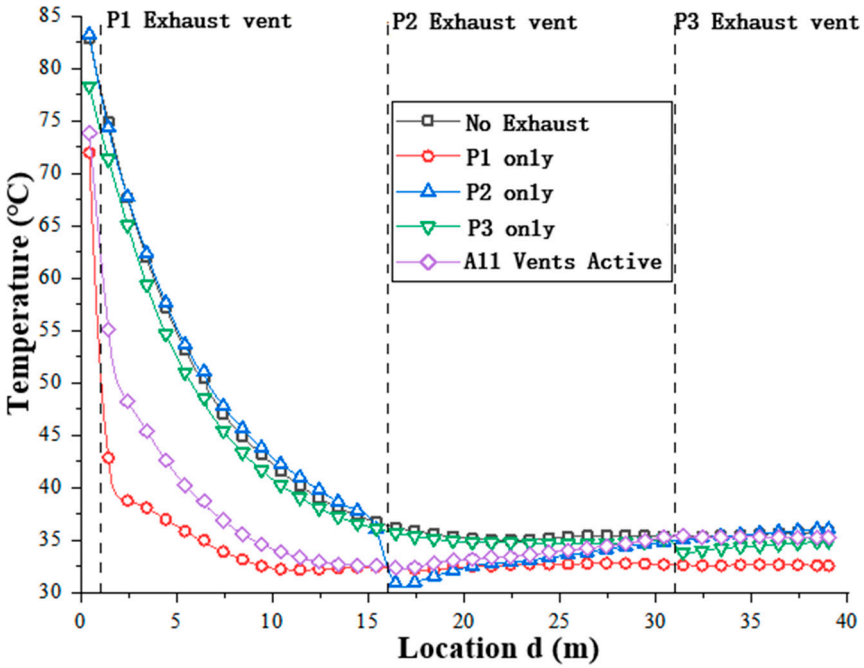

Figure 3. Ceiling temperature distribution of the branch tunnel.

3.3. Influence of Different Exhaust Volumes on Smoke Flow in the Branch Tunnel

This section further analyzes the exhaust effectiveness under different exhaust volumes when opening only vent P1 and examines the ceiling temperature distribution pattern in the branch tunnel. Figure 4 shows the ceiling temperature distribution under different exhaust volumes. This suggests that increasing the exhaust volume from 10 m^3/s to 16 m^3/s progressively lowers the branch tunnel ceiling temperature, but further increases to 18–20 m^3/s show abnormal temperature rises due to excessive induced velocity.

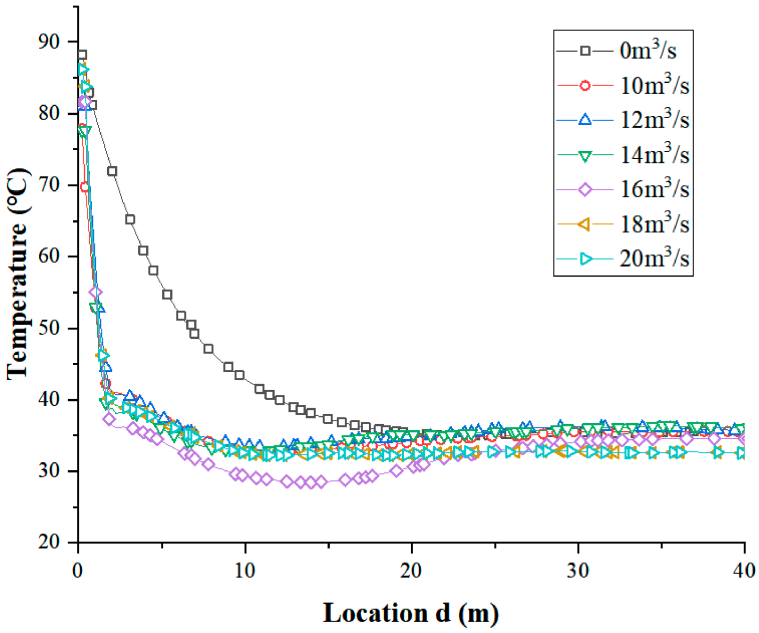

Figure 4. Ceiling temperature distribution under different exhaust volumes.

https://doi.org/10.3390/engproc2026146021

As established in the existing literature [12], the temperature decay model caused by smoke spreading along the tunnel can be generalized using the following relationship:

$$\frac{\Delta T_x}{\Delta T_{max}} = Ae^{\frac{Bx}{H}} + Ce^{\frac{Dx}{H}} \quad (1)$$

where ΔT_x is the temperature rise (K), ΔT_{max} is defined as the temperature increase at the location of maximum temperature above the fire source (K), x is defined as the distance from the fire source (m), H is the height from the fire surface to the tunnel ceiling (m), and A, B, C, and D are coefficients to be fitted. Therefore, a predictive model is developed in this study to estimate the ceiling temperature decay in the branch tunnel. The model, taking the branch tunnel entrance as its reference point, accounts for the effect of different exhaust volumes. Considering economy and safety, no fitting is performed for exhaust volumes greater than 16 m^3/s.

Table 3 shows the fitting coefficients for the branch tunnel ceiling temperature decay model. The coefficient of determination R^2 is greater than or equal to 0.95, which suggests that the model can effectively predict the ceiling temperature decay.

Table 3. Fitting coefficients for the ceiling temperature decay model.

Exhaust Volume (m^3/s)	*A*	*B*	*C*	*D*	R^2
10	0.45	0.001	0.60	−2.55	0.95
12	0.44	0.005	0.67	−3.9	0.95
14	0.42	0.0058	0.75	−4.45	0.97
16	0.41	0.0065	0.81	−5.62	0.96

The predictive model for the branch tunnel ceiling temperature decay can be obtained, as shown in Equation (2). As shown in Figure 5, the experimental data agree well with the predictive model, with most errors within 10%, and the results confirm that Equation (2) can reliably predict the ceiling temperature decay pattern in the branch tunnel.

$$\frac{\Delta T_x}{\Delta T_{max}} = (-0.008V + 0.53)exp(\frac{(0.001V - 0.01)x}{5}) + (0.035V + 0.25)exp(\frac{(-0.5V + 2.25)x}{5}) \quad (2)$$

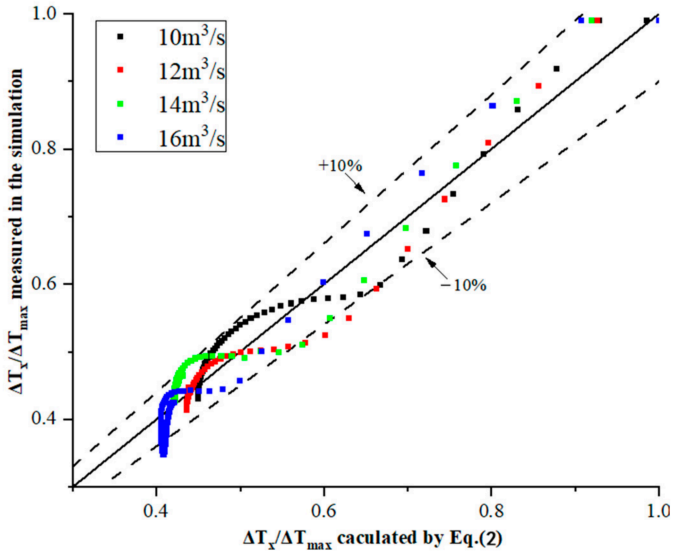

Figure 5. Comparison of measured and predicted values for branch tunnel ceiling temperature.

4. Conclusions

This study addressed the challenge of fire smoke control in inclined T-shaped tunnels by proposing a cooperative smoke control system. The principal findings include:

(1) When the opposite jet velocity exceeds 1.5 m/s, the smoke spread length tends to be stable. A smaller bifurcation angle results in a longer spread length. As the distance from fire source to bifurcation center increases, the smoke spread length also increases.

(2) When only the exhaust vent at the branch tunnel entrance (P1) is open, the ceiling temperature significantly decreases under all cases, achieving optimal smoke exhaust effectiveness. Other schemes (opening P2, P3, or all vents) are less effective and may even cause abnormal local temperature increases in the branch tunnel due to induced air velocity.

(3) Increasing the exhaust volume from 10 m^3/s to 16 m^3/s progressively lowers the branch tunnel ceiling temperature, but further increases to 18–20 m^3/s show abnormal temperature rises due to excessive induced velocity. Finally, a prediction model for the relationship between the ceiling temperature decay pattern and the exhaust volume under cooperative smoke control was proposed.

Author Contributions: Conceptualization, F.L. and M.W.; methodology, F.L.; validation, J.W. and K.L.; investigation, K.L.; resources, F.L.; data curation, J.W.; writing—original draft preparation, J.W.; writing—review and editing, M.W.; supervision, F.L.; project administration, F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 52178064), Chongqing Science and Technology Commission (Grant No. cstc 2021jcyj-msxmX0677, CSTB2022TIAD-KPX0101), and Chongqing Construction Science and Technology Planning Project (Grant No. 2021(5-8)).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Liu, Y.; Yang, D.; Xiao, Y.; Mao, S.; Yang, M. Combining diverse driving forces for smoke control in complex urban traffic link tunnels (UTLTs) using one-dimensional flow modelling. *Sustain. Cities Soc.* **2018**, *43*, 265–274. [CrossRef]
2. Zhang, X.; Ma, W.; Tao, L.; Zeng, Y.; Wen, Y. Smoke control and temperature distribution of tunnel fires under longitudinal ventilation combined with shaft exhaust. *Case Stud. Therm. Eng.* **2025**, *65*, 105365. [CrossRef]
3. Li, X.; Yang, Y. Study on the Influence of Smoke Vent Arrangement on the Natural Smoke Exhaust Effect in Urban Traffic Link Tunnels. *Fire* **2025**, *8*, 49. [CrossRef]
4. Li, X.; Zhu, G.; He, L. Study on the smoke mass flow in T-shaped tunnel fire. *Case Stud. Therm. Eng.* **2024**, *61*, 104848. [CrossRef]
5. Shi, Y.; Qian, S.; Zhao, P.; Guo, P.; Gao, Z. Influence of smoke exhaust volume and smoke vent layout on the ceiling centralized smoke exhaust effect in tunnel fires. *Fire* **2024**, *7*, 78. [CrossRef]
6. Xiao, Z.; Yang, Y.; Zhang, X. Study on fire smoke control in combination mode of opposite jet and shaft exhaust in highway tunnel. *Fire Sci. Technol.* **2020**, *39*, 344–347.
7. Hou, Y.; Wang, Y.; Qiao, B. The Influence of Smoke Exhaust Power of Tunnel Opposite Jet on the Phenomenon of Inhalation and Penetration. *Sci. Technol. Eng.* **2025**, *25*, 6136–6145. [CrossRef]
8. Chen, S.; Yang, Y.; Zhang, X. Study on stratified stability of smoke in tunnel under the action of opposite jet and shaft. *Fire Sci. Technol.* **2021**, *40*, 1438–1442.
9. Chen, L.; Mao, P.; Zhang, Y.; Xing, S.; Li, T. Experimental study on smoke characteristics of bifurcated tunnel fire. *Tunn. Undergr. Space Technol.* **2020**, *98*, 103295. [CrossRef]

10. Weng, M.; Lu, X.; Liu, F.; Du, C. Study on the critical velocity in a sloping tunnel fire under longitudinal ventilation. *Appl. Therm. Eng.* **2016**, *94*, 422–434. [CrossRef]
11. Heskestad, G. Fire plumes, flame height, and air entrainment. In *SFPE Handbook of fire Protection Engineering*; Springer: New York, NY, USA, 2016; pp. 396–428. [CrossRef]
12. Ingason, H.; Li, Y.Z. Model scale tunnel fire tests with longitudinal ventilation. *Fire Saf. J.* **2010**, *45*, 371–384. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.