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Study on Performance of Coordinated Ventilation Strategies during T-Shaped Subway Station Hall Fire

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Abstract: A subway transfer station hall is crowded and complex in structure, which makes evacuation more difficult in case of a fire, but also provides more strategic options for smoke extraction. Full-scale experiments and numerical simulations are conducted to investigate the feasibility and performance of coordinated ventilation in a T-shaped transfer station hall, accounting for different fire source locations, ventilation modes, and fire shutter operations. It is found that the optimal ventilation strategy varies based on the fire location within the T-shaped configuration. For fires on the 'T's horizontal side, lateral airflow from longitudinal fans can effectively disrupt smoke spreading, with coordinated extraction strategies outperforming the traditional methods. However, for fires on the 'T's longitudinal side, horizontal fans are ineffective in controlling smoke flow, making the traditional fire shutter closure optimal. The idea of dispersing hot smoke to a reasonable degree can create better evacuation conditions for people near a fire, while creating almost no new danger zones.

Keywords: subway station hall fire; full-scale experiments; coordinated ventilation; smoke propagation characteristics; fire safety

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1. Introduction

With the acceleration of urbanization, the subway, as an important part of the modern urban transportation system, carries many passengers and has become one of the important symbols used to measure the degree of urban modernization [1–5]. However, as the subway network continues to expand and the number of transfer nodes increases, fire safety issues at transfer stations have gradually become a critical factor affecting subway safety [6–9]. A T-shaped transfer station has a typical multi-layer design, where the process of smoke diffusion in fire scenarios is complex. The extraction system of a station hall and each platform has a variety of combined smoke extraction modes, but the optimization of these smoke extraction modes under different fire conditions remains to be studied. In a subway station fire scenario, high-temperature smoke has the potential to suffocate pedestrians and reduce visibility, which has an important impact on the safe evacuation of personnel [10–15]. Therefore, it is crucial to control and effectively extract smoke within the station.

In recent years, researchers have carried out extensive studies on subway fire smoke and discussed the generation mechanism, the flow patterns, and the control measures of smoke [15–20]. Long et al. [21] investigated the effects of different ventilation methods under fire scenarios through numerical simulation and optimized the collaborative mode of the ventilation system in subway stations. This collaborative mode is crucial for preventing the spread of smoke and reducing the concentration of pollutants. Long et al. [22] studied the effects of fire location and the heat release rate on subway platforms, conducted a series of numerical simulations under natural ventilation conditions, and proposed a model for predicting the height of the smoke layer. Chen et al. [23] used numerical simulations to study airflow velocity distribution and the critical conditions for smoke control in a stairwell area. The study encompassed a range of flow mechanisms, from pure buoyancy flow to forced convection flow, with the objective of providing a theoretical foundation for the accurate control of smoke in subway stations. Chen et al. [24] investigated how rectangular obstacles affect temperature distribution on the ceiling, the vertical temperature profile, and the airflow dynamics in subway station fire scenarios. They conducted both small-scale experiments and simulations, exploring various factors, such as the fire source location, the heat release rate, the blockage level, and obstacle placement. Cong et al. [25] conducted a series of 1:3 reduced-scale experimental tests to examine the smoke temperature characteristics in a train carriage within a longitudinally ventilated tunnel under various fire sizes and ventilation rates. Subsequently, the smoke temperature characteristics under varying HRRs and ventilation velocities were elucidated. Liu et al. [26] studied the critical wind speed (minimum wind speed) on a landing to prevent smoke from spreading from the platform through the landing to the upper floor in the case of a platform fire through theoretical analysis and a series of CFD simulations.

However, there are relatively few studies on the diffusion and extraction modes of smoke in T-shaped transfer station fires. Zhou Feng [27] proposed corresponding fire separation measures based on the standard requirements for a situation in which the side platform of a large subway transfer station is on the same floor as the common station hall. They also analyzed the possible problems in the corresponding smoke extraction control mode of the side platform. Xie et al. [28] proposed control measures for the aspects of fire separation and smoke control in view of large common station halls in large subway transfer stations. By using the FDS numerical simulation method, it was concluded that the fire and the smoke spread area can be effectively controlled by using the secondary drop mode of the fire shutter. Yuan et al. [29] studied the influence of two smoke extraction modes on the mechanical smoke extraction effect of a station floor when the station floor is on fire. The authors concluded that all the smoke control zones of the station floor had to be opened for smoke extraction. In addition, a small number of papers used equal-scale models to study flue gas. Cheng et al. [30] employed a 1:10 scale fire model to investigate fire smoke diffusion in the transfer channels of multi-line subway stations. They conducted fire experiments under various conditions in the transfer channels, analyzing factors such as ceiling temperatures and the extent of smoke spread. Chen et al. [31] designed a fire scene based on a 1:10 scale fire experimental model of a subway multi-line interchange station. They obtained an optimal smoke evacuation scheme for a fire at a station hall and the platform of a cross-interchange station in dangerous locations.

In full-scale experiments, the laws of smoke diffusion and ventilation modes in subway tunnels have received significant attention from researchers. Weng et al. [32] investigated the rate at which temperature decreases along the tunnel ceiling and examined the smoke control strategies in a single-portal tunnel with one opening. The simulation results demonstrated that the smoke temperature and the decay rate of temperature distribution on the tunnel ceiling along the longitudinal direction increased as the HRR increased. Qin et al. [33] simulated evacuations in special subway stations. They analyzed evacuation scenarios by setting up fire scenarios and changing the ventilation rates in the station. The evacuation pressure was found to be predominantly concentrated at the stairways, with the exit widths demonstrating a minimal impact on pressure mitigation. Long et al. [34] conducted a full-scale experiment in a double-island subway station to study smoke movement and ventilation effects under different ventilation conditions during a fire. Liu et al. [35] also conducted full-scale experiments and numerical simulations of a hub station, analyzing temperature dispersion under these scenarios.

Despite extensive research, due to the complexity and unpredictability of subway systems and the unpredictability of fire occurrences, the study of subway smoke primarily relies on numerical simulations of scaled models. Therefore, by combining previous research and the through comprehensive analysis of numerical simulation experiments and on-site full-scale experiments, this paper aims to deeply explore how to prevent and control subway smoke under special circumstances such as fire shutter failure, providing scientific basis and technical support for improving subway fire safety.

2. Full-Scale Experiments and Numerical Setup

2.1. Experimental Setup

2.1.1. Overview

As shown in Figure 1, the station hall as a whole is T-shaped. Metro Line 8 runs transverse to the left side, and Line 10 runs vertical to the right side. There are 3 exits for Line 8 and 2 exits for Line 10. Celling smoke barriers have been installed in the middle of the station halls of both lines, dividing the public area into two smoke compartments.

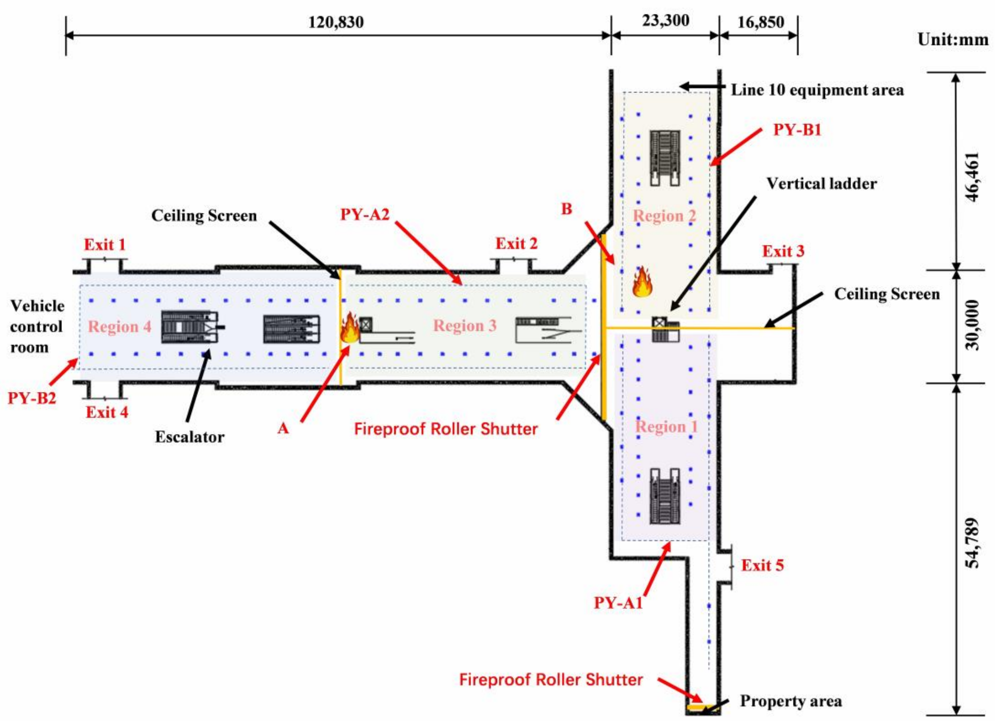


Figure 1. A perspective view of the station hall.

At the Line 8 station, the public area of the station hall is 3000 m^2, divided into two smoke compartments. Smoke extraction fans in the public area were independently installed in the smoke extraction fan room at both ends of the station with an air volume of 130,000 m^3/h and a full pressure of 1000 Pa, and the air extraction duct of the air conditioning system doubles as a smoke extraction duct.

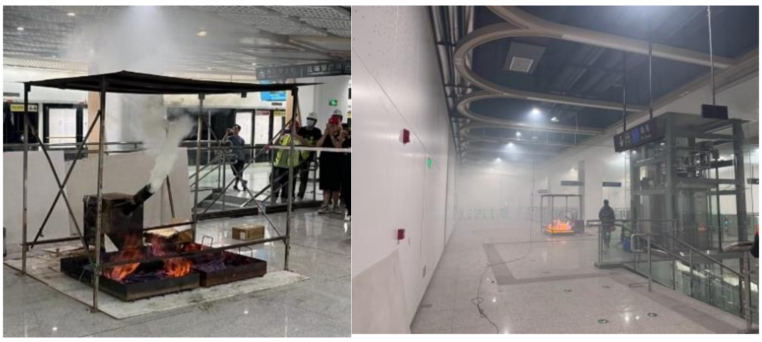
At the Line 10 station, the public area of the station hall is 3500 m^2, divided into two smoke compartments. Smoke extraction fans in the public area were also independently installed in the smoke extraction fan room at both ends of the station with an air volume 151,200 m^3/h and a full pressure 1200 Pa. More details on smoke compartments and fans for the station hall are listed in Table 1. In the following section, we refer to smoke compartment ID 1–4 as Regions 1–4.

Table 1. Mechanical ventilation system configuration.

Smoke Compartment ID	Smoke Compartment Area (m^2)	Designed Exhaust Flow Rate (m^3/h)	Air Volume of Exhaust Fan (m^3/h)
1	1500	90,000	130,000
2	1500	90,000	130,000
3	1750	105,000	151,200
4	1750	105,000	151,200

2.1.2. Fire Source Design

Methane pool fires are used to simulate baggage fires in this experiment, with a typical power of 1.5 MW [36]. According to a study by Zhang et al. [37], fire is more likely to occur in crowded and narrow space areas, such as stairs and entrances in subway stations. Therefore, an experimental fire source device (manufactured by China Academy of Safety Science and Technology, Beijing, China) was set near the middle stair in of the station hall, and the layout location is shown in Figure 2. A smoke generator near the fire source was set up near the oil pans to produce white smoke to show the flow process of hot gas and evaluate its diffusion range. In order to protect the station facilities above the fire source, a protection frame was deployed at the fire source, which was hollow on all sides and only shielded by an iron plate with the approximate size of 2 m × 1.8 m on the top. Compared to the scale of the station hall, the protection frame is small enough to ignore its effect on smoke flow (as shown in Figure 2b).



(**a**) (**b**)

Figure 2. Fire source system and T-shaped station hall diagram: (**a**) Fire source system, (**b**) Fire and smoke in station hall.

A rectangular oil basin with the size of 1.682 m × 1.190 m was used to contain fuel to produce fire, with a maximum heat release rate (HRR) of 1.5 MW. Fire power was calculated using

$$Q = \varphi \Delta M H \tag{1}$$

where Q is the HRR, kJ/s, φ the combustion efficiency factor, ΔM the fuel mass loss rate, g/s, and H is the calorific value of fuel, kJ/g. Since the station hall is much larger than the fire source area in this experiment, the fire source was fully burned, and the combustion efficiency factor was assumed to be 1. The mass loss rate was actually measured in the experiment, and the heat release rate (HRR) is depicted in Figure 3.

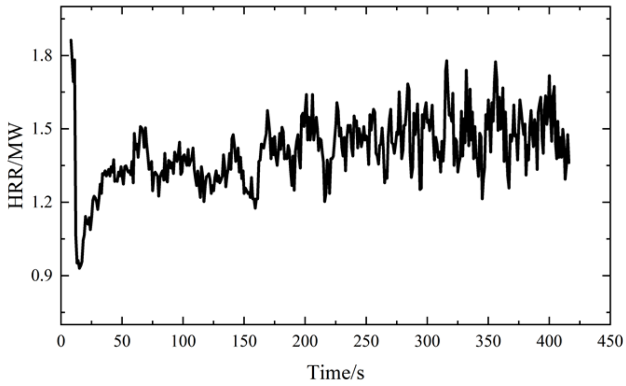
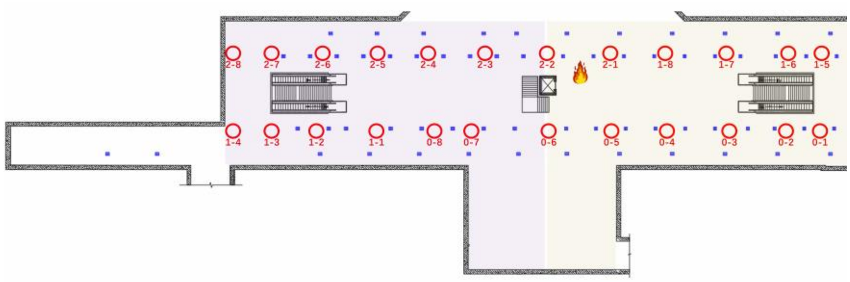


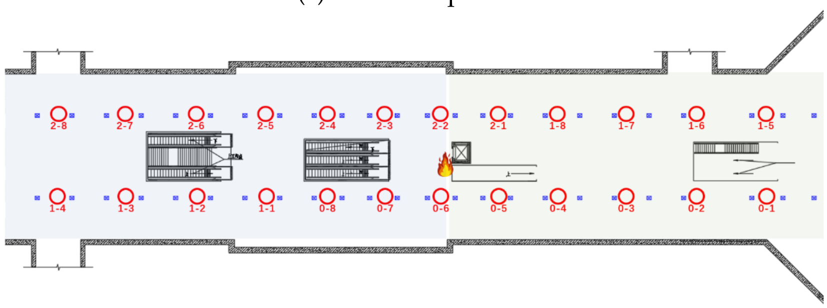
Figure 3. Heat release rate in experiment.

2.1.3. Experimental Conditions and Temperature Measurement Arrangement

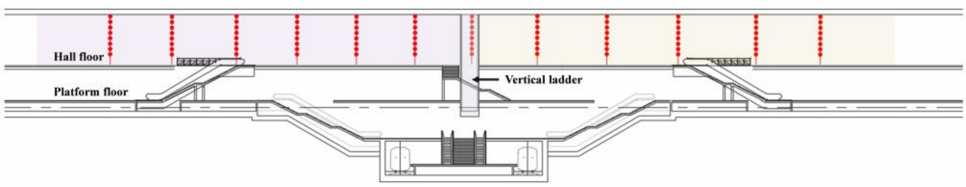
A fire source was established in the station hall, and a series of experiments were conducted with a fire source scale of 1.5 MW, the fire shutter lowered, three fans (PY-A1, B1, and B2) turned off, and PY-A2 operating in forward mode. A number of thermocouple strings with a measuring range of 0~127 °C were hung from the ceiling to measure temperatures at different locations and heights. The fire location and the arrangement of thermocouple strings are shown in Figure 4. Each string contains 8 thermocouples with an equal distance of 0.5 m, and the top thermocouple of each string is positioned right at the ceiling's height.



(**a**) Line 10 top view.



(**b**) Line 8 top view.



(**c**) Side view.

Figure 4. Thermocouple distribution diagram. The red circle indicates the location of the thermocouple string, and the blue square indicates the location of the smoke exhaust port.

2.2. Numerical Setup

Since full-scale fire experiments in subways are difficult and expensive to conduct, numerical methods are used to gain more insights into T-station fires. The Fire Dynamic Simulator V6.8 (FDS6.8) is commonly used in fire studies of various types of buildings, including subways. The simulation duration is 360 s when the fire starts, which is the expected maximum evacuation time.

2.2.1. Model Configuration

The station hall was modeled in full size according to subway design drawings, as shown in Figure 5. The model size is 144.0 m × 169.6 m × 7.7 m, which represent the longitudinal length of the Line 10 station hall, the length in the Line 8 station hall's longitudinal direction, and the hall height, respectively. The model includes all the stairs, exits, smoke outlets, fire curtains, and smoke barrier walls. The boundary conditions of exits were all set to 'open'. Each extraction port was set with a velocity boundary condition determined by the flow rate of each fan.

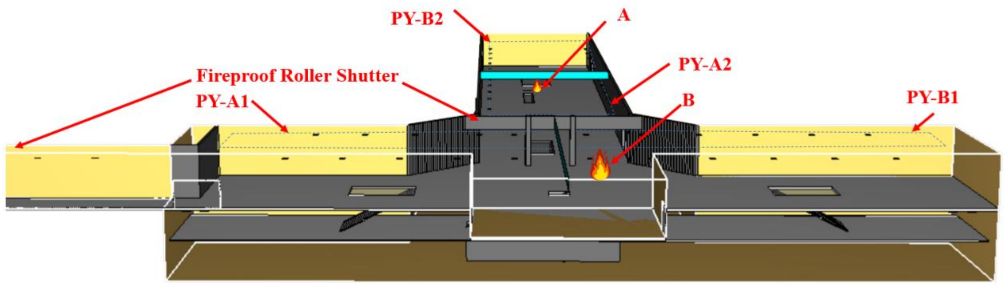


Figure 5. FDS model diagram.

2.2.2. Fire Scenarios

According to the Metro Safety Assessment Standard of China [38], the fire source power selected was 1.5 MW. For the T-shaped station hall, the fire source was positioned on two sides. The influence of the cooperation of fireproof roller shutters and smoke extraction fans on the smoke extraction effect was investigated, as shown in Table 2.

Table 2. Simulated condition with 1.5 MW.

Sim. Case	Fire Source Location	Fireproof Roller Shutters	PY-A1	PY-B1	PY-A2	PY-B2
S11	B	Down	S	F	S	S
S12			F	F	S	S
S13		Up	F	F	S	S
S14			F	F	F	S
S15			F	F	F	F
S16			F	F	R	S
S17			F	F	R	R
S21	A	Down	S	S	F	S
S22			S	S	F	F
S23		Up	S	S	F	F
S24			F	F	F	F
S25			R	R	F	F

Note: F: forward rotation (for extraction); R: reversal rotation (for supply); S: shut down.

According to current disaster prevention requirements, fireproof roller shutters are required to be activated to prevent fire and hot smoke from spreading to a larger area. The fans in each smoke compartment extract smoke and hot gases independently. Alternatively, roller shutters are allowed to be raised to explore the effect of coordinated smoke extraction using multiple fans, which is coordinated ventilation. For the T-type station, fans for Line 8 were used to assist smoke extraction from the Line 10 fires in cases S13–S17, and fans from Line 10 were used to assist smoke extraction from the Line 8 fires in cases S23–S25.

2.2.3. Grid Sensitivity Analysis

Above a certain threshold size, smaller meshes can give more accurate results, but time consumption will increase exponentially. Considering the time cost and computational burden of full-scale simulations, three sizes of 0.25 m, 0.50 m, and 1.0 m were selected as the edge length of each grid. Taking the ceiling temperature near fire as an example, the grid sensitivity test results are shown in Figure 6. Mean absolute error (MAE) was used to evaluate the deviation between the results of different sizes. The grid size of 1.0 m gives unreasonable results, while 0.50 m and 0.25 m perform similarly. As can be seen in Table 3, reducing the grid size from 0.50 m to 0.25 m does not bring much accuracy improvement, but time consumption increases by about 14 times. Therefore, the grid size of 0.50 m × 0.50 m × 0.50 m was selected for further numerical simulations.

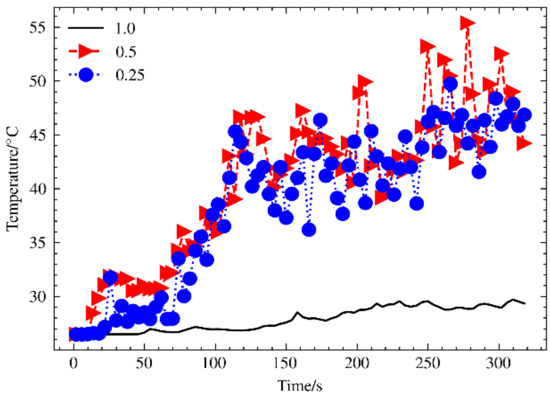


Figure 6. Distribution of ceiling temperature under different mesh sizes.

Table 3. MAE and CPU time for different grid sizes.

Grid Size (m)	MAE (°C)	CPU Time (h)
1.0 × 1.0 × 1.0	6.91	0.274
0.50 × 0.50 × 0.50	1.96	5.23
0.25 × 0.25 × 0.25	-	71.9

2.3. Comparison Between Experiment and Simulation Results

A full-scale experiment was conducted in the Line 10 station hall. The fire source was located at B, with an HRR of 1.5 MW. Only fan PY-B1 was turned on for smoke extraction, and the rest were turned off. The results of the two thermocouple temperatures closest to the fire source and for simulation S11 are compared in Figure 7. Although the turbulence model makes the numerical results a little oscillatory, the temperature rise rate is close to the experimental one in general. There are some local deviations between the numerical and experimental results, for example after 300 s, but the simulation temperature is lower than that in the experiment. However, in most cases, the average deviation does not exceed 5 °C, which is considered to be within the acceptable limits.

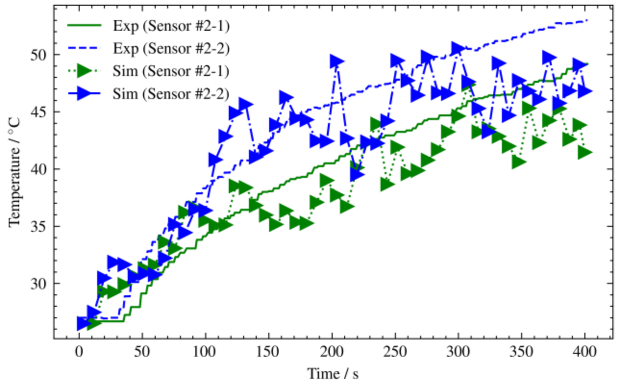
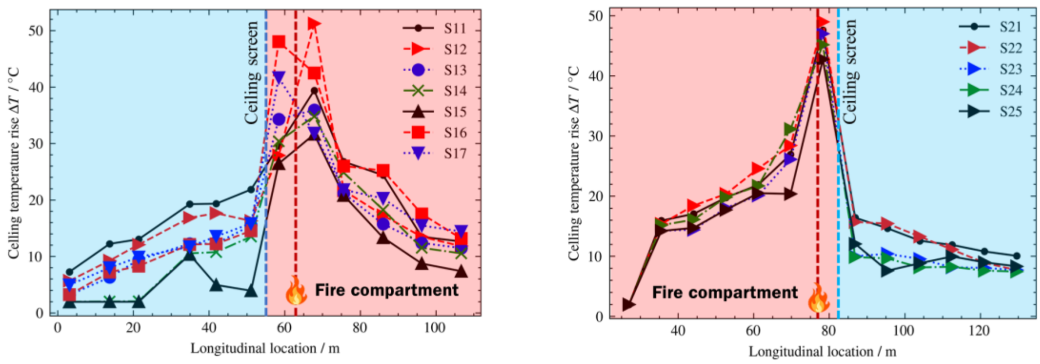


Figure 7. Comparison of ceiling temperature between FDS and experimental data.

3. Results and Discussion

3.1. Fire Locations

The ceiling temperature rises along the longitudinal direction of the station hall for fire sources A and B, as depicted in Figure 8. Across all the scenarios, the ceiling temperature across the ceiling smoke barrier decreases significantly, demonstrating that the smoke barrier is an effective smoke control measure. However, for both fire sources A (S11) and B (S21), activating only one fan is insufficient to contain smoke within the smoke compartment.



(**a**) Line 10. (**b**) Line 8.

Figure 8. Distribution of ceiling temperatures in Lines 8 and 10.

The coordinated ventilation strategies yielded different effects depending on the fire source locations within the T-shaped station hall. For Line 10 fire A, utilizing the Line 8 fans in a coordinated manner (S14–S17) achieves better results compared to inaction (S13). As shown in Figure 9, the coordination of the Line 8 fans significantly enhances visibility at a height of 2 m, with S17 demonstrating the most optimal effect. In Figure 8a, the temperature distribution also reveals marked differences. Conversely, for Line 8 fire B, the support from Line 10 fans does not provide a significant cooling effect and may even have adverse consequences. As illustrated in Figure 10, fan linkage tends to concentrate hot smoke towards the end of the Line 8 station hall, which houses the station control room and two exits. Although there are other exits, the emergency instructions will guide people to escape in the direction away from the fire source, and their instinctive reaction will be to find the nearest exit. This will result in passengers in half of the Line 8 station hall being directed to the two dangerous exits.

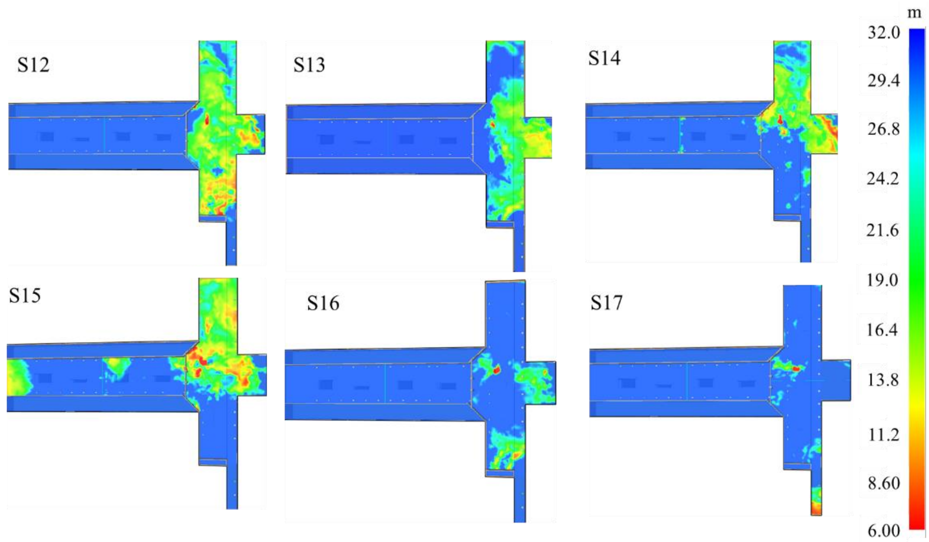


Figure 9. Visibility profile at 2 m height of Line 10 station hall.

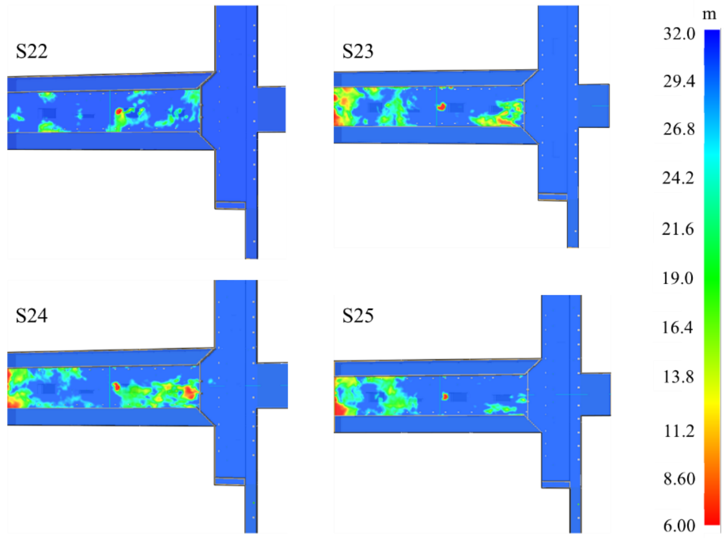


Figure 10. Visibility profile at 2 m height of Line 8 station hall.

The reason for this difference is that the airflow due to fire shutter failure has different effects on the two sides of the T-shaped station hall. Horizontal flow was introduced into the middle position of Line 10, interrupting the spread of smoke from one end to the other. However, in the case of fires in Line 8, the basic pattern that hot smoke propagated longitudinally was not changed. Figures 11 and 12 depict longitudinal visibility at 360 s for S11–S17 and S21–S25, respectively. As shown in Figure 12, the smoke barrier at the junction of the two station halls is far away from the fire source, and there is a lack of sufficient hot smoke to cross the smoke barrier. Although there is no impact on the Line 10 station hall, unfortunately the fans of Line 10 cannot provide help to those in Line 8. Therefore, when a fire occurs on Line 10, raising the fire shutter and using the fans on Line 8 to assist in smoke extraction can achieve better results. However, when a fire occurs on Line 8, closing the fire shutter would be the best option.

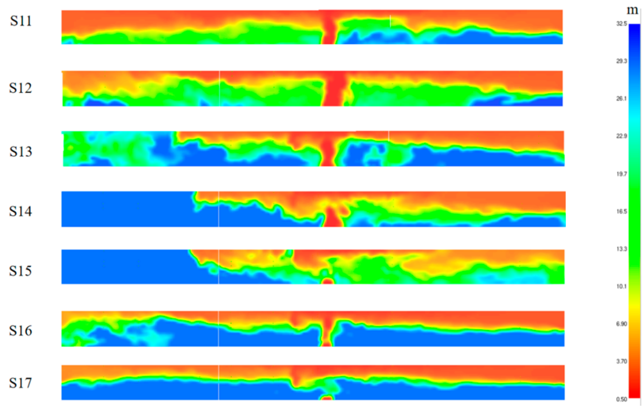


Figure 11. Longitudinal slice plots of visibility at 360 s for conditions S11–S17.

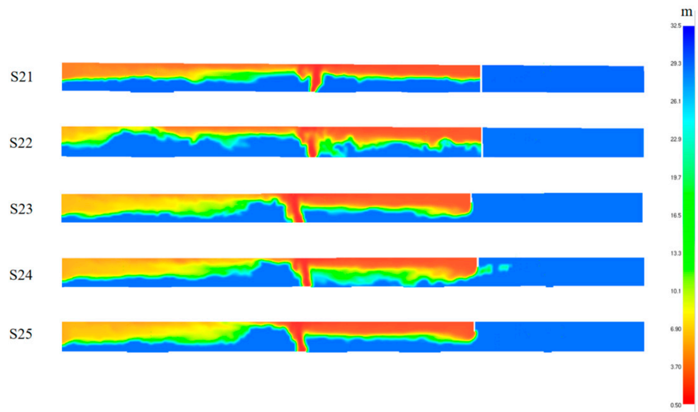


Figure 12. Longitudinal slice plots of visibility at 360 s for conditions S21–S25.

3.2. Ceiling Screen and Fireproof Roller Shutters

As illustrated in Figure 13, when the fireproof roller shutter is closed, the fire does not impact the adjacent line. In the event of fire shutter failure, the fire in Line 8 (S23) has a minimal effect on Line 10, while the smoke from Line 10 (S13) can infiltrate Line 8. Notably, during case S13, the fan for Line 8 was inactive. In this scenario, Figures 9 and 13 show that no smoke was detected at a height of 2 m within 360 s, and the temperature increase did not exceed by 1 °C. This outcome is well below the danger threshold, suggesting that the strategy of directing more smoke to Line 8 (S14–S15) may be considered to facilitate coordinated smoke extraction.

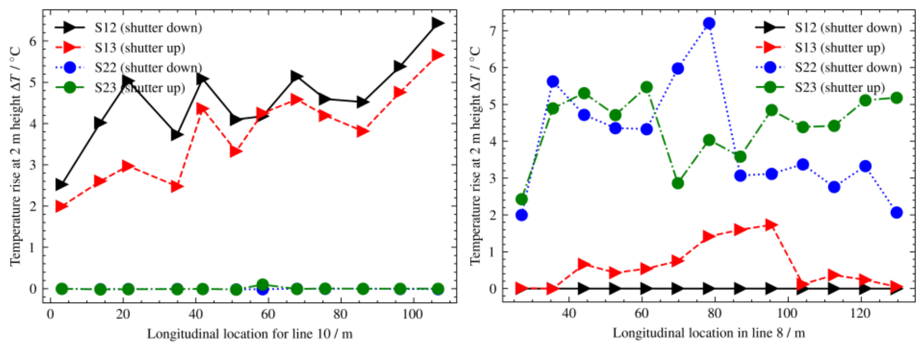


Figure 13. Temperature distribution with shutter open or closed.

For the fire in Line 8, the failure of the fire shutter results in elevated temperatures in Region 4. Two of the three exits for Line 8 are located at the end of Region 4, making personnel evacuation more challenging. While the failure of the fire shutter may facilitate a coordinated smoke extraction strategy for Line 10, it ultimately becomes a liability for Line 8.

The velocities at various heights for the fire shutter are depicted in Figure 14. The positive values indicate air flowing into Line 8, while the negative values signify air flowing into Line 10. In cases S14 and S15, the fan in Line 8 extracts smoke, resulting in air flowing from Line 10 to Line 8. The velocity is lower at lower heights and higher at greater heights due to the diffusion of hot smoke. In conditions S16 and S17, the fan in Line 8 supplies air, causing air to flow from Line 8 to Line 10 at lower heights. However, the flow direction reverses above 5 m, which is a consequence of the pressure dynamics between hot smoke and the supplied airflow. This creates a zero-velocity height near 5 m; above this point, flow is dominated by hot smoke, while below it, cold air prevails. If only PY-A2 and PY-B2 supply air, it is insufficient to prevent smoke from encroaching into Line 8. Here, the raised fire curtain serves as an effective smoke barrier, successfully inhibiting the spread of hot smoke into Line 8.

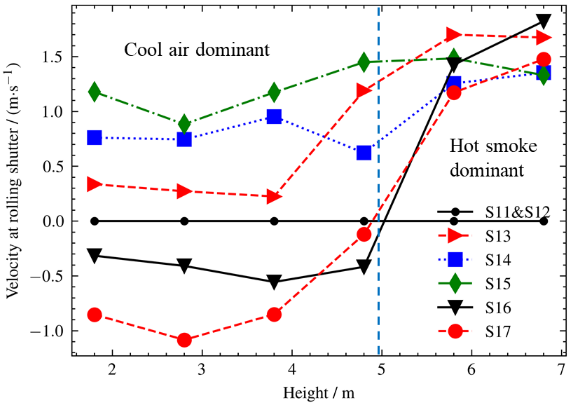


Figure 14. Velocity of fire shutter at 360 s.

3.3. The Effect of the Opening and Closing of the Smoke Exhaust Fan on Smoke Characteristics

3.3.1. Line 10

According to the analysis results of the ceiling temperature rises for S11 and S12 shown in Figure 8, when a fire occurs in the station hall of Line 10, opening two smoke extraction fans is more effective than opening just one. Compared to S11, the high-temperature range on the S12 ceiling is reduced, and the associated risk factor is lower. The temperature in the 2 m section of Region 1 in the station hall generally remains low, visibility improves, and the carbon monoxide concentration decreases (Figure 15). The amount of smoke in the channel leading to the property area is significantly reduced, resulting in a lower impact on the property area. When the fire curtain is fully opened, operating both smoke extraction fans allows for the faster extraction of smoke from the station hall, lowering the ceiling temperature and preventing gas buildup. This, in turn, enhances the overall safety of the station hall.

When the fire shutter is not deployed and no smoke-retaining wall is set up in the station hall of Line 10, the high-temperature area in Region 1 of S14 (Figure 8) is significantly smaller than that in S13. This is due to the temperature drop in non-ignition areas 1 and 3 caused by smoke being extracted from Line 8. The PY-A2 fan on Line 8 helps maintain a normal temperature in the public area, increases visibility, and reduces the carbon monoxide concentration. However, the smoke extraction effect at the entrance and exit of Region 2 in Line 10 does not improve significantly.

According to the ceiling temperature analysis (Figure 8) of S14 and S15, the full operation of all four extraction fans causes more smoke to be transferred to the public area of Line 8. As a result, the amount of smoke and the high-temperature area on the ceiling of

Line 8 increase. However, a higher flue gas temperature, an increased carbon monoxide concentration, and improved visibility at the 2 m height in Region 2 (Figure 15) actually facilitate evacuation. The decline in visibility in Region 3 is minimal and has almost no impact on evacuation. Overall, the visibility and working conditions in S15 are superior to those in S14 and S13.

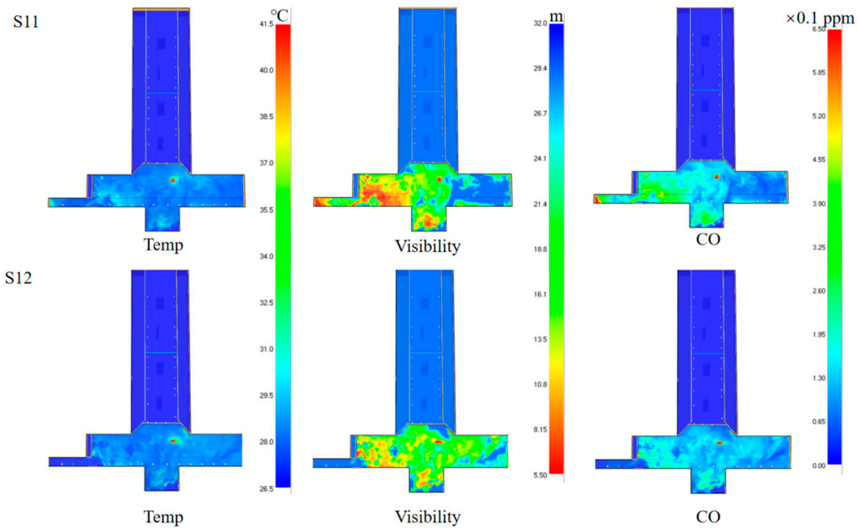


Figure 15. Two m height slices at 360 s in conditions S11 and S12.

When the fire shutter does not drop and the smoke-retaining wall of the station hall of Line 10 is not set, the high-temperature area of Region 1 of S14 (Figure 8) is significantly smaller than the high-temperature area of S13, which is due to the temperature drop in the non-ignition area of Regions 1 and 3 due to smoke extraction on Line 8. The PY-A2 fan of Line 8 basically keeps the temperature of the public area normal, increases visibility, and reduces the carbon monoxide concentration, but the smoke extraction effect at the entrance and exit of Region 2 of Line 10 does not improve significantly. According to the analysis results of the ceiling temperature (Figure 8) in S14 and S15, the full operation of the four extraction fans leads to the transfer of more smoke to the public area of Line 8, which causes an increase in the amount of smoke in Line 8 and the high-temperature area of the ceiling. However, the smoke temperature, the carbon monoxide concentration, and visibility increase at the 2 m height of area 2 (Figure 16) are conducive to evacuation. The visibility decline in area 3 is not obvious, which has almost no impact on evacuation. The visible working conditions of S15 are superior to those of S14 and S13.

The simulation results of the analysis of condition S16 are shown (Figure 17). Reversing the smoke extraction fan of Line 8 to replenish air will control flue gas in the Line 10 station hall. However, some smoke will move into Region 3 in condition S17. Opening the two fans will not make flue gas spread to Line 8, but will lead to the Line 10 station hall ceiling temperature rising. According to the longitudinal slice map of smoke (Figure 11), the smoke layer under the S17 conditions is the most stable compared with those in the other conditions.

When a fire occurs in the station hall of Line 10, the analysis results of several modes show that the extraction effect of opening the fans in Region 2 only is far less impactful than that of opening multiple extraction fans. Opening multiple extraction fans can effectively control flue gas in the fire area and prevent spread to another fire zone and the station hall of Line 8. When the fire shutter is not released, the smoke extraction effect of S17 is the best.

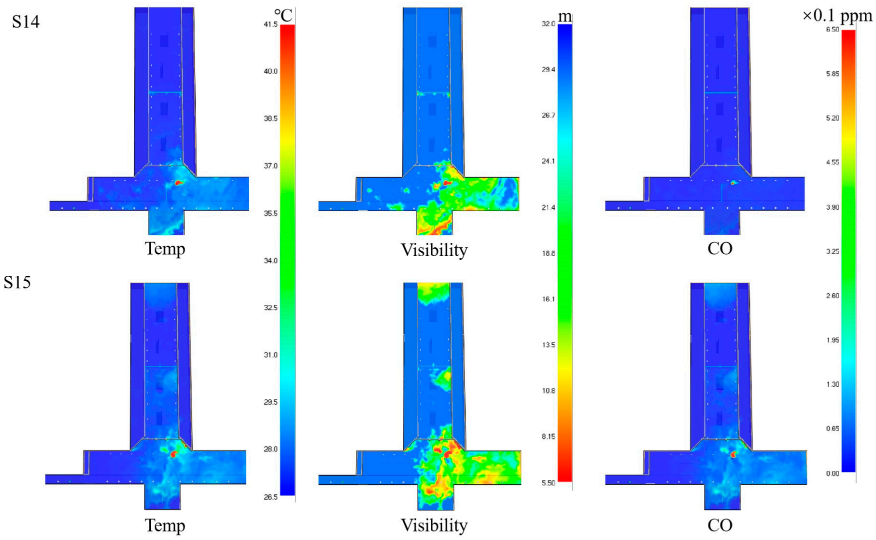


Figure 16. Two m height slices at 360 s in conditions S14 and S15.

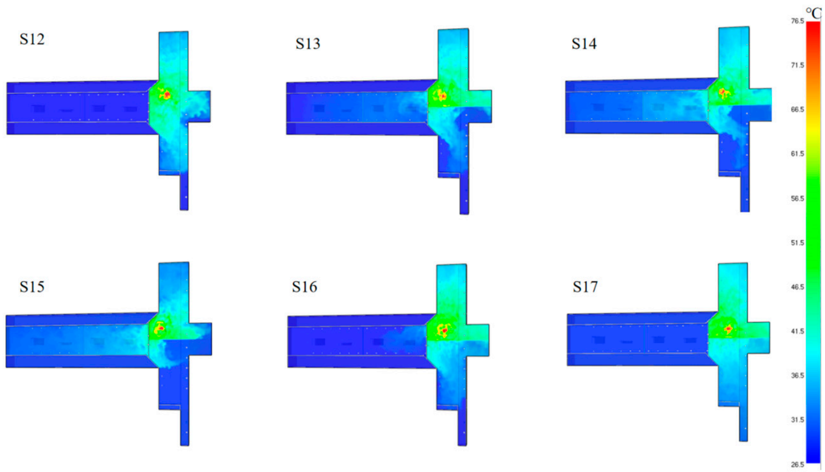


Figure 17. The ceiling temperature for cases S12–S17 at 360 s.

Therefore, when a fire occurs on Line 8, the operation of the fan on Line 10, whether in positive or reversed mode, will not disrupt the hot smoke flow pattern established on Line 8. In this case, collaborative smoke extraction offers no advantage, and the traditional strategy of closing the fire shutter remains the most effective approach. Conversely, when a fire occurs on Line 10, lateral flow induced by the fan on Line 8 interferes with the smoke transmission pattern. This disruption enables the synergistic smoke extraction strategy to achieve outcomes that surpass those of the current traditional strategy.

3.3.2. Line 8

When the fire source is located in the middle of the station hall of Line 8, it can be seen from the ceiling temperature field section (Figure 8) that the two smoke extraction fans reduce the spread of smoke to other areas. According to the temperature, visibility, and carbon monoxide section at the height of 2 m (Figure 12), flue gas in Region 4 of working condition S21 spread to the terminal vehicle control room and the entrance and exit, blocking the view of the observation window of the vehicle control room and affecting evacuation safety at the entrance and exit. In case S22, Region 4 has less smoke, and visibility exceeds 10 m. Before the terminal vehicle control room and the entrance and exit, the smoke extraction effect is good.

According to the ceiling temperature field section of S24 and S25 (Figure 8), the two smoke extraction functions of Line 10 can reduce the amount of flue gas in Line 10. However, according to the temperature, visibility, and carbon monoxide section at 2 m height (Figure 18), the inversion of the two smoke extraction fans in Line 10 of working condition S25 will also significantly reduce visibility in the vehicle control room at the end of Region 4 and visibility at 2 m from the two exits.

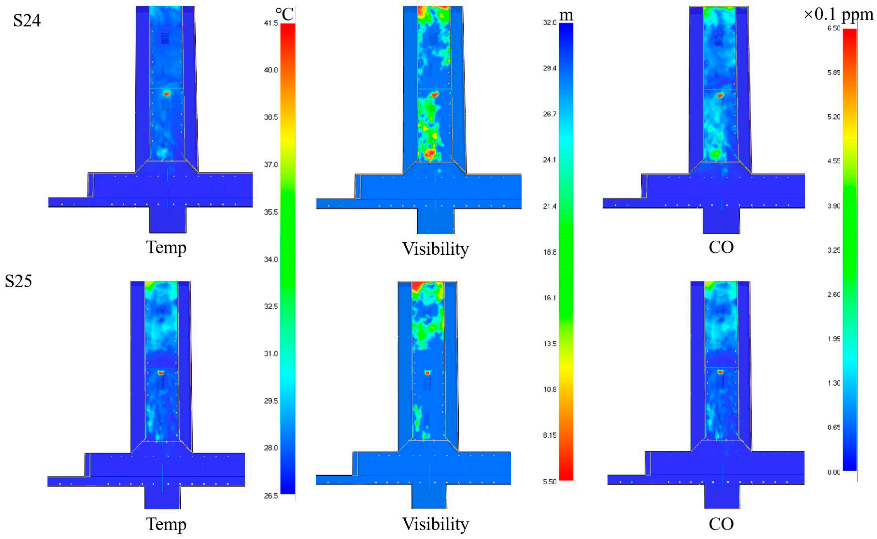


Figure 18. Two m height slices at 360 s in cases S24 and S25.

When a fire occurs in the station hall of Line 8, the analysis results of several extraction modes show that the extraction effect of the extraction fan only in Region 3 is far less impactful than that of multiple extraction fans. Opening the extraction fan can effectively control flue gas in the fire area and prevent the spread to another region and the station hall of Line 10. The effects of smoke extraction and smoke control in cases S21, S23, S24, and S25 are far less impactful than those in case S22.

4. Conclusions

In this study, a full-scale, numerical model was established to investigate the coordinated ventilation strategy of a T-shaped subway station hall fire, which included two fire source locations, five ventilation modes, and the coordination of roll fire shutters. The reliability of the numerical results was verified by full-scale fire and hot smoke experiments. The influence between the two sides of the T-shaped station hall was found to be not consistent, resulting in different optimal ventilation strategies. The main conclusions are as follows:

(1) When a fire occurs in the longitudinal side of 'T', the fans at the horizontal side, whether operating forward or in reverse, cannot disrupt the hot smoke flow pattern on the longitudinal side. Coordinated ventilation offers no assistance, making the traditional strategy of closing the fireproof roller shutter the most effective. Conversely, when a fire occurs in the horizontal side of 'T', lateral flow introduced by the fans on the longitudinal side can interrupt the propagation pattern, resulting in superior outcomes compared to those of the current strategy.

(2) During coordinated ventilation, when the fan in the non-fire area supplies air, cold air is forced into the fire area; however, this does not prevent hot smoke from spreading from the ceiling. In this case, the closed fireproof roller shutter acts as a ceiling screen, playing a crucial role in inhibiting the spread of smoke.

(3) All the fans working simultaneously to extract smoke can effectively distribute hot smoke throughout the station hall. Under the influence of a baggage fire (1.5 MW), the danger zone will not expand, significantly reducing the temperature near the fire source and improving visibility, which helps to create a longer escape window. Supplying air to non-fire areas, while extracting smoke from the fire area is the optimal strategy to prevent outward smoke spread. However, this comes at the cost of the those in the fire area experiencing the highest temperatures and lowest visibility, making it suitable for situations where personnel can easily evacuate. In appropriate scenarios, collaborative ventilation can yield better evacuation conditions than those of independent ventilation.

(4) The smoke flow patterns under the coordinated ventilation modes can also provide a reference for other T-shaped station halls with similar shapes (length-to-width ratio or the length of both sides of T) and exit layouts. In subsequent studies, more detailed discussions on geometric parameters and suggestions for station design can be presented.

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References

1. Wu, J. Research on Nanchang Metro Culture Construction. Master's Thesis, Jiangxi University of Finance and Economics, Nanchang, China, 2022.
2. Chen, G.; Wang, S.; Ran, Y.; Cao, X.; Fang, Z.; Xu, Z. Intelligent monitoring and quantitative evaluation of fire risk in subway construction: Integration of multi-source data fusion, FTA, and deep learning. *J. Clean. Prod.* **2024**, *478*, 143832. [CrossRef]
3. Long, Z.; Zhong, M. Predicting smoke temperature distribution beneath ceiling for a large subway station fire. *J. Build. Eng.* **2024**, *98*, 111138. [CrossRef]
4. Sun, J.; Lu, Z.; Zhou, D. Optimization analysis of evacuation facility parameters in interval tunnels under subway train fire accidents. *Phys. A Stat. Mech. Appl.* **2024**, *651*, 130020. [CrossRef]
5. Zhou, D.; Hu, T.; Wang, Z.; Chen, T.; Li, X. Influence of tunnel slope on movement characteristics of thermal smoke in a moving subway train fire. *Case Stud. Therm. Eng.* **2021**, *28*, 101472. [CrossRef]
6. Wang, K.; Cai, W.; Zhang, Y.; Hao, H.; Wang, Z. Numerical simulation of fire smoke control methods in subway stations and collaborative control system for emergency rescue. *Process Saf. Environ. Prot. Prepublish* **2020**, *147*, 146–161. [CrossRef]
7. Shi, C.; Li, J.; Xu, X. Full-scale tests on smoke temperature distribution in long-large subway tunnels with longitudinal mechanical ventilation. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2021**, *109*, 103784. [CrossRef]
8. Wang, X.; Liu, B.; Ma, W.; Feng, Y.; Li, Q.; Sun, T. Simulations on Evacuation Strategy and Evacuation Process of the Subway Train Under the Fire. *Fire* **2024**, *7*, 464. [CrossRef]
9. Yan, X.; Yang, H.; Mo, H.; Xie, Y.; Jin, Z.; Zhou, Y. Numerical Simulation on the Smoke Prevention Performance of Air Curtains in an Island-Type Subway Station. *Fire* **2023**, *6*, 177. [CrossRef]

10. Chen, J.; Long, Z.; Liu, C.; Cai, S.; Xu, B.; Cheng, H.; Zhong, M. Investigation of the performance of lateral ventilation in subway station fires. *J. Wind Eng. Ind. Aerodyn.* **2022**, *228*, 105133. [CrossRef]
11. Peng, M.; Zhang, S.; Yang, H.; He, K.; Cong, W.; Cheng, X.; Zhang, H. Experimental study on confinement velocity in tunnel fires with longitudinal ventilation. *J. Wind Eng. Ind. Aerodyn.* **2020**, *201*, 104157. [CrossRef]
12. Zhang, T.; Han, R. Numerical study on the influence of subway platform air curtains on smoke diffusion. *Case Stud. Therm. Eng.* **2023**, *50*, 103439. [CrossRef]
13. Fan, X.; Yang, J.; Zhang, H.; Wan, Z.; Liu, J.; Liu, Z.; Zheng, W. Prediction of back-layering length in subway tunnel with on-fire train running. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2023**, *141*, 105375. [CrossRef]
14. Teodosiu, C.; Kubinyecz, V. Platform Screen Doors in a Subway Station with a Train on Fire. *Appl. Sci.* **2022**, *12*, 8296. [CrossRef]
15. Wang, J.; Wang, Y.; Wu, P.; Wu, P.; Jiang, J. Study on emergency ventilation mode for multisource fires in a typical interchange subway station. *Int. J. Vent.* **2022**, *21*, 157–176. [CrossRef]
16. Zhao, H.; Yu, H.; Yuan, Y.; Li, P.; Chen, J. Cyclic loading behavior of a repaired subway station after fire exposure. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2019**, *84*, 210–217. [CrossRef]
17. Zhang, J.; Li, Y.-F.; Dai, B.-Q.; Li, X.-J.; Huang, Y.-B. The Effect of Exhaust Velocity on Smoke Exhaust in Subway Platform Fire. *Procedia Eng.* **2018**, *211*, 1018–1025. [CrossRef]
18. Wu, F.; Jiang, J.-C.; Zhou, R. Smoke Flow Temperature beneath the Ceiling in an Atrium-style Subway Station with Different Fire Source Locations. *Procedia Eng.* **2018**, *211*, 794–800. [CrossRef]
19. Chen, J.; Zhong, M.; Qiu, P.; Long, Z.; Cheng, H. A study of repeatability of hot smoke test in a subway station. *Case Stud. Therm. Eng.* **2023**, *41*, 102666. [CrossRef]
20. Lan, B.; Li, Y.R.; Li, P.C.; Gong, H.F. Numerical simulation of the chimney effect on smoke spread behavior in subway station fires. *Case Stud. Therm. Eng.* **2022**, *39*, 102446. [CrossRef]
21. Long, Z.; Zhong, M.; Chen, J.; Cheng, H. Study on emergency ventilation strategies for various fire scenarios in a double-island subway station. *J. Wind Eng. Ind. Aerodyn.* **2023**, *235*, 105364. [CrossRef]
22. Long, Z.; Chen, J.; Qiu, P.; Zhong, M. Study on the smoke layer height in subway platform fire under natural ventilation. *J. Build. Eng.* **2022**, *56*, 104758. [CrossRef]
23. Chen, J.; Li, G.; Pan, R.; Long, Z.; Zhong, M. Numerical study on the airflow characteristics and smoke control condition in stair area of subway stations. *J. Build. Eng.* **2024**, *84*, 108577. [CrossRef]
24. Junfeng, C.; Jijian, L.; Xiangliang, T.; Ling, Z.; Huihang, C.; Maohua, Z. Study on the effect of obstacles on smoke diffusion and airflow structure in subway stations. *Build. Environ.* **2023**, *242*, 110553. [CrossRef]
25. Wei, C.; Kun, H.; Hui, Y.; Long, S.; Xudong, C. Experimental study on temperature characteristics in a subway train carriage with lateral openings in a longitudinally ventilated tunnel. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2023**, *131*, 104814.
26. Liu, Y.; Li, Y.Z.; Ingason, H.; Liu, F. Control of thermal-driven smoke flow at stairways in a subway platform fire. *Int. J. Therm. Sci.* **2021**, *165*, 106937. [CrossRef]
27. Feng, Z. Smoke control of side platform and the same concourse of metro transfer station. *Fire Sci. Technol.* **2020**, *39*, 213–216.
28. Xie, Y. Numerical simulations on fire control of subway transfer station sharing one concourse. *Fire Sci. Technol.* **2017**, *36*, 1233–1235.
29. Yuan, J.P.; Liao, Y.J.; Zhou, S.D. Smoke exhaust mode for large metro transfer station hall. *Eng. J. Wuhan Univ.* **2015**, *48*, 805–808.
30. Cheng, H. Model experimental study on fire in metro multi-line transfer station-(4)fire in transfer channel. *J. Saf. Sci. Technol.* **2021**, *17*, 12–19.
31. Chen, J.; Zhong, M.; Cheng, H.; Long, Z.; Yang, Y. Model experimental study on fire in metro multi-line transfer station:(2)fire in cross-transfer station. *J. Saf. Sci. Technol.* **2020**, *16*, 5–11.
32. Weng, M.C.; Yu, L.X.; Liu, F.; Nielsen, P.V. Full-scale experiment and CFD simulation on smoke movement and smoke control in a metro tunnel with one opening portal. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2014**, *42*, 96–104. [CrossRef]
33. Qin, J.; Liu, C.; Huang, Q. Simulation on fire emergency evacuation in special subway station based on Pathfinder. *Case Stud. Therm. Eng.* **2020**, *21*, 100677. [CrossRef]
34. Long, Z.; Liu, C.; Yang, Y.; Qiu, P.; Tian, X.; Zhong, M. Full-scale experimental study on fire-induced smoke movement and control in an underground double-island subway station. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2020**, *103*, 103508. [CrossRef]
35. Liu, F.; Liu, Y.; Xiong, K.; Weng, M.; Wang, J. Experimental and numerical study on the smoke movement and smoke control strategy in a hub station fire. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2020**, *96*, 103177. [CrossRef]
36. Shi, C. *Experimental and Numerical Analysis of Fire in Deeply Buried Underground Stations*; Science Press in BeiJing: Beijing, China, 2009.

37. Zhang, L.; Wu, X.; Liu, M.; Liu, W.; Ashuri, B. Discovering worst fire scenarios in subway stations: A simulation approach. *Autom. Constr.* **2019**, *99*, 183–196. [CrossRef]
38. *GB/T 43392-2023*; Safety performance test and assessment method for metro disaster prevention system. Standards Press of China: Beijing, China, 2023.