sustainability

Article

A Study on the Influence of Rail Top Smoke Exhaust and Tunnel Smoke Exhaust on Subway Fire Smoke Control

Sihui Dong [1], Kang Wang [2,*] and Chenxu Jia [1]

[1] School of Traffic and Transportation Engineering, Dalian Jiaotong University, Dalian 116028, China; shdong@djtu.edu.cn (S.D.); cxjia@djtu.edu.cn (C.J.)
[2] College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China
* Correspondence: wk@stu.xust.edu.cn; Tel.: +86-152-4250-0427

Abstract: The special emergency plan for subway fires in China stipulates that when a fire occurs at a train stop, it is necessary to confirm whether the fire mode of the tunnel ventilation system is implemented. Because of the setting mode of tunnel ventilation and smoke exhaust in the station track area, the smoke exhaust at the rail top and tunnel cannot operate at the same time. To study the influence of rail top smoke exhaust and tunnel smoke exhaust on subway fire smoke control when a train stops at a station, we take an island station as an example. A 1:1 full-scale numerical model is established to study the smoke spread area, temperature field distribution, and carbon monoxide concentration. The results show that when a train fire occurs in a subway station, the rail top smoke exhaust mode has the best smoke exhaust effect compared with the other three smoke exhaust modes. In this mode, the smoke diffusion in the carriage is the slowest and the available escape time of personnel is the longest. Therefore, it is recommended to adopt the rail top smoke exhaust mode in case of train fire in the subway station; that is, open the smoke exhaust outlet on the rail top for smoke exhaust, and organize personnel to evacuate to the safe position of the platform through the connecting channel and escape exit. If conditions permit, local small fans can also be added to meet the requirements of smoke exhaust. The research results can provide guidance for the emergency plan and provide strong support for promoting the improvement of the fire emergency plan.

Keywords: subway fire; rail top smoke exhaust; tunnel smoke exhaust; smoke exhaust mode; flue gas control

Citation: Dong, S.; Wang, K.; Jia, C. A Study on the Influence of Rail Top Smoke Exhaust and Tunnel Smoke Exhaust on Subway Fire Smoke Control. *Sustainability* **2022**, *14*, 4049. https://doi.org/10.3390/su14074049

Received: 16 February 2022
Accepted: 26 March 2022
Published: 29 March 2022

1. Introduction

As an urban rail transit tool with large passenger capacity and punctuality, the subway has become an important means of solving urban traffic problems [1]. However, because of the limited space, high personnel density, smoke exhaust difficulty, and heat extraction in the subway, fire accidents often cause many casualties and property losses. Thus, subway fire accidents should not be ignored [2]. The most effective way to reduce the risk of fire accidents is to design reasonable smoke exhaust methods to ensure the safe evacuation of personnel [3].

The experimental research on subway smoke control has mainly focused on the location of the fire source and the original design structure. Ji [4] studied the influence of opening different smoke vents on the entrainment effect of the smoke layer and the difference in smoke exhaust effects when the fire source was located at the end and middle of the platform. Meng [5] revealed the distribution characteristics of visibility, temperature field, and CO toxic gas concentration in the tunnel and platform areas under the coupling action of water mist and longitudinal wind when the fire source was located in different positions. Hou [6] conducted a multipoint cold smoke test at the subway transfer station to simulate the smoke diffusion law of the station under the condition of multiple ignition sources. Giachetti [7] found that the original design structure of the subway has a more important impact on fire smoke control than the location of the fire source in the subway. Peng [8] carried out experimental research on flue gas distribution temperature under different door conditions. He [9] studied the smoke exhaust characteristics of a subway tunnel with wide roofs (its width equal to the tunnel width) under the condition of natural ventilation. Cong [10] conducted an experimental study on the effect of smoke screen height under the ceiling of a subway station platform on the temperature distribution of fire-induced airflow. Liu [11] studied the optimum smoke screen depth required to prevent smoke from spreading from the platform floor to the lobby floor. Long [12] studied important parameters such as vertical temperature distribution in case of fire in the underground double-island subway station. However, the development of experimental research has been limited by the design size, fire source type, and other conditions that cannot meet the needs of fire smoke control under multi-parameter conditions. For the presentation of research results, there has been a lack of visual forms such as a temperature and CO concentration cloud diagram [13].

With the continuous development of computational science, numerical simulation solves the problem of multi-parameter condition experimental research to a certain extent with the relevant equations of fluid control [14]. Numerical simulation has the advantages of high efficiency, cost-saving, and convenient operation, and it can simulate a variety of conditions. It can reproduce the distribution of the temperature field and CO concentration field when a fire occurs. It has become the main means of subway fire smoke control. Unlike experimental research, numerical simulation is not limited by the modeling requirements, and the original design structure and multi-parameter conditions of the subway can be compared. Meng [15] compared and analyzed the performance of various ventilation modes of subway stations when adopting fully enclosed screen doors (PSD) and half-height safety doors. Li [16] studied the influence of PSD opening mode on mechanical smoke exhaust in a subway station fire. Wang [17] designed a ventilation and smoke exhaust scheme according to the structural characteristics of a multi-story subway station. Wang [18] analyzed the ventilation and smoke exhaust methods of the multi-story crosscomplex subway. Li [19] studied the optimal operation effect of the overall ventilation system of the transfer station. Zhong [20] found that the platform stairs could reduce the air inlet speed at the stair entrance. Gao [21] analyzed the influence of dome structure on the fire smoke control of subway stations. Chen [22] concluded that setting an air curtain at the entrance to the stairs prevents smoke more efficiently than sending wind energy into the station hall. Liu [23] studied the critical speed of preventing smoke from spreading from the platform to the upper stairs through the stairs in case of a platform fire. We found that in many simulation studies on subway fire structure design, there are few reports on subway self-owned smoke exhaust structure (tunnel and rail top). However, existing studies have shown that the elimination of rail top smoke exhaust will significantly reduce the smoke exhaust effect of train fire [24]. Studying only the smoke exhaust effect of the tunnel cannot achieve the original intention of optimal design of subway fire smoke control.

In addition, the special emergency plan for subway fire in China stipulates that when there is a fire at a train stop, it is necessary to confirm that the fire mode of the tunnel ventilation system is implemented. However, the setting mode of tunnel ventilation considers the smoke exhaust in the railway area of the station; thus, the smoke exhaust at the rail top and tunnel cannot be operated at the same time. This leads to the problem of the optimal smoke control scheme design under the mode of tunnel ventilation, which considers the smoke exhaust in the railway area of the station. In view of this, we propose building a full-scale model of a subway tunnel. Under the conditions of rail top smoke exhaust and tunnel smoke exhaust, we intend to analyze the smoke spread area, temperature field distribution, and CO concentration in the event of a subway tunnel fire, and to determine the optimal smoke control mode under the mode of tunnel smoke exhaust or rail top smoke exhaust on the basis of large-scale system smoke exhaust. The study provides strong support for the improvement of the subway fire emergency plan.

2. Theoretical Model

2.1. Basic Governing Equation

According to the mixing characteristics of gas fuel, combustion products, and gas turbulence around the combustion during a subway tunnel fire, the large eddy current model was adopted, and the basic control equations are shown as follows.

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0 \tag{1}$$

where ρ is the density (kg·m^{-3}); t is the time (s); $\vec{u}$ is the velocity vector (m/s); and ∇ is the Laplace operator.

Component conservation equation:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho Y_i \vec{u}) = \nabla \cdot (\rho D_i \nabla Y_i) + m_i \tag{2}$$

where Y_i represents the mass fraction of component i, D_i represents the diffusion coefficient of component i (m^2/s), and m_i represents the mass generation rate of the second component per unit volume (kg·m^{-3}·s^{-1}).

Momentum conservation equation:

$$\rho\left[\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} + \nabla p\right] = \left[\rho g + \vec{f} + \nabla \cdot \vec{\tau}\right] \tag{3}$$

where p is the pressure (Pa), g is free-fall acceleration (m/s^2), f is the externally applied force vector (N), and τ is the viscous force tensor (N).

Energy conservation equation:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h \vec{u}) = \frac{\partial p}{\partial t} + \vec{u} \cdot \nabla p - \nabla \cdot \vec{q_r} + \nabla \cdot (k \nabla T) + \sum_i (\nabla h_i \rho D_i \nabla Y_i) \tag{4}$$

where h is the specific enthalpy ($J \cdot kg^{-1}$), $\vec{q_r}$ is radiation flux (W/m^2), k is thermal conductivity ($W \cdot m^{-1} \cdot k^{-1}$), and T is the temperature (K).

Ideal gas equation of state [25,26]:

$$p_0 = \rho T R \sum_i \frac{Y_i}{M_i} \tag{5}$$

where R is the gas constant ($J \cdot \mathrm{mol}^{-1} \cdot k^{-1}$); M_i is the molar mass of component i (kg/mol).

2.2. Mechanical Smoke Exhaust Control Equation

When the flue gas layer is stable, we have

$$\dot{m}_e = \rho_g V_e, \tag{6}$$

$$\dot{m}_p = f\left(\dot{Q}_C,\ D_f\right) \tag{7}$$

where $\dot{m}_e$ is the mass flow of mechanical smoke exhaust (kg/s), ρ_g is the flue gas density, and V_e is the volume flow of smoke exhaust (m^3/s).

Designers can estimate the amount of smoke exhaust required by the smoke exhaust system to prevent the smoke from being reduced to a safe height within the safe evacuation time. The general safety height is calculated by the following formula:

$$H_c = 1.6 + 0.1\,H \tag{8}$$

where H is the building height.

3. Model Construction

3.1. Fire Growth Model

Since the combustion process is composed of the incubation period with slow growth at the initial stage and a subsequent significant growth period, the model was used to describe the changing relationship of heat release rate with time in the firing process, and the description formula is as follows:

$$Q = \alpha t^2 \tag{9}$$

where Q is the heat release rate of the fire source (kW), α is the fire growth coefficient (kW/s^2), and t is the fire development time (s). The fire growth coefficient α is taken as 0.1878.

3.2. FDS Software Introduction and Model Verification

FDS (Fire Dynamics Simulator) software is a powerful fire dynamic simulator developed by the National Institute of Standards and Technology (NIST) [27]. The software is suitable for simulating fire scenarios with thermal drive and low-speed airflow. FDS software is also a field simulation software based on computational fluid dynamics (CFD). It solves the continuity equation, mass equation, momentum equation, and energy equation through the basic governing equation in Section 2.1 and obtains the distribution changes of fire-related physical quantities such as temperature, gas velocity, and gas concentration. At present, many scholars use FDS software to simulate subway fires. Luo [28] used FDS to research the possibility of adopting different ventilation modes for smoke confinement in a subway station fire accident. Tavakolian [29] used FDS software smoke evacuation in an island platform station, and a two-sided platform station was simulated in a three-dimensional configuration. Many experiments and field studies have verified the feasibility of FDS software to study subway smoke control. Therefore, we used FDS software for numerical modeling.

At present, the parameters of the numerical model are generally selected according to the design specifications. In our study, the ventilation volume of large-scale system smoke exhaust was 40 m^3/s. This was the same as the research [30] parameters of track smoke exhaust in the single tunnel and double-track tunnel. We took an island station as an example, and a 1:1 full-scale numerical model was established to study the smoke exhaust effect of rail top.

3.3. Model Parameter

Taking the island subway station as the research object, we situated the island platform between the up and down railways for both up and down passengers, which connected the up and down tunnels. An island station in a city generally runs east–west with a total length of 174.3 m. The public area of the platform was about 1250 m^2, and the public area of the station hall was about 750 m^2. There were four entrances and exits: A, B, C, and D. The station was divided into three floors, and the loading area was separated from the rail area by PSD. The size of PSD at both ends of the train was 1.60 m $\times$ 2.15 m, and the size of the other PSD was 2.0 m $\times$ 2.15 m, with 24 PSD on each side of the platform. The platform train adopted six-car marshaling, the calculated length of the platform was 118 m, the calculated length of the platform within the PSD range was 113 m, the width was 20 m, and there were three connecting channels. The three-dimensional calculation model was constructed using Pyrosim. The model was divided into 14 grid areas, and the grid on the platform floor was encrypted. The default grid was closed, and the grids at exits A, B, and C were set as open grids to achieve the air pressure balance inside and outside the station. The building material was concrete, the smoke baffle and PSD were set as glass, and the escalator in the station was replaced by steps in the model; the model floor height was the height from the station floor to the ceiling. The physical model and the locations of exits, air supply, and exhaust on each platform layer are shown in Figure 1.

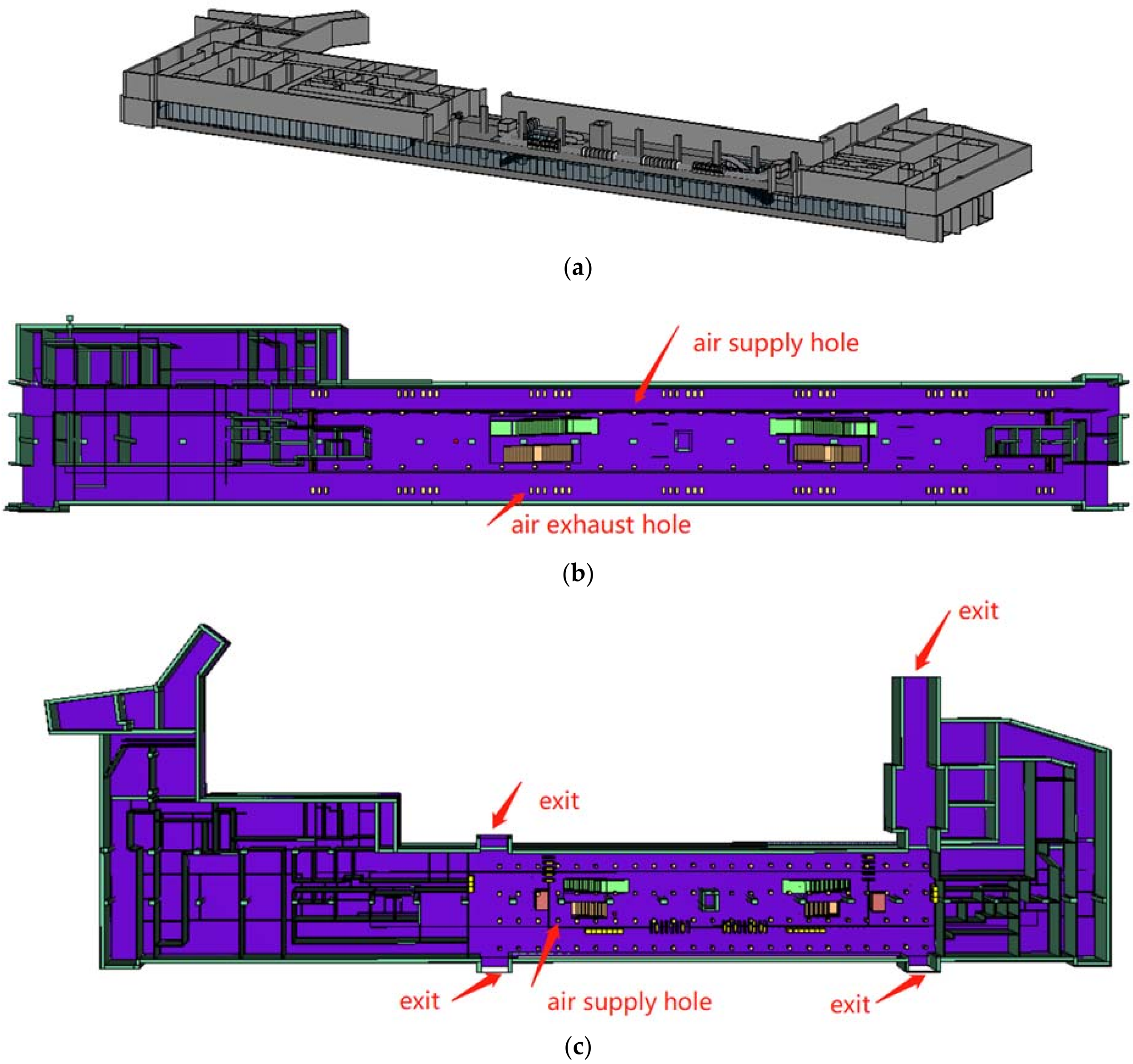


Figure 1. Calculation model. (**a**) Overall model. (**b**) Platform floor plan. (**c**) Plan of station hall floor.

3.4. Working Condition Design

We assumed that the fire scenario began when the lithium battery in a passenger's luggage on the train short-circuited and caught fire, igniting the luggage, other electrical appliances, and cables in the train. The platform train fire was selected as the growth t^2 type, and 7.5 MW was used as the simulated fire source intensity to simulate the fire scenario in the middle carriage after the train arrived at the station at the peak of passenger flow. A time of 400 s was set to reach the maximum power of 7.5 MW. After the fire, all screen doors were opened for passengers to leave the compartment quickly. Under the condition of opening the smoke exhaust system of the station, we started the tunnel fan or the rail top smoke exhaust system for smoke exhaust. The working condition settings are shown in Table 1.

Table 1. Operating mode.

Fire Condition	Platform Smoke Exhaust/(m^3/s)	Air Supply in Station Hall/(m^3/s)	Rail Top Smoke Exhaust /(m^3/s)	Left End TVF/ (m^3/s)	Right End TVF/(m^3/s)
C1	−40	+40	−60	—	—
C2	−40	+40	—	+60	−60
C3	−40	+40	—	−60	+60
C4	−40	+40	—	−60	−60

"+" indicates air inlet; "−" indicates air exhaust.

4. Results and Analysis

4.1. Smoke Spread Process

To study the influence area and characteristics of smoke spread during the progression of the subway fire, the smoke-spreading cloud diagrams at 420 s under four working conditions were compared, as shown in Figure 2.

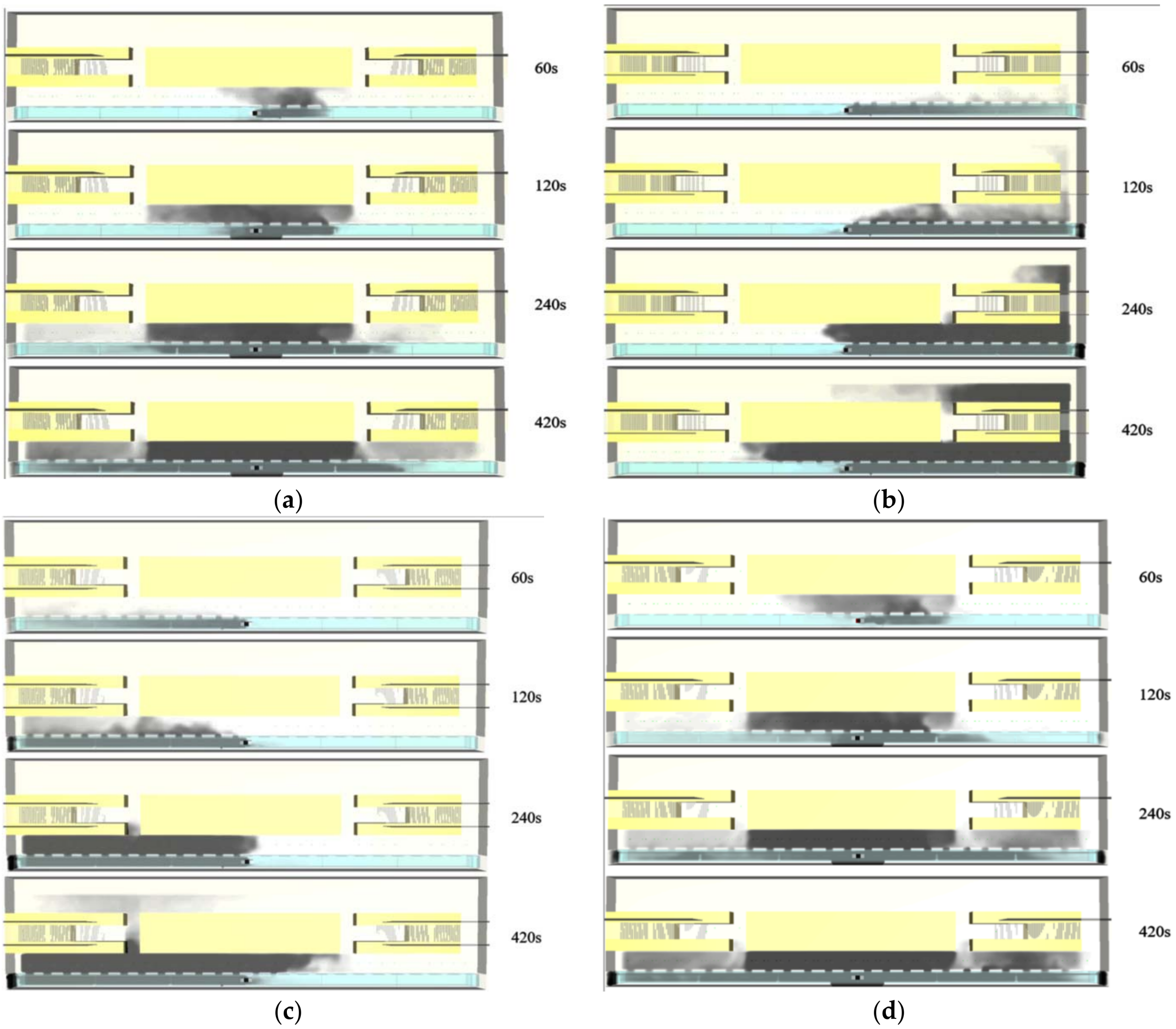


Figure 2. Smoke-spreading process. (**a**) C1. (**b**) C2. (**c**) C3. (**d**) C4.

As shown in Figure 2, in working C1, at the beginning of the fire, the flue gas spread to the right of the fire source in the carriage. At 60 s, the flue gas spread to the first carriage of the fire source and then to the platform through the door. On the platform, the flue gas started to flow to the left again because it was blocked by the air inlet of the connecting passage stairs. At 120 s, the smoke in the train was controlled in the first carriage on the left and right sides of the fire source. The smoke on the platform spread to the left to the connecting channel and was also blocked by the air inlet of the stairs; the smoke was controlled between the two connecting channels. As the smoke spread on the platform was hindered, the smoke spread in the carriage accelerated. At 240 s, the smoke in the carriage was obviously aggravated, and the smoke obviously affected the second carriage on both sides of the fire source. The middle section of the platform was filled with smoke, and some smoke broke through the barrier of the connecting channel "wind curtain" and spread to both ends of the platform. At 420 s, except for the rightmost carriage in the train, the smoke was diffused in other trains and platforms on the fireside to varying degrees. The smoke at both ends of the platform was significantly thinner than that in the middle of the platform, and the three platform-connecting channels and two stairways were not affected by the smoke from beginning to end.

Under working C2, the flue gas flowed obviously to the right side of the fire source at high speed. The flue gas in the train reached the carriage at the right end in 60 s. After 120 s, the smoke in the carriage was more obvious. Some of the smoke in the tunnel and on the platform was discharged through the outlet at the right end. The smoke on the platform was obviously aggravated. More smoke flowed from the carriage to the platform and quickly to the fire detection platform through the rightmost connecting channel under the action of airflow. Fortunately, the smoke on the platform was thin. Gradually, the train filled with smoke, and a large amount of smoke began to accumulate on the platform, and the air inlet of the connecting channel on the platform could hardly produce a wind curtain effect on the smoke under the influence of tunnel exhaust. At 240 s, the smoke quickly filled the platform on the right half side and spread to the platform on the side of the non-fire tunnel through connecting channel No. 3. Moreover, the smoke spread into the No. 2 connecting passage, threatening the access to the No. 2 evacuation staircase. At 420 s, the smoke on the train and platform was very thick. The three carriages on the right were completely shrouded in smoke. The smoke on the platform accelerated to the left, and the platform on the fireside, connecting channels 2 and 3 and the right end of the platform on the other side, were covered by thick smoke.

Working C3 was the air inlet of the right tunnel and the air outlet of the left tunnel. The law of flue gas spread was similar to C2, but the direction of flue gas flow was opposite. In addition, since there was no connecting channel at the left end of the platform to connect with the platform on the other side, the smoke continuously collected at the left end of the platform and discharged outside the station through the tunnel smoke exhaust and mechanical smoke exhaust of the platform. The flue gas that could not be discharged in time continued to gather at the left end and finally overcame the wind pressure at the port of the connecting channel and entered the connecting channel. As shown in Figure 2, in connection channel 1, it was obvious that smoke gathered at 240 s, and it can be seen that smoke diffused to the platform on the non-fire side through the connection channel at 420 s. However, fortunately, there was no obvious smoke accumulation in the stairway behind the smoke baffle.

Working C4 was the tunnel exhaust on both sides and was a platform air supplement. The smoke exhaust effect was similar to that of working C1. At 60 s, the smoke spread to the first carriage on the left side of the fire source and to the platform through the door. On the platform, the smoke was blocked by the air inlet of the connecting channel stairs and began to flow to the left again. At 120 s, the smoke in the train spread rapidly, and a small amount reached the end carriage of the train; the smoke on the platform was heavier, but it remained controlled between the two connecting channels. As the spread of smoke on the platform was hindered, the smoke in the carriage became thicker. At 240 s, the middle section of the platform was filled with smoke, and some smoke broke through the "wind curtain" of the connecting channel and spread to both ends of the platform. The smoke at both ends of the platform was more obvious, but this was not caused by the smoke in the middle section of the platform breaking through the wind curtain of the connecting channel; it was mainly the result of the accumulated smoke in the carriage at the end of the train flowing to the platform again. At 420 s, the whole train on the fireside and the platform was affected by smoke to varying degrees. The smoke in the middle of the platform was much thicker than that at both ends. Although there was no smoke in the stairway, there was little smoke in both connecting channels, which affected the evacuation and transfer of personnel between the two platforms.

From the perspective of the smoke spread range, working C2 and C3 were more unfavorable. The smoke spread area was large, almost half of the platform area, and working C1 and C4 were slightly better. From the perspective of personnel escape, the smoke in working C2 and C3 spread rapidly, and the smoke in the carriage spread from the fire source to the end carriage of the train in 60 s. Thus, there was not enough time for passengers to escape from the carriage. Working C4 was slow, the smoke spread to the end carriage of the train in 240 s, and the smoke in working C1 was the slowest. In addition, under the settings of working C2, the smoke filled the connecting channel of the rightmost platform, which affected the transfer of the main door from the platform on the fireside to the platform on the non-fire side, and the two outlets of connecting channel 2 were blocked by smoke, which had a serious impact on people who wanted to escape through the stairs on the right. Under C3, the entire connecting channel 1 was full of smoke. Compared with the rightmost connecting channel under C2, personnel escape was more affected. Although there was smoke entering the platform at the non-fire side, it was thinner than working C2 and had little impact on personnel evacuation. Under C1 and C4, there was no smoke spreading to the platform on the non-fire side. The smoke on the platform was concentrated in the middle, and the overall effect was better than C2 and C3. Further comparing C1 and C4, we found that the smoke at both ends of the platform in C4 was thicker, and the smoke in the train carriage spread faster. Therefore, among the four working conditions, working C1 had the best effect, the smoke in the carriage spread slowly, most of the smoke on the platform was controlled between the two connecting channels, and the connecting channels were not affected by the smoke evacuation.

4.2. Temperature Field

To understand the temperature distribution characteristics in a subway fire, we analyzed the high temperature distribution area threatening to the human body in a fire and compared the temperature distribution characteristics of 330 and 420 s under four working conditions, as shown in Figure 3.

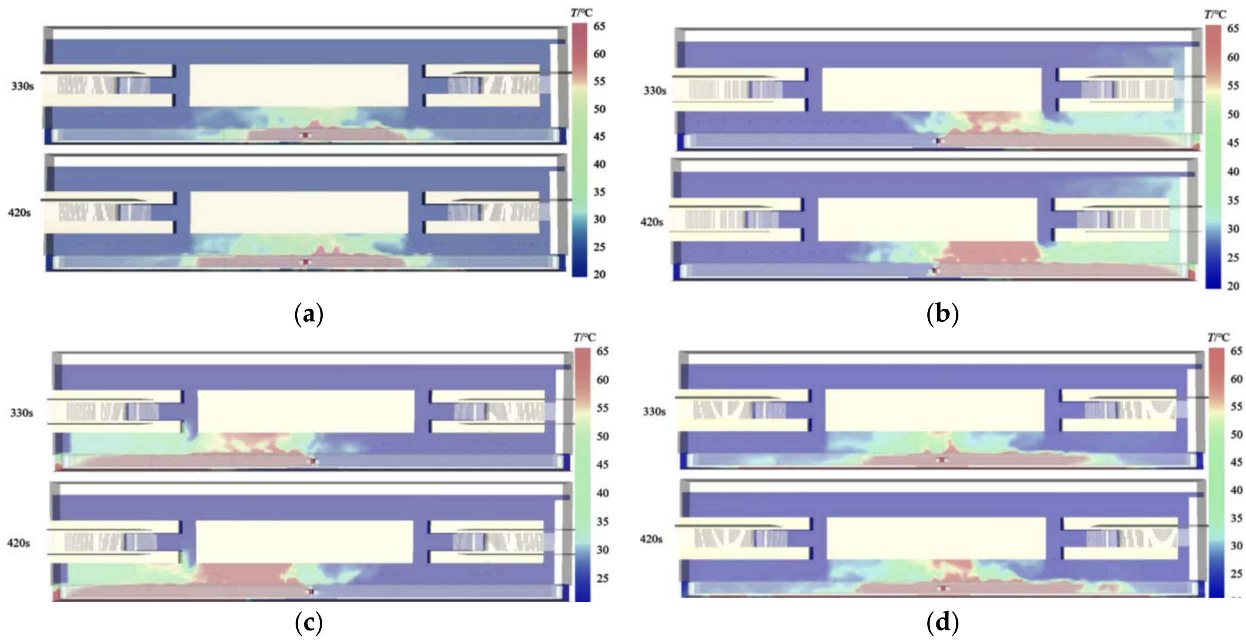


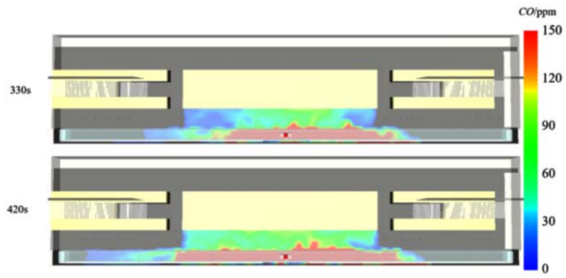
Figure 3. Temperature field. (**a**) C1. (**b**) C2. (**c**) C3. (**d**) C4.

Temperature distribution on the platform: under C1, the temperature on the platform was basically below the dangerous value, and only the PSD near the fire source was above 65 °C. The temperatures on the platforms of working C2 and C3 were much higher than that of working C1. The area about 30 m from the core of the platform was above 65 °C, and the minimum temperature in the downwind direction was also above 40 °C. The temperature distribution law on the platform of C4 was similar to that of C1, but the overall temperature was higher than that of C1, in which the high temperature area above 65 °C was concentrated near the fire source. Therefore, for passengers on the platform, working C1 was the best and they would not be threatened by high temperature.

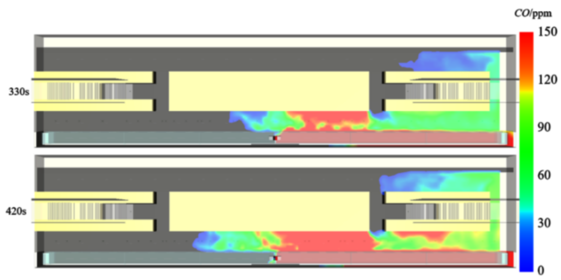
Temperature distribution in the compartment: working C1 followed the law of decreasing from the fire source to the compartments on both sides. At 330 and 420 s, the high temperature area above 65 °C changed little, and the range was about the length of the two compartments on both sides of the fire source. Under working C2 and C3, the upwind direction of the fire source was 20 °C, and the downwind direction was dangerous, being basically above 65 °C. Under C4, the high temperature area above 65 °C in the carriage was larger than that in C1. Therefore, under the four settings, passengers in the train would be in greater danger after a fire. The best way was to escape to the safe area of the platform as soon as possible.

4.3. CO Concentration

The cloud diagrams of CO concentration changes are shown in Figure 4.



(**a**)



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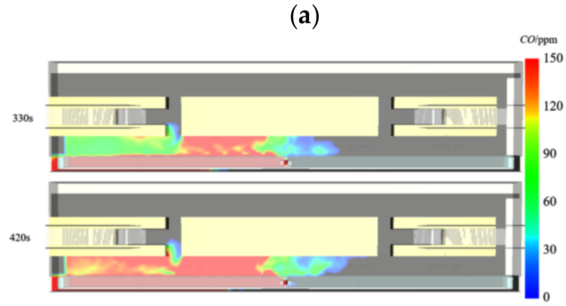

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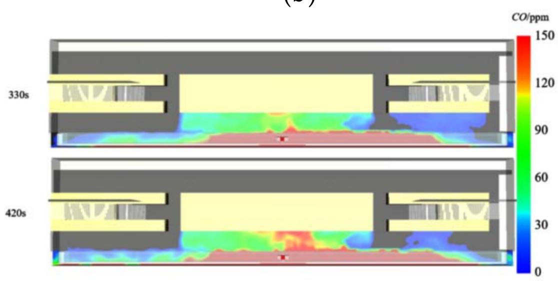

(**d**)

Figure 4. CO concentrations. (**a**) C1. (**b**) C2. (**c**) C3. (**d**) C4.

The codistribution law was consistent with the flue gas spread process. When working C1 was set at 420 s, most areas of CO concentration on the platform were between 0 and 90 ppm, and only the maximum concentration at the PSD in the middle of the platform reached 120 ppm. Therefore, we determined that the CO concentration on the platform was safe for personnel evacuation under working C1. At 330 s, the area where CO exceeded the dangerous value accounted for half of the train, distributed in two carriages on both sides of the fire source. The CO concentration distributions of working C2 and C3 were much more serious than that of working C1. At 420 s, the CO concentration in the compartment downwind of the train exceeded the dangerous value of 150 ppm. Under C2, the area with CO concentration above 90 ppm on the platform covered the platform on the non-fire side, and the CO concentration in the area affected by flue gas on the platform was generally above 40 ppm. Under C3, the left side of the platform on the fireside of the whole platform was above 150 ppm, and some areas were covered in the connecting channel. Under C4, the CO concentration in the carriage was the most dangerous. The area above 150 ppm covered two-thirds of the whole train. The CO concentration on the platform was much better than that under C2 and C3, but it was not as good as C1. The CO concentration in the middle area of the platform was still above 150 ppm, and the CO concentration at the right end of the platform was detected at about 30 ppm. In terms of the CO concentration field, the control effect of C1 was much better than those of other conditions.

5. Conclusions

To explore the rationality of the special emergency plan for a subway fire in China, we established a full-scale numerical model for a city subway. Taking an island station as an example, the variation characteristics of the smoke spread area, temperature field distribution, and CO concentration were analyzed, and the effects of rail top smoke exhaust and tunnel smoke exhaust on subway fire smoke control were studied innovatively. The specific results are as follows:

(1) Among the four working conditions, the rail top had the best smoke exhaust effect, the smoke in the carriage spread slowly, most of the smoke on the platform was controlled between the two connecting channels, and the connecting channels were not affected by the smoke evacuation.
(2) The temperature on the platform under the C1 working condition of rail top smoke exhaust was basically below the dangerous value, and only the PSD near the fire source was above 65 °C. During a fire, the passengers in the train were more endangered. The best way was to escape to the safe area of the platform as soon as possible.
(3) At 420 s under C1 smoke exhaust condition at the rail top, most areas of CO concentration on the platform were between 0 and 90 ppm, and only the maximum concentration at the PSD in the middle of the platform reached 120 ppm. The CO concentration on the platform was safe for personnel evacuation.

To sum up, for stations with tunnel ventilation and smoke exhaust in the station rail area, in case of fire at the train stop, we propose that the rail top smoke exhaust should be opened immediately, and personnel should be organized to evacuate to the safety of the platform through connecting passages and escape exits. If conditions permit, local small fans can also be added to meet the requirements of smoke exhaust. The follow-up study should refine the detailed rules of the plan and adopt more numerical and experimental means to promote the improvement of the plan, so as to further improve the operation safety of rail transit.

Author Contributions: Conceptualization, S.D. and K.W.; methodology, S.D. and K.W.; software, S.D.; validation, S.D., C.J., and K.W.; formal analysis, C.J.; investigation, C.J.; resources, S.D.; data curation, S.D.; writing—original draft preparation, K.W.; writing—review and editing, K.W.; visualization, S.D.; supervision, S.D.; project administration, S.D.; funding acquisition, S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the National Natural Science Foundation of China, grant number 51875073.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was financially supported by the following funds: The National Natural Science Foundation of China (51875073). The authors are also grateful to the anonymous reviewers for their constructive comments.

Conflicts of Interest: The authors declare no conflict of interest.

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