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Fire Risk Analysis of Luggage in Subway Station based on FDS

Shengkai Qin

School of Electrical Engineering and Automation, Henan Polytechnic University, Jiaozuo 454000, China

ABSTRACT

This paper examines the fire risk in subway stations using FDS software, establishing fire models for both subway cars and platforms. It simulates a luggage fire scenario to investigate its impact on personnel evacuation. The study reveals that luggage fires spread rapidly within subway cars and on platform levels, leading to a sharp decline in visibility, significant increases in temperature and CO concentration, thereby posing a severe threat to evacuation efforts. By constructing and simulating an evacuation model, this research calculates evacuation times under various scenarios and compares these with the time it takes for danger to arrive. Results indicate that evacuation can be completed before danger arrives in all simulated fire scenarios. This research proposes strategies for subway fire prevention and control, including the rational layout of subway facilities, utilization of advanced firefighting equipment, and establishment of fire zones, aiming to reduce the likelihood and spread of fires, enhance subway fire prevention and control capabilities, improve personnel evacuation efficiency, and ensure operational safety.

KEYWORDS

FDS; Fire Simulation; Luggage Fire; Personnel Evacuation; Fire Prevention and Control.

1. INTRODUCTION

As an important part of modern urban transportation, the metro has developed rapidly around the world in recent years. In China, the development of subway is particularly significant, and it has become an indispensable part of the urban transportation network. However, due to its unique environment and spatial characteristics, subway fire has significant dangers and characteristics, including: fire is difficult to detect and extinguish, the underground space is closed, the source of fire is not easy to be found, and it is difficult for firefighters to arrive at the scene of the fire quickly, and it is difficult to extinguish the fire; the fire will lead to a sharp drop in the oxygen content in the subway, and the combustion consumes a large amount of oxygen, which poses a threat to the safety of people's lives; the fire will produce a large amount of toxic smoke The fire will produce a large amount of toxic smoke, toxic gases and soot is not only harmful to the human body, but also affect the line of sight, increasing the difficulty of evacuation; subway smoke and heat effect is poor, the subway space is narrow and closed, smoke and heat is difficult to effectively discharged, exacerbating the hazards of the fire; the evacuation of people is difficult, the evacuation channel is limited, the smoke, flames and panic make evacuation become chaotic and difficult. In summary, subway fires have many unique characteristics and dangers, and it is crucial to strengthen prevention and emergency management.

The causes of subway fires are varied and complex, including malfunctioning electrical equipment, unauthorized operation of fires, passengers carrying flammable and explosive materials, arson,

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leakage of gas pipes, fires in connecting commercial or residential buildings, vehicle failures, problems in tunnel design and construction, natural factors, and management negligence [1-2].

At present, a lot of work has been carried out by scholars at home and abroad in the research of subway fire simulation [3-12]. In the research content covers the causes of subway fire, fire spread law, smoke diffusion characteristics, personnel evacuation behavior and other aspects. The research methods mainly include experimental research and numerical simulation. Experimental research is limited by experimental conditions, cost and safety, which makes it difficult to conduct large-scale and full-size experiments. Numerical simulation methods have gradually become the mainstream of subway fire research, and computer simulation technology, such as FDS and other fire simulation software, is mainly used to simulate and analyze the fire scenarios by constructing subway fire simulation models. Yang Zhou et al [13] took a double-decker underground subway station in a certain place as a research object to study the smoke flow and the safe evacuation strategy of passengers in the event of subway fire. Wang Jipo [14] constructs a corresponding model for the occurrence of fire in the corridor of the underground equipment area and compares and simulates the effects of several different smoke evacuation schemes in the area. Yi Xin [15] established a combination of 1:10 small-size subway tunnel fire experimental device and FDS fire numerical simulation to study the effect of longitudinal ventilation wind speed on the temperature field distribution law and smoke spreading process of subway tunnel fire.

This paper uses FDS fire simulation software to establish a model simulation of luggage fire in subway carriages and subway platforms, so as to gain a deeper understanding of the characteristics and hazards of fire in subway stations, analyze the impact of fire on the evacuation of subway station personnel, and put forward measures for the prevention of subway fires and emergency response, so as to improve the ability to prevent and control fires, safeguard the safety of personnel, reduce economic losses, and enhance the level of subway operation and management.

2. FIRE DYNAMICS SIMULATION SOFTWARE AND THEORETICAL FOUNDATIONS

2.1. FDS Fire Dynamics Simulator

FDS is a program developed by NIST, the U.S. fire research agency, for solving fire-driven fluid flow problems, in which the main function is to use field simulation to solve the spatial distribution of various state parameters and their changes with time during the fire process. The software can represent the phenomena and the distribution of relevant physical quantities during the fire in a more detailed way, and the accuracy of FDS has been generally verified and highly evaluated through a large number of experimental studies [16]. Meanwhile, FDS has a complete program structure and powerful data processing functions, and the accuracy of its simulation results has been verified by various experiments.

2.2. FDS Solves the Equation

The FDS simulation software solves the equations as follows:

Continuity Equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial\left(\rho u_j\right)}{\partial x_j}=0 \tag{1}$$

Momentum conservation equation:

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial \rho u_i u_j}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial P \tau_{ij}}{\partial x_j} \tag{2}$$

Component conservation equations:

$$\frac{\partial \rho m_s}{\partial t}+\frac{\partial \rho u_i m_s}{\partial x_j}=\frac{\partial}{\partial x_i}\left(\frac{\mu}{Sc}\frac{\partial m_s}{x_j}\right)-w_s \tag{3}$$

Energy conservation equations:

$$\frac{\partial \rho C_P T}{\partial t}+\frac{\partial \rho C_P u_j T}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\mu}{Pr}\lambda\frac{\partial C_P T}{\partial x_j}\right)+w_s Q_s \tag{4}$$

Where: ρ is the component density, g/m^3; u is the component velocity, m/s; g is the component mass, g; C_p is the constant pressure specific heat, J/(kg·K); T is the component temperature, K; μ is the component viscosity coefficient, Pa·s; P_r is the Planck's number; and $w_s Q_s$ is the source of interference.

3. MODEL BUILDING

The fire simulation software FDS is used to construct the physical model of the subway interval tunnel, as shown in Fig. 1 and Fig. 2. This paper assumes that the fire simulation of different working conditions occurring when the subway train stops at the subway station, the whole model consists of subway station and subway car two parts, the subway tunnel for the open space, while the subway station and subway car for the closed rectangular structure.

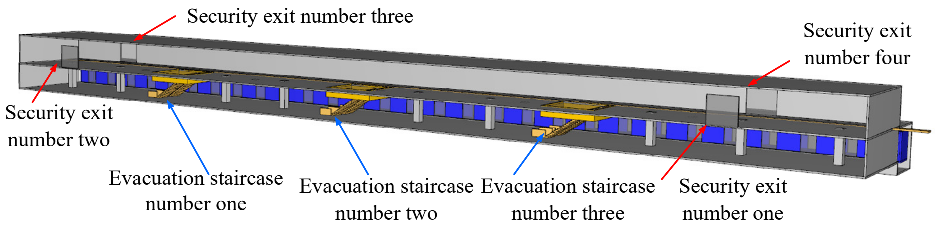

Fig 1. Subway station model diagram

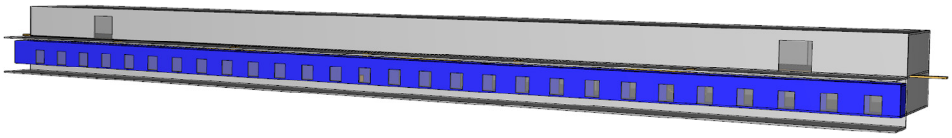

Fig 2. Subway train model diagram

3.1. Model Parameters

The initial temperature of the simulation model environment is 20℃, the initial pressure is 0.1MPa, the environmental humidity is 40%, and the simulation time is 360 s. The standard underground two-storey island-type station is located in the first basement level for the concourse level, and the second basement level for the platform level. Station effective platform length of 144m, station hall level height of 4.8m, platform level height of 4.2m, platform level and station hall level width are 13.6m, subway column length of 144m, 3m wide, 3.8m high, subway tunnel width of 6m, 6m high, subway tunnel platform one side of the tunnel, the tunnel above and above the station hall level were equipped with 5 mechanical smoke exhaust, smoke exhaust wind speed 5m/s, the station platform is equipped with 3 groups of The platform has three sets of stairs leading to the station hall level, and the specific model parameters are shown in Table 1.

Table 1. Model-related parameters

	Length	Width	Height	Thickness	Material composition
Station Hall Level	144m	13.6m	4.8m	0.2m	concrete
Platform level	144m	13.6m	4.2m	0.2m	concrete
Subway car	144m	3m	3.8m	0.2m	stainless steel
Subway tunnel	144m	6m	6m	0.2m	concrete

3.2. Model Mesh

In the FDS calculation process, meshing is an important part of the simulation calculation process. Reasonable configuration of the mesh can not only improve the accuracy of the simulation results, but also effectively reduce the time required for computation, which in turn improves the simulation efficiency and realizes efficient work. Although, theoretically, a more detailed grid division can bring about higher computational accuracy, since fire scenarios often contain thousands of grid cells, the pursuit of higher accuracy often means that longer computation time must be accepted. In this simulation, a uniform grid division is used, and the grid sizes are all 0.5 m. This not only ensures computational accuracy but also maintains the effective transfer of data between the grids. The total number of meshes in this model is 250160, the details of the meshes are shown in Table 2, and the mesh division is shown in Figure 3.

Table 2. Detailed parameters of each grid

Area Name	Grid Size/m	Number of Grids
Station Hall Level	0.5×0.5×0.5	84960
Platform level	0.5×0.5×0.5	103840
Subway tunnel	0.5×0.5×0.5	61360

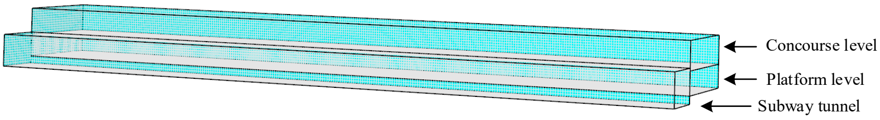

Fig 3. Grid division of the subway station model

3.3. Measurement Point and Slice Setup

In this subway station model, 9 measurement points are arranged on the platform level, located in three groups of stairs at a height of 2.2m, and 3 measurement points are arranged at an interval of 0.4m in each group of stairs, each group of measurement points includes carbon monoxide concentration measurement points, temperature measurement points, and visibility measurement points; 12 measurement points are arranged on the concourse level, located at a height of 2m on both sides of the concourse level wall and 1m from the wall, and 3 measurement points are arranged at an interval of 0.4m in each group of stairs. Three measurement points were arranged, and each group of measurement points included carbon monoxide concentration measurement points, temperature measurement points, and visibility measurement points. The subway station model measurement point layout is shown in Figure 4.

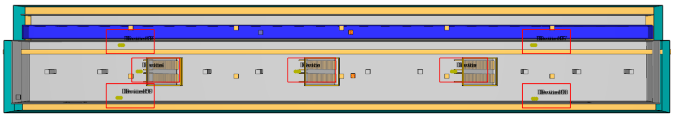

Fig 4. Point layout for measurement

In order to view and analyze the simulation results more intuitively, carbon monoxide concentration, temperature, visibility, etc. can be recorded and analyzed in the whole plane range by creating 2D slices. In this subway station model, four positions of slices are set up, which are located in the plane where the center axis of the subway train is located (Y=16m), in the plane where the horizontal center axis of the subway train is located (Z=2m), in the plane where the center axis of the overall model is located (X=75m), and in the plane where the horizontal plane of the station concourse level is located at a distance of 2m from the floor of the station concourse level (Z=6.6m), and each of these positions includes a temperature slice, a carbon monoxide concentration slice, visibility slices. The subway station model slice arrangement is shown in Figure 5.

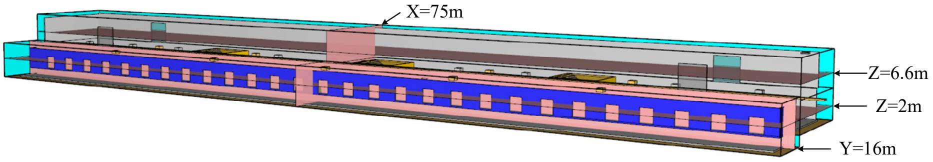

Fig 5. Slice settings

3.4. Working Condition Design

This paper is mainly for the subway station platform level, subway internal fire simulation analysis, the middle of the platform level and the middle of the subway car respectively set the fire source power of 3MW luggage fire. The baggage fire adopts mechanical smoke exhaust for the fire on the platform level and tunnel smoke exhaust for the fire in the subway car. The specific working condition setting parameters are shown in Table 3.

Table 3. Subway fire simulation parameters

Condition number	Location of fire source	Power of fire source	Smoke Exhaust Method
GK1	Platform level	3MW	mechanical smoke exhaust
GK2	Subway car	3MW	tunnel smoke exhaust

4. FIRE SIMULATION AND ANALYSIS OF RESULTS

The simulation of baggage fires was carried out on the platform level of the subway station and the subway car respectively, focusing on the analysis of the smoke spreading process, the evolution of the visibility with time, the evolution of the temperature with time, and the concentration of CO, to explore the impact of baggage fires on the evacuation of people in the subway station.

4.1. GK1 Fire Simulation Results and Analysis

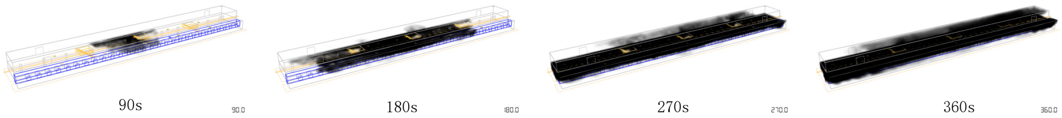

Fig 6. The process of smoke spreading during the fire on the platform level of GK1

The simulation results of the smoke spreading process of the fire on the platform level of GK1 subway are shown in Figure 6. The simulation analysis shows that when a fire occurs in the middle of the platform level, the smoke first forms a high-concentration area around the fire source, and then spreads to the opposite side of the platform through the lateral channel. During this process, the smoke exhaust fan is activated and starts to discharge the smoke. However, due to the rapid spread of smoke, a small amount of smoke was still entering the station concourse level through the passageway at 180 seconds after the fire. By 360 seconds after the fire, the smoke concentration at the station concourse level had increased significantly, affecting the evacuation of people.

In the case of fire in subway carriages and platform level, the change of visibility has a crucial impact on the evacuation of people. As shown in Figures 7 and 8, the evolution of visibility over time at the platform level and the station concourse level of GK1, respectively, we can clearly see the impact of the fire on the visibility of different areas and its change process over time. After simulation and analysis, it can be seen that after the fire on the platform level of the subway, the smoke spreads rapidly in all directions, resulting in a sharp decrease in visibility. At 190s of the fire, the visibility out of the evacuation staircase is less than 10 meters, which increases the evacuation time and the risk of people getting lost in the evacuation process. At 360s of the fire, the visibility situation on the station hall level showed a significant difference. The visibility at the safety exit on the left side of the concourse level was less than 10 meters, which seriously affected the evacuation of people. The visibility at the exit on the right side of the concourse level was more than 10 meters, which was better and allowed people to evacuate more smoothly.

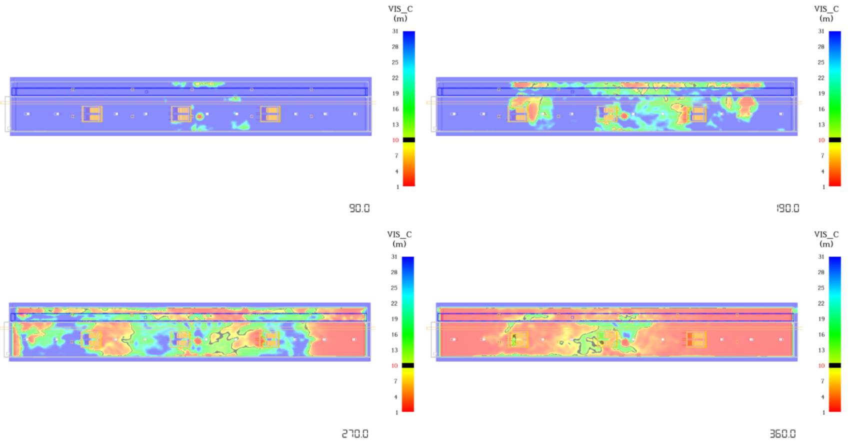

Fig 7. Visibility on the platform level of GK1

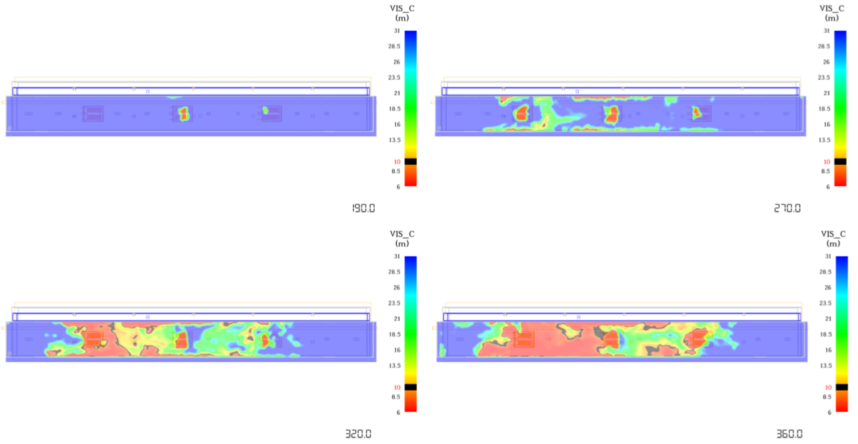

Fig 8. Visibility on the station hall level of GK1

As shown in Fig. 9, the temperature slice of Y=6m in GK1 subway station can visualize the temperature changes in different locations in the subway station after the fire. By analyzing the temperature slices, it can be found that the high temperature gas mainly accumulates in the ceiling of the platform level, and the high temperature region spreads along the ceiling in all directions, forming an obvious high temperature zone. This phenomenon indicates that the heat generated by the fire is mainly concentrated in the upper space of the station level and has a tendency to spread in all directions. The presence of high-temperature gases has already posed a threat to the temperature environment on the platform level, and if the fire continues to spread, the high-temperature gases may further spread to other areas on the platform level, resulting in a continuous rise in temperature. According to the requirements for safe evacuation, the temperature of the smoke layer should be controlled within 60°C. If the fire is not effectively controlled, the temperature may rise rapidly, thus seriously affecting the safe evacuation of personnel.

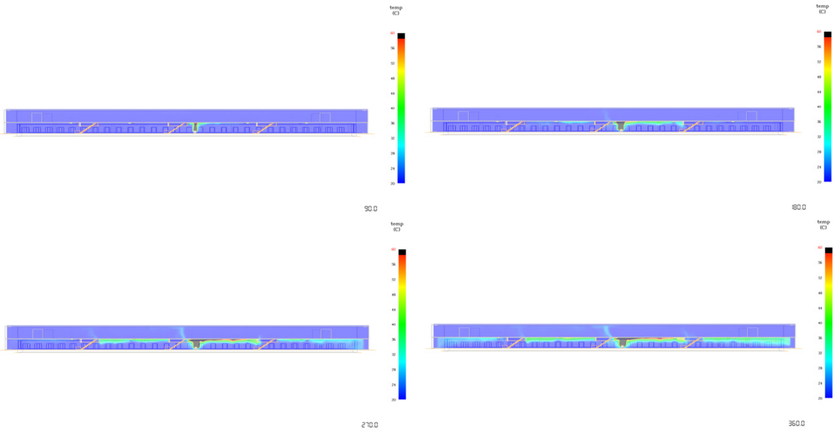

Fig 9. Temperature at GK1 (temperature slice at Y=6m)

During the evacuation of personnel, the CO concentration needs to be strictly controlled below 250 ppm [17] in order to effectively ensure the safety of personnel during the evacuation process. As shown in Fig. 10, the CO concentration slice at Y=6m in GK1 subway station can visualize the change of CO concentration at different locations in the subway station after the fire. By analyzing the CO concentration slices, it can be found that the CO concentration in the subway station increases significantly with time, especially in the fire area and its periphery. The CO concentration is higher above the fire area, and the high concentration area gradually expands with time.

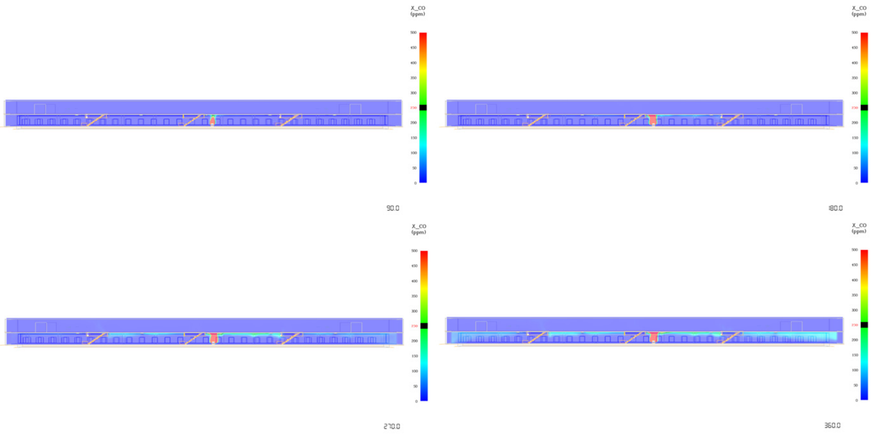

Fig 10. CO concentration at GK1 (CO concentration slice at Y=6m)

4.2. GK2 Fire Simulation Results and Analysis

The simulation results of the smoke spreading process of fire in GK2 subway carriages are shown in Figure 11. The simulation analysis shows that when a fire occurs in the middle position of the subway carriage, the smoke first spreads rapidly to both sides in the carriage, and due to the relatively narrow space in the carriage, the smoke can fill the whole carriage in a short time. Subsequently, the smoke spreads to the platform level through the connecting passages and doors at both ends of the carriage. During this process, the concentration of smoke gradually increased. 180 seconds after the fire, a small amount of smoke entered the concourse level through the stairway area on the platform level. At this point, the concentration of smoke on the concourse level was relatively low, but was beginning to affect visibility. By 360 seconds after the fire, the smoke concentration in the stairway area on the concourse level had increased significantly. The high concentration of smoke in this area seriously affected evacuation. In contrast, smoke concentrations in other areas of the concourse level were relatively low, allowing evacuation to proceed more smoothly.

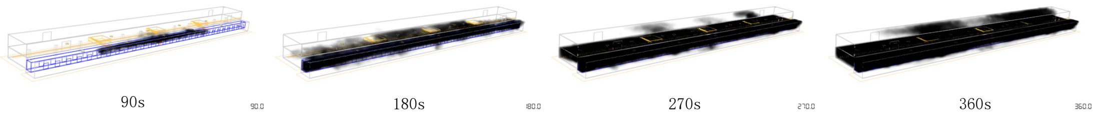

Fig 11. The process of smoke spreading during the fire on the platform level of GK2

This case simulates a baggage fire in a subway train, so the temperature slice, visibility slice and CO concentration slice at Y=6m in the model are replaced to Y=16m, which is the middle position of the subway car. As shown in Figures 12 and 13, the evolutions of visibility over time at the platform level and the concourse level when the fire occurred in the GK2 subway car are shown, respectively.

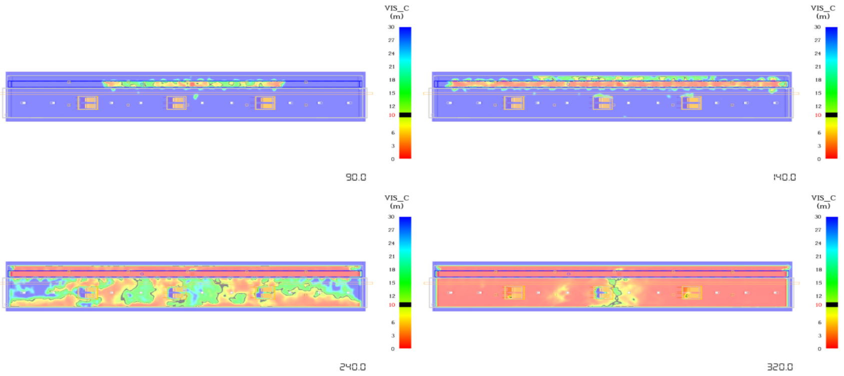

Fig 12. Visibility on the platform level of GK2

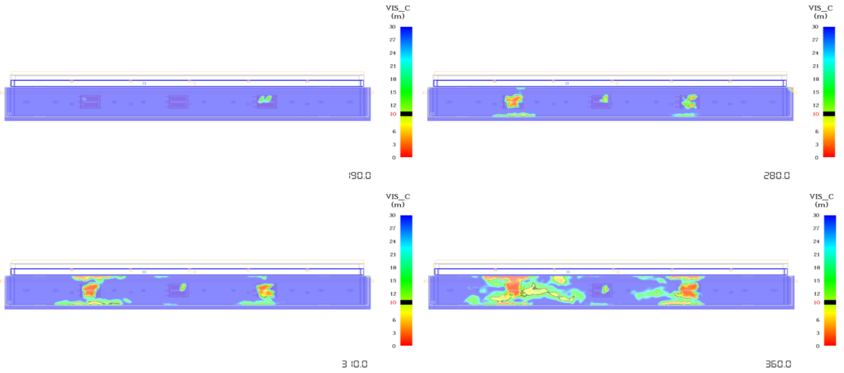

Fig 13. Visibility on the station hall level of GK 2

The simulation analysis shows that the visibility in the subway carriages decreases sharply when the fire occurs to 140s, and the visibility in the whole carriages is less than 10 meters, which makes the personnel in the carriages unable to identify the direction of evacuation effectively, and leads to the personnel in the subway can not be evacuated safely; when the fire occurs to 240s, the visibility of the left and right evacuation staircases on the platform level is less than 10 meters, and the smoke has passed through the connecting channels at both ends of the carriages and the station hall level, which is the middle position of the station hall. When the fire broke out to 240s, the visibility of both the left and right sides of the evacuation staircases on the platform level was less than 10 meters, and the smoke had already spread to the platform level through the connecting passages and doors at both ends of the carriages, resulting in a significant decrease in the visibility at the evacuation staircases. When the fire occurred in 360s, the visibility at the safety exits on both sides of the station hall level was more than 10 meters, and at this time, the visibility at the safety exits on both sides of the station hall was relatively good, and the personnel could be evacuated smoothly.

The temperature slice at Y=16m in the GK2 subway station is shown in Fig. 14. By analyzing the temperature slice, it can be found that the high temperature gas mainly accumulates at the top of the subway carriages, and the high temperature area spreads along the top of the carriages to the two ends of the train, which rapidly forms an obvious high temperature zone at the top of the carriages, and there is no obvious change in the temperature of the platform level and the station concourse level, but the temperature may continue to rise with the continuous spread of the smoke. The maximum temperature inside the subway carriages can reach more than 300 °C, seriously affecting the safe evacuation of people.

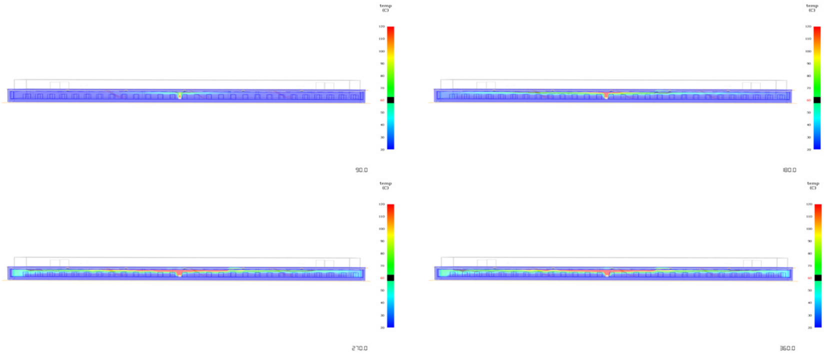

Fig 14. Temperature at GK2 (temperature slice at Y=16m)

The CO concentration slice at Y=16m inside the GK2 subway station is shown in Figure 15. By analyzing the CO concentration slices, it can be found that the CO concentration in the subway carriages increases significantly with time, especially in and around the fire area. At 90s of the fire, the CO concentration in most of the carriages had already exceeded 250 ppm, which means that the air quality in the carriages had already reached a level that is extremely harmful to human health. At 360s of the fire, the CO concentration on the platform and concourse levels had not yet increased significantly, but the CO concentration inside the subway carriages was already very high, and with the continuous flow of smoke, the CO concentration on the platform and concourse levels would continue to increase, which in turn would affect the safe evacuation of people.

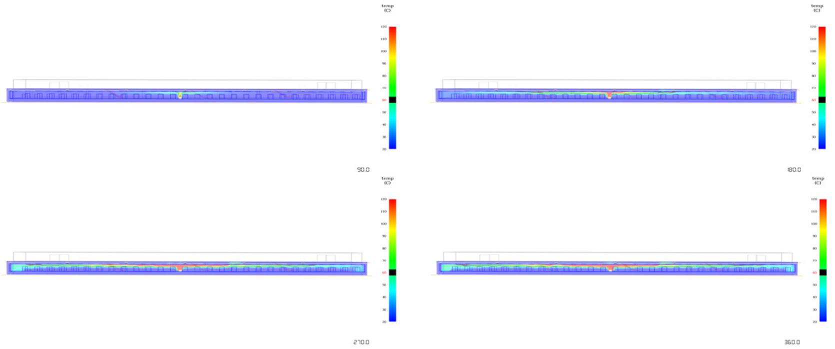

Fig 15. CO concentration at GK2 (CO concentration slice at Y=16m)

5. IMPACT OF FIRE SIMULATION ON EVACUATION

Fire simulation is of great significance in the study of personnel evacuation, which provides a scientific basis for the formulation and optimization of evacuation strategies by simulating the dynamic process of fire occurrence and development. By simulating fire scenarios, it can provide a scientific basis for evacuation path planning, evacuation time assessment, evacuation facility layout optimization and evacuation strategy development, thus improving the safety and efficiency of personnel evacuation in fire scenarios. By using PyroSim software in conjunction with Pathfinder software, the evacuation process under different fire scenarios is simulated, the actual evacuation time of the personnel is calculated, and the safety of the evacuation process is evaluated and judged based on the safety evacuation standards for personnel.

5.1. Construction of the Evacuation Model

The simplified model of the subway station and subway car is established by Pathfinder software, and the relevant parameters of the model are consistent with those constructed in PyroSim, which is divided into the platform level and the station hall level, in which the platform level is arranged with the train tunnel and evacuation staircase, and the station hall level is arranged with the evacuation staircase and the safety exits, ignoring the rest of the structure, and the passengers evacuate from the platform level to the station hall level through the evacuation staircase, then evacuate to the safety exits from the station hall level. The passengers are evacuated from the platform level to the station hall level through the evacuation stairs, and then evacuated from the station hall level to the safety exits.

As shown in Figure 16, the subway evacuation model is schematic. Combined with the number of subway carriages, considering the overall evacuation, set the total number of evacuees for 1860 people, assuming that all the exits are open, simulating the evacuation of personnel to the outdoor situation, the evacuation path is set for the personnel to choose the nearest safety exit.

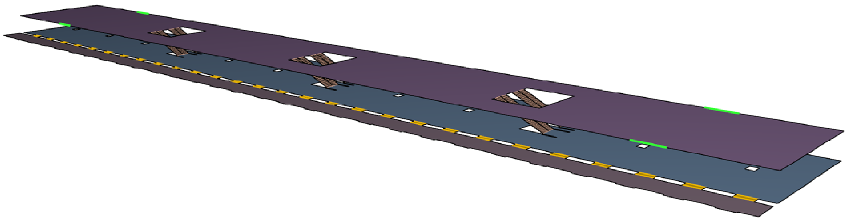

Fig 16. Schematic diagram of personnel evacuation model

5.2. Evacuation Results

The evacuation of the subway station platform level, station hall level and subway personnel were simulated, and the evacuation start time was set at 90s after the fire occurred, as shown in Figure 17 for the evacuation process of the subway station subway carriages and platform level and the evacuation process of the subway station hall level.

By analyzing the evacuation simulation results, it can be seen that the evacuation action time (ASET) of subway carriages is 30 s. Considering the fact that the evacuation process may be affected by a variety of uncertainties, such as the fire develops faster than expected, the smoke spreads faster than expected, which leads to reduced visibility, etc., it is necessary to multiply the evacuation action time by 1 and 2, so that the evacuation action time can be multiplied by 1 and 2, respectively. Therefore, the evacuation action time is multiplied by 1.5 times as a kind of safety margin to ensure that in the most unfavorable situation, the personnel still have enough safe time to complete the evacuation, so 1.5 times the evacuation action time of subway car is 45s, and the total time for evacuation completion is 135s after the fire; the evacuation action time of subway platform level is 139s, and 1.5 times the evacuation action time of subway platform level is The evacuation action time for the subway platform level is 139s, 1.5 times the evacuation action time for the subway platform level is 208s, and the total time for evacuation completion is 298s after the fire; the evacuation action time for the subway station hall level is 167s, and 1.5 times the evacuation action time for the subway platform level is 250s, and the total time for evacuation completion is 340s after the fire; the evacuation time of the people is as shown in Table 4.

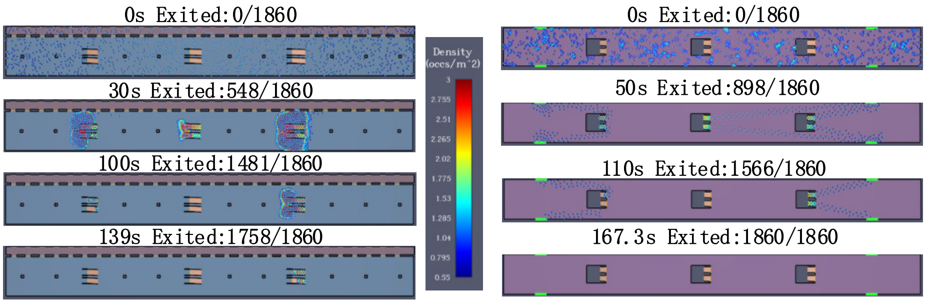

Fig 17. Evacuation process

Table 4. Evacuation time of personnel

Floor	Start time of evacuation /s	Evacuation operation time /s	1.5 times evacuation action time /s	evacuation time /s
Subway Car	90	30	45	135
Platform level	90	139	209	298
Station Hall Level	90	167	250	340

5.3. Subway Fire Safety Determination

After the comparison and analysis of fire simulation and evacuation simulation, the danger arrival time of GK1 subway carriages and platform layer is 360s, and the danger arrival time of station hall layer is more than 360s; the danger arrival time of GK2 subway carriages is 140s, and the danger arrival time of platform layer is 320s, and the danger arrival time of station hall layer is more than 360s.

The danger arrival time is greater than 360 s. Therefore, the fire scenarios simulated in this paper can ensure the safe evacuation of personnel, and the evacuation safety of each condition is shown in Table 5.

Table 5. Safety assessment

working condition	placement	Time of danger/s	Evacuation time/s	Safety Determination
GK1	Subway Car	360	135	safe
	Platform level	360	298	safe
	Station Hall Level	>360	340	safe
GK2	Subway Car	140	135	safe
	Platform level	320	298	safe
	Station Hall Level	>360	340	safe

6. CONCLUSION

(1) Through fire risk assessment, the main sources of fire risk can be identified and corresponding preventive measures can be taken, such as rationalizing the layout of metro facilities, adopting advanced firefighting equipment, and setting up fire protection zones, in order to reduce the risk of fire occurrence and spread.

(2) Through evacuation simulation, problems in the evacuation process can be identified and evacuation facilities and paths can be optimized to improve evacuation efficiency. Meanwhile, the introduction of intelligent technical means, such as intelligent monitoring systems and evacuation guidance systems, can further enhance the efficiency and accuracy of subway safety management.

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