Numerical Simulation of Smoke Control in Underground Space

1. Introduction

As the city develops, the land resource is becoming extremely scarce, which has impelled people to exploit the underground space [1–3]. As a result, the underground constructions are emerging constantly in cities, such as the subways, the underground commercial streets, the underground concourses, and the underground parks. The development of underground space started much earlier in European countries and 150 years have passed since the London’s first subway constructed in 1845. In China, the exploitation of urban underground space goes back to 1950s. Whereas Chinese underground space shows an enormous development potential, new problems for the fire safety arises as well.

The underground construction has a poor ability of natural ventilation. While the ground building can organize natural ventilation by windows, underground space can only connect the outsides through mechanical devices such as entrances, exits, ventilated shafts and the narrow crosssection. Once the fire happens in the underground space, the smoke moves following the same direction of personnel evacuation, which will give rise to a more severe damage compared with a fire in the surface of the building. In recent years, domestic and foreign researches have been carried out on smoke control in underground constructions.

Yang [4] carried out a group of full-size experiments in the MRT system and put forward smoke exhaustion strategies corresponding to different fire positions, which serves as a good reference. Huang et al. [5] study analyzed the effect of fire location on carbon monoxide concentration and smoke layer height and the effects of mechanical exhaust on temperature, exhaust system layout, and exhaust rate. Liu et al. [6] studied the spread of smoke under natural ventilation and found that the maximum temperature in the smoke layer decreased with the longitudinal spread of smoke. Hu et al. [7] made a full-size experiment about the performance of mechanical smoke extraction in an underground corridor, studied on how the relative distance between the air makeup vent and the smoke vent affected the efficiency of mechanical smoke extraction. He found that the
smoke would be exhausted more efficiently provided that the position of air makeup has a distance from the smoke vent, therefore the future research should be directed at the quantitative study on finding the best distance between the air makeup vent and the smoke vent. Hu et al. [7] pointed out as well that activating the smoke control system too early would have a malign effect on smoke extraction. In order to ensure the safety and reliability of underground subway ventilation system, Wang et al. [8] simulated and recorded the height of smoke layer, air flux of shaft, and smoke movement route. It was found that smoke diffusion along the ground floor ceiling could be suppressed by outdoor air flowing into the exhaust fan and smoke did not accumulate in the mezzanine. Long et al. [9] conducted a full-scale fire experimental study on smoke movement and control in subway stations. It is found that the influence of exhaust system on smoke propagation time is related to the location of fire source. Shi et al. [10], through theory analysis, built up a calculation model of mechanical ventilation rate for the large space in a warehouse. His team carried out a whole size of hot smoke test to study the course of fire spreading according to the air change per hour in the warehouse, and put forward the method of assisting the mechanical smoke extraction in the dangerous warehouse. Liu et al. [11] studied the ceiling temperature, smoke layer thickness, and temperature distribution in the station through full-scale experiments. Experiments have proved that the spread of smoke can be effectively controlled when the mechanical smoke exhaust system is turned on. Zhou et al. [12] carried out numerical simulation on the effect of positive pressure ventilation in superlarge underground space. The smoke control effect under this condition was analyzed. The study found that the mechanical exhaust volume has a greater impact on the flue gas control effect than the air supply volume. Through a small size experiment, Ji et al. [13] from USTC draw a conclusion that the smoke vent should not be set at the position where the smoke took one-dimensional horizontal motion in a long aisle, and the distance between the smoke vent and the fire source should not exceed 1.33 times in width than that of the aisle so as to decrease the air turbulence in the low-layer caused by the exhaust. When the mechanical smoke extraction was operated in an aisle with one opening, it would be better to start solely the smoke vent opposite the makeup air vent or to unlock the smoke vents on each side of the fire source. However, in an aisle with openings at both ends, the smoke vents on each side of the fire source should be activated [13]. In model experiments conducted by Luo et al. [14], while fire occurred in large space metro station hall, the ceiling exhaust nearly caused no reduction effect on smoke temperature, because the ceiling vents were too small compared with the space. Wang et al. [15] analyzed the characteristics of a subway fire site, ventilation and smoke exhaust device, put forward the idea of active disaster relief, put forward the expert system-decision support system for disaster rescue autonomous dynamic decision method, and determined the best air control and smoke exhaust scheme. It has high reference value. Tie [16] studied the smoke propagation process during fire in a 1/12th large space building apparatus, found that the smoke descent faster with fire occurred in the middle than in one end.

In this study to an underground bus station as the prototype, the chosen building smoke bay geometric model is established and FDS is suitable for solving the N-S equation of low-speed heat-driven flow. When a fire occurs in the underground Space, the software can well simulate the smoke flow and temperature changes during the fire. Through the comparative analysis of the relevant parameters of the exhaust air supply system performance, to provide theoretical support for the study of such problems.

2. Geometric Model

The details of an underground bus station are listed as follows: fire resistance rating: I, construction category: I, overall building area: about 38000 m², and three parts of the layout: the municipal traffic road, the bus area, and the waiting area. Automatic fire alarm system, sprinkler system, and mechanical smoke extraction system are installed in the building. There are five smoke screens (each 2 m high) in the bus area and six light courts (each 300 m²) in the waiting area. A firewall is installed along the centerline of the municipal traffic road to separate the station into two longitudinal symmetry fire compartments, as shown in Figure 1.

The paper selects the smoke bay in the middle of the building to make a numerical simulation analysis of the smoke control. The CFD model used in this study is FDS developed by NIST. FDS [17–19] is suitable for solving the N-S equation of low-speed heat-driven flow, and it can simulate the smoke flow and the heat transfer commendably. To highlight the movement of smoke, this simulation adopts the combustion parameters of polyurethane with the smoke generation fraction of 0.05.

The model size is 50 m × 60 m × 7 m, and the area of the smoke bay is 2200 m². Under the premise of economy and engineering calculation accuracy, the mesh size is set as 0.5 m × 0.5 m × 0.5 m. The fire source is located in the middle of the bay, as shown in Figure 2. The white on the left is the firewall, the right side is the exterior wall with a stairwell close to it, and the anteroposterior yellow baffles are smoke screens.

3. Model Analysis and Numerical Simulation

3.1. Fire Source. As the underground bus station is equipped with automatic alarm system and automatic sprinkler system, and the chief fire source might be the luggage carried by passengers. According to the building specification and the parameters of the sprinkler head, the safety factor is set as 1.5-fold. It could be confirmed that the maximum heat release rate in the fire is 6.0 MW under the control of automatic fire extinguishing system, as shown in Figure 3. In the simulation test, the fire source is T square fire and the growth factor is 0.0765 kW/s², which belongs to the rapid fire [20], as shown in Table 1. Assuming that the smoke
extraction and the air makeup system open in 30 seconds after the fire occurs.

3.2. Smoke Extraction and Air Makeup System. In this paper, a smoke bay is selected in the underground transit station, and four different smoke control programs are set (Table 2) to provide a quantitative reference for the smoke exhaust design, compared to the simulation results.

4. Results and Analysis

Temperature and visibility slices are generated within FDS in a Y-Z plane, and monitoring point is set to get the
Table 2: Four different smoke control modes (“—” means closed).

<table>
<thead>
<tr>
<th>No.</th>
<th>Exhaust of the smoke bay</th>
<th>Air supply</th>
<th>Exhaust of adjacent smoke bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>B</td>
<td>Open</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>C</td>
<td>Open</td>
<td>Open</td>
<td>—</td>
</tr>
<tr>
<td>D</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
</tbody>
</table>

Table 3: Criteria of human safety.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limits</th>
<th>Limits consider the safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature 2 m height from the floor (°C)</td>
<td>&lt;100</td>
<td>≤60</td>
</tr>
<tr>
<td>Visibility 2 m height from the floor (m)</td>
<td>&gt;5</td>
<td>≥10</td>
</tr>
</tbody>
</table>

Figure 4: Four modes of temperature distribution plane graphs (X = 40 m). (a) Temperature distribution mode A (t = 480 s). (b) Temperature distribution mode B (t = 480 s). (c) Temperature distribution mode C (t = 480 s). (d) Temperature distribution mode D (t = 480 s).

Figure 5: Temperature comparison under 4 modes at the plane graph (Z = 4 m).
temperature and visibility changes. Temperature and visibility requirement of human safety is shown in Table 3.

4.1. Temperature Distribution. It can be seen from Figure 4 that the high temperature areas in the four modes are located in the upper part of the smoke exhaust area. High temperature smoke accumulates in the upper layer and the smoke screens effectively prevent the smoke from spreading to the neighboring partition. In contrast, mode A has a higher temperature (the top layer temperature up to 82°C) and more high temperature regions. Figure 5 reflects that the sequence of the average temperatures at the plane $Z = 4 \text{ m}$ from high to low is $A > B > C > D$.

While starting the smoke extraction system, opening the air makeup system will ensure a more efficient smoke exhaust. But it should be noted that the velocity of air makeup should not be too large to disturb the smoke stratification. The makeup volume here is less than half of the exhaust.

4.2. Visibility. Figure 6 conveys that the upper zone visibility is worse and the lower zone is better. There is a clear distinction between the upper and the lower form which we can infer that the smoke layer is stratified well. Because the smoke extraction systems have been activated both in the smoke bay and in the adjacent area, the smoke has been
discharged faster and relatively less smoke occupies the upper area of mode D. Meanwhile, Figure 7 shows that at the height of \( Z = 4 \) m, the visibility in the model A and B is reduced below 10 m, whereas the visibility is no less than 10 m in mode C and D.

5. Conclusions

As far as this study is concerned, for underground bus stations, the source of fire may mainly come from the luggage carried by passengers. Assuming that the smoke exhaust and air supply system is opened within 30 s after the fire, three devices are set up: exhaust outlet, air supply, and exhaust of adjacent smoke bin. Through temperature comparison, it can be found that the high temperature areas in the four modes are all located in the upper part, and the open-air supplement system can exhaust smoke more effectively. Through the visibility comparison, it can be inferred that the smoke layer is well stratified, and the smoke in the upper area is reduced when the smoke exhaust system is turned on.

Therefore, in case of fire in the local building, the smoke curtain should be activated in time and the smoke exhaust system in the relevant area should be activated. Opening the smoke prevention system in the surrounding area will not only accelerate the diffusion of the smoke to the area, but also accelerate the failure of the smoke to prevent the smoke from sinking. It should be pointed out that once the upper air filling system is opened, the smoke stratification will be disturbed, so it is necessary to consider to fill the air from the lower part. Therefore, in case of fire in the local lower space, the smoke exhaust device should be opened in a timely and effective manner to ensure the smooth air in the underground space and reduce the casualties caused by the high temperature toxic smoke produced by the fire.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

