Research Article

Numerical Simulation of Smoke Control in Underground Space

Hao-wei Yao,1,2 You-xin Li,1,2 Ke-feng Lv,1,2 Jin-guang Zhang,3 Zhong-bin Lv,3 Dong Wang,3 Zhen-yu Zhan,3 Xiao-ge Wei,1,2 Huai-tao Song,1,2 and Heng-jie Qin1,2

1College of Building Environment Engineering, Zhengzhou University of Light Industry, Zhengzhou 450001, China
2Zhengzhou Key Laboratory of Electric Power Fire Safety, Zhengzhou 450001, China
3State Grid Henan Electric Power Company, Zhengzhou 450052, China

Correspondence should be addressed to Hao-wei Yao; yaohaowei@zzuli.edu.cn

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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 outside through mechanical devices such as entrances, exits, ventilated shafts and the narrow cross-section. 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, there-
fore the future research should be directed at the qua-
titative 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 tem-
perature distribution in the station through full-scale ex-
periments. 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
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, ven-
tilation 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 50m × 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 sys-
tem, 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 au-
tomatic 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
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

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**Table 1:** T square fire type.

| Growth rate type | $a$ (kW/s²) | Characteristics of the time ($t_f$/s) |
|------------------|-------------|--------------------------------------|
| Slow fire        | 0.0029      | 600                                  |
| Medium fire      | 0.0117      | 300                                  |
| Rapid fire       | 0.0469      | 150                                  |
| Superquick fire  | 0.1876      | 75                                   |

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**Figure 1:** A plane graph of the underground bus station.

**Figure 2:** The FDS model of the smoke bay.

**Figure 3:** Heat release rate changes with the time.
Table 2: Four different smoke control modes ("—" means closed).

| No. | Exhaust of the smoke bay | Air supply | Exhaust of adjacent smoke bay |
|-----|--------------------------|------------|-------------------------------|
| A   | —                        | —          | —                             |
| B   | Open                     | —          | —                             |
| C   | Open                     | Open       | —                             |
| D   | Open                     | Open       | Open                          |

Table 3: Criteria of human safety.

| Parameter                                | Limits | Limits consider the safety factor |
|------------------------------------------|--------|----------------------------------|
| Temperature 2 m height from the floor (°C) | <100   | ≤60                              |
| Visibility 2 m height from the floor (m)  | >5     | ≥10                              |

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 $Z = 4$ 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 $Z = 4 \text{ m}$, 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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