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Experimental and numerical study on the smoke movement and smoke control strategy in a hub station fire

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ABSTRACT

Smoke movement is more complex in a station fire hub than in a common situation, and it is also difficult to deal with. In this paper, full-scale experiments were conducted to investigate the ceiling temperature, smoke-layer thickness and the temperature distribution within the station. The effect of smoke exhaust system and the velocity at staircase on smoke flow were investigated when the fire source located near the staircase, using a series of FDS numerical simulation. From the full-scale experiment and simulation results, several conclusions were made: (1) The full-scale experiment results showed that the sprinkler system was capable of confining the temperature rise if it is activated; (2) Meanwhile, it also proved that the propagation of smoke could be effectively controlled when the mechanical smoke exhaust system is switched on; (3) Based on the simulation results, smoke spread rapidly in the platform floor at the early stage and then it entered into the staircase when the smoke exhaust system was absent; (4) Even though the exhaust and supply system opened, smoke could still propagate through the staircase if there's no downward airflow at the entrance; (5) When the downward airflow existed, smoke still cannot be effectively discharged without the smoke exhaust system.

1. Introduction

Underground station hub has drawn a lot of attention because of its relatively sealed environment and narrow section. In case of fire, the toxic gases produced by the incomplete combustion are hard to discharge promptly out of the station. A lot of passengers will be trapped in the underground station and the smoke will definitely expose them into danger. In case of the fire, whether the smoke can be discharged out of the station and leave the staircase free of smoke is crucial to the evacuation for passenger and the suppression for fireman. A common strategy for the hub station is urgently needed.

At present, many scholars have carried out the research on the smoke back-layering flow behavior (Hu et al., 2008; Li et al., 2010; Oka and Atkinson, 1995; Wu and Bakar, 2000), smoke stratification characteristics (Newman, 1984; Nyman and Ingason, 2012; Tang et al., 2017; Yang et al., 2010) or smoke temperature distribution characteristics (Bailey et al., 2002; Hu et al., 2004, 2005; Kim et al., 1998) and related topics in the underground space, such as tunnel and soon. Researches on fire smoke in subway station mainly focus on ventilation mode, smoke emission parameters, ceiling temperature calculation, personnel evacuation and other aspects. Generally, three methods have been established in research of the hub station fire: full-scale experiment, small-scale experiment and the numerical simulation.

Many scholars have carried out small scale experiments and numerical simulations on the study of ventilation mode, smoke exhaust parameters and other factors in subway stations fire:Abu-Zaid studied the smoke spread at different fire locations in a subway station by using computational fluid dynamics, and emphasized the importance of mechanical ventilation for evacuation (Abu-Zaid, 1996). Chien et al. (2003) took a representative subway station of Taipei Rapid Transit System as the research object to simulate the smoke diffusion process of the subway station fire. The function of the smoke exhaust system and the chimney effect were analyzed. In Rie's work (Rie et al., 2006), three type of tunnel jet fan operating modes and their influence on the smoke control effect was studied. Park et al. (2006) carried out numerical simulation to study the influence of exhaust volume on the motion characteristics of hot smoke. Roh et al. (2009) used fire simulation and evacuation simulation to study the influence of PSD and ventilation on the safety of passengers in subway train fire. Gao et al. (2012a, 2012b) studied CO concentration and smoke diffusion under hybrid ventilation conditions, and further studied the effects of ventilation form, fire source location and heat release rate. Many scholars investigated the

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Nomenclature

c_p	air specific heat capacity at constant pressure (J/kg K)
d	distance from the fire to the end wall (m)
D	perimeter of the smoke section that contacts the tunnel surface (m)
D^*	characteristic fire diameter (m)
g	acceleration of gravity (m/s^2)
h'	total heat transfer coefficient (W/m K^2)
H	distance between the fire source and the ceiling (m)
H_c	height of the ceiling (m)
H_i	assumed smoke layer height (m)
H'	interface height of the smoke layer (m)
K_1	empirical constant in Eq. (9)
K_2	parameter in Eq. (10)
k	parameter in Eq. (10)
$\dot{m}$	smoke mass flow rate (kg/s)
$\dot{Q}$	fire heat release rate (kW)
Q^*	dimensionless heat release rate
r_1	integral ratio of the lower layer temperature
r_2	integral ratio of the upper layer temperature
r_f	radius of fire source (m)
r_i	sum of r_1 and r_2
ΔT	smoke temperature rise at a distance of x from the reference point (K)
ΔT_0	smoke temperature rise at the reference point (K)
ΔT_{max}	maximum temperature rise under the ceiling (K)
T_a	ambient temperature (K)
u	ventilation velocity (m/s)
u'	dimensionless ventilation velocity (m/s)
x	distance from fire source (m)
x_0	distance from reference point to fire source (m)
z	height of data points (m)

Greek letters

δx	nominal size of a mesh cell (m)
ρ_a	ambient air density (kg/m^3)

effect of smoke confinement with different ventilation mode in the buried station (Luo et al., 2014; Zhang et al., 2018; Zhou et al., 2018). Zhong et al. (2015) studied the influence of piston wind caused by tunnel train on the smoke flow of platform fire. Giachetti et al. (2017) studied the effects of the number of accesses and ventilation modes on smoke diffusion in subway stations. In addition, some scholars (Li and Zhu, 2018; Meng et al., 2014a; Wang et al., 2018; Yang et al., 2011) have studied the influence of platform screen doors (PSD) on smoke exhaust and evacuation in subway stations fire by numerical simulation.

The evacuation of personnel in subway station fires is also the focus of scholars' research. Many scholars (Li et al., 2012; Shi et al., 2012; Song et al., 2018; Zhong et al., 2008) have used evacuation simulation software and formulas to study the features of occupant evacuation behavior, the evacuation time, the passage flow rate of various forms of subway stations, such as cross interchange subway and deep buried metro station.

There is also a part of the study on the calculation of the ceiling temperature of subway stations fire. Ji et al. (2011a) proposed the ceiling maximum temperature prediction model in a platform fire based on the 1:8 small-scale experiments. The effect of end wall on the maximum temperature is taken into account, and a simplified calculation method of the correlation is proposed Meng et al. (2014b, 2017) studied the effect of smoke barrier height and fire heat release on the temperature distribution beneath the platform ceiling and the longitudinal temperature distribution along the tunnel ceiling were investigated. Wu et al. (2018) concentrated on the ceiling temperature distribution under the different fire locations in an atrium-style subway station, using numerical simulation. An experimental model of subway deep-buried station, with a scale of 1:10 was established by Shi et al. (2006) and Zhong et al. (2006), and a prediction model for the ceiling maximum temperature is proposed. Liu et al. (2019) studied the ventilation mode by FDS numerical simulation and full-scale experiments. Taking into account the parameters of tunnel ventilation fan (TVF), jet fan, ceiling duct, and the available co-work modes, the safety of tunnel under semi-hybrid ventilation mode was discussed.

When a platform fire took place, smoke will develop rapidly and spread to the upper layer through the staircases, it is affected by the chimney effect. However, the staircase is the vital path for evacuation. To keep the staircase safe, Chinese code (GB50157-, 2013) stipulates that the exhaust smoke volume should be calculated based on the area of a single smoke compartment multiplied by 1 m^3/m^2•min. The downward velocity should not be less than 1.5 m/s at staircases and escalators from hall to the platform. For a long period, the effects of the air velocity on smoke flow at staircases and escalators has been a concern to researchers and policy makers. Based on the theoretical analysis, Zhong (2007) conducted small scale experiments and proposed the prediction model for critical wind speed to prevent smoke. Furthermore, a theoretical analysis and numerical study by Fluent, Ji (2008) determined the critical parameters setting of air curtain, applied at the staircase to confine smoke.

In summary, there are many studies on smoke control in subway station fire, but most of them focus on the influence of different smoke exhaust modes or parameters on smoke control. The influence of downwind at staircases and its combined action with smoke exhaust system and air supply system on smoke exhaust and control remains to be further studied. The influence of the downwind at staircases, smoke exhaust system and air supply system on the smoke control near the

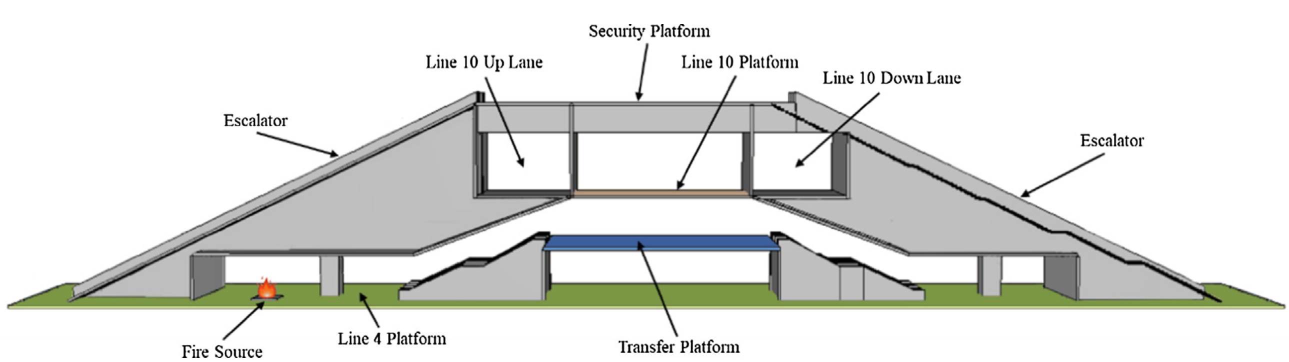

Fig. 1. The schematic of the station platform.