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Performance of smoke elimination and confinement with modified hybrid ventilation for subway station

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ABSTRACT

Smoke is the element of a fire that causes the greatest loss of life. The importance of eliminating smoke is underscored in the fire safety engineering of underground subway stations. In this study, an experiment and a numerical simulation were performed to determine the efficacy of different ventilation modes. The experiment was conducted on a 1:50 scale model of a subway station and a complementary Fire Dynamics Simulator (FDS) simulation was performed on a full scale station. The influences of natural ventilation, mechanical ventilation and hybrid ventilation were examined.

The results indicated that natural ventilation was good for smoke elimination when the fire source was under the dome, and the gas temperature measured in the middle of the basement 1 decreased significantly as the size of the vent increased. Smoke was exhausted from the basement 1 and fresh air supplied into the basements 2 and 3, which had the best efficacy when managing the smoke diffusion. No matter that the fire source was under the dome or out of the atrium, the carbon monoxide (CO) concentration was the smallest when the modified hybrid ventilation system was in operation. At the same time, changes in the natural ventilation vent had an influence on smoke elimination and the efficacy of smoke elimination became better with the increasing of the dimension of the vent when the fire location was under the dome.

1. Introduction

As more people migrate to cities, China has started to experience problems related to transportation in urban centers; traffic congestion is becoming more prominent. Subways are well known for their advantages such as, high speed, large capacity, and low energy consumption (Lei et al., 2012). As in other countries, subway systems have been increasingly constructed in many Chinese cities in recent years and an increasing number of people prefer to use the subway system as their main mode of travel. For example, there are seven underground railway line in operation currently with two more being constructed and four further lines being planned in Beijing. On October 12, 2009, the first Monday after the National Day vacation, the daily passenger load record reached 5.05 million (Jiang et al., 2010). Subway systems have large transit passenger flows; and therefore, heavy casualties and tremendous losses of property may happen if a fire takes place at a station (Park et al., 2006). For instance, there was a fire accident that took place at Daegu subway in Korea, caused by arson, and the entire subway station was quickly filled with smoke, which resulted in a large number of casualties (Yanfeng et al., 2012). In Baku, the capital of Azerbaijan, a large accidental fire broke out in the subway station and there were 289 people dead and 265 people injured as a result (Gao et al., 2012a). Compared with the high temperature, it is the smoke that causes the greatest number of fire-related deaths (Cox and Kumar, 1987). According to statistical data, the number of people killed by toxic smoke in building fires reached to 85% (Hu et al., 2008). Due to the volume of the subway stations and the limitation of space, lots of stations are constructed underground. For example, the New York City subway system consists of over 1000 km of revenue track and 468 stations, with approximately 60% underground. Due to the thermal buoyancy, the smoke flows upward. This is very frustrated for the firefighter's rescue operations. Therefore, firefighters are not able to approach the fire area and assess the accident properly, which has a detrimental influence on the passenger's evacuation. In addition, the evacuation paths coincide with the smoke path, so the visibility will be reduced, posing a psychological threat to the evacuees, especially to the people who are not familiar with the station. When compared with a single station, there are often more passengers in an interchange station. When a fire happens at an interchange station, the smoke will spread rapidly to the entire station and the injuries and casualties will be overwhelmingly

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Nomenclature

C_{mi}	the highest smoke concentration of the middle of the basement 1
D_i	diffusion coefficient of the elements i
H	height of the model
K	heat transfer coefficient
f	external force
g	acceleration of free fall
h	total enthalpy of flow field
L	length of the model
m_i	generation mass of one of the elements
P	pressure
q_r	the flux equation of thermal radiation
q	the heat released by the fluid combustion
t	temperature
t_{mi}	the highest smoke temperature of the 12 points in the middle of the basement 1
$\vec{u}$	velocity of the air
V	discharging velocity
W	width of the model
Y_i	mass fraction of the element i

Greek letters

α	the ration of physical dimensions between the experiment model and the actual design
ρ	air density
τ	time
Δ	Laplace operator
$\overrightarrow{\tau_F}$	viscous force
τ_m	time for experiment
τ_r	time for real design

Abbreviations

CO	carbon monoxide
DNS	direct numerical simulation
Fr	Froude number
HRR	heat release rate (kW)
LES	large eddy simulation
Re	Reynolds number
RANS	Reynolds-averaged Navier–Stokes equation

disastrous. Major fire accidents underscore the importance of fire safety in subway stations and it is necessary to enhance the smoke control system to maintain a safe evacuation path for the passengers.

Over the past decades, many scholars have studied fires in subway stations. The platform screen door (PSD) was studied to prevent smoke spreading and enhance safety when boarding the subway train (Roh et al., 2009). In this research, the Fire Dynamics Simulator code was used to predict smoke spread and the available safe egress time to estimate the effect of PSD and ventilation on the passenger's safety in a subway train fire. It was found that the passengers on platforms with PSD and ventilation system had about 350 s of available time, which was much more than that passengers had without the PSD and ventilation system in the subway station. Hu et al. (2007, 2008) researched the confinement of fire-induced smoke and carbon monoxide transportation by air curtains in channels. The use of air curtains was studied both experimentally and through numerical simulations to determine if the use of air curtains could confine the smoke and carbon monoxide. Results showed that the smoke and CO gas released by the fire mainly remained near the fire region at one side of the air curtain, and the gas temperature and CO concentration dropped significantly in the protected zone at the other side. In addition, for a fire in a confined space, as the air curtain discharge velocity increased the CO concentration first increased and then decreased. Elicer-Cortés et al. (2009) studied heat confinement in tunnels between two double-stream twin-jet (DS-TJ) air curtains. In this paper, a numerical simulation was carried out to investigate more accurately the ability of the two DS-TJ curtains to confine the heat released by an intense heat source located inside a tunnel-like geometry. All of these research focused on the confinement of smoke diffusion, but the measurement of elimination was not proposed. The smoke would accumulate near the fire region and people who stayed near that region would be in danger. Moreover, as the fire duration increases, once there is enough smoke produced, the smoke confinement measures would play little role in helping people's evacuation.

Park et al. (2006) evaluated the effect of a fire at a subway station and measured the velocity at various points on a platform and the flow rate at over/under platform extraction points and air-vents. Numerical analysis of the heat and smoke behavior for two exhaust capacities showed that the capacity of the exhausts was significant and that larger exhaust capacities enhanced the control of the smoke. Yan et al. (2011) studied the performance of smoke control under uneven smoke exhaust velocity and a numerical simulation of smoke flow in a tunnel was conducted under three different smoke extraction system modes. It could be generalized that the smoke control performance was better in well-distributed vents than for unevenly distributed vents. The researchers reflected that once appropriate ventilation measurements are adopted, then smoke would be eliminated efficiently, which would be beneficial for people's evacuation.

Different ventilation modes have been proposed and most of the measurements taken were related to mechanical ventilation. During a fire emergency a well-designed ventilation system will save many people's lives (Yuan and You, 2007; Modic, 2003; Carvel et al., 2001). Gao et al. (2012b) studied fire-induced smoke control via hybrid ventilation in a huge transit terminal subway station. Hybrid ventilation integrates natural and mechanical ventilation components to create a highly efficacy and healthy ventilation system for a building. During their research, the fire source was set under the dome and the influence of the location of the fire source was ignored. At the same time, the smoke would spread into the lower floor once the pressure difference is big enough. In this study brings, to smoke control more efficiently, a hybrid ventilation system with different ventilation systems on different floors is proposed.

2. Measurement of temperature

2.1. Description of subway station and ventilation system

The research was conducted in a typical subway interchange station with three stories below the ground level as shown in Fig. 1. There was a cross-shaped concourse in basement 1, with the dimensions of $105\ \mathrm{m\ L} \times 40\ \mathrm{m\ W} \times 5\ \mathrm{m\ H}$ and there were four exits from basement 1 leading to open ground. At the same time, there was a platform in basements 2 and 3, with the dimensions of $125\ \mathrm{m\ L} \times 24\ \mathrm{m\ W} \times 5\ \mathrm{m\ H}$ and $48\ \mathrm{m\ L} \times 24\ \mathrm{m\ W} \times 5\ \mathrm{m\ H}$,