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Smoke spreading analyses in a subway fire scale model

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ABSTRACT

This paper is an experimental study of smoke spreading in a subway station. A subscale model based on the *Fr* Froude number similitude was elaborated. Smoke spreading was analyzed according to subway geometry (number of openings) and ventilation volumetric flow rate. In this context, evacuation way must remain smoke-free to ensure the safety of passengers in case of fire on the platform. As the vertical of hot air may initiate stack effect, which is to be avoided, appropriate ventilation conditions needed to be determined. With this in mind, three main parameters were considered: ventilation mode (push-pull or extraction mode), stairway number, and railway network. The efficiency of push-pull and all extraction modes were compared to a single extraction mode with a reduction of critical volumetric flow approximating 19 and 13% respectively. The influence of pressure loss in tunnel opposite to ventilation on the stack effect was also studied. The outlet temperatures of stairways and free smoke areas were our major concern, and the safety criterion pointed out.

1. Introduction

Smoke control and preservation of passenger evacuation routes during a subway fire are important issues. In subway stations, the evacuation routes correspond to station accesses (stairwells) which are located on platforms. Subway operators use smoke control systems and aim for optimal ventilation. To reach this goal, an extensive research is need. In real-size, tests can be carried out in subway stations and generate useful feedback (Hu et al., 2008; Pan et al., 2011; Simcox et al., 1992; Casalé et al., 2006), but induce important costs (budget and instrumentation) and cannot be done without disrupting the operation of tunnels and stations. So an experimental alternative consists on subscale model (Woods et al., 2006; Oka and Atkinson, 1995; Vauquelin, 2007; Saito et al., 1995Y), commonly based on the Froude number similitude. It can provide extensive data and enhance our understanding; in addition it is cheaper and more available than the real-size approach. For example, Blanchard et al. (2012) use a 1.5 MW heptane pool in a 1/3 subscale tunnel under forced ventilation conditions to highlight the relationship between the heat flux received by the ceiling and critical velocity. Ingason (2007) use the same similitude approach and underline the interactions between heat release rates (HRR) and the flame length from the combustible they used (wood cribs). An over possibility to avoid real-size experiments is to use numerical approach as Hwang and Edwards (2005) or Lee and Ryou (2006). This study Lee and Ryou, 2006 simulate a 1/20 subscale model of a tunnel with different aspect ratios and HRR. Their results show that (1) aspect ratio affects smoke development in tunnels and (2) temperature along the ceiling increases with the increased HRR.

The specificity study of fire and smoke development in station and in particular around platform, is the interaction between the forced ventilation issues from the ventilation system, generally positioned in tunnel, and the natural flow induced by the presence of opening as staircases. Some works have been devoted to the flow movement in subway stations and in particular on the influence of natural ventilation (Rie et al., 2006; Yuan and You, 2007; Yang et al., 2007; Park et al., 2006). In a scenario with fire outbreaks near staircases, Chen et al. (2003) numerically demonstrated the importance of stack effect management in a natural convection strategy – i.e. no ventilation was recommended for smoke spreading management. Gao et al. (2012) studied smoke spreading in a Chinese subway station under different smoke control strategies using the well-known Fire Dynamic Simulation (FDS) software; hybrid ventilation (forced ventilation and roof windows) was found to be a promising method for fire smoke control. From numerical predictions, Hu et al. (2014) studied ventilation system influence by coupling three ventilation systems: in tunnel, on platform and under platform. The optimal emergency ventilation was found to corresponding to exhaust mode with the tunnel ventilation system in priority and to aid it the platform ventilation system (in exhaust mode). In addition, they shown that the system located under the platform have a negative influence on the emergency ventilation when it was coupled with the tunnel ventilation system.

In the present work, an experimental subscale model of a subway station was developed to study smoke spreading and its change with regard to ventilation mode, stairways and tunnels. Our subscale model

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Nomenclature

A	cross-flow section (m^2)
c_p	specific heat capacity at constant pressure ($J\ kg^{-1}\ K^{-1}$)
D_h	hydraulic diameter (m)
g	gravity ($m\ s^{-2}$)
L	length (m)
$\dot{q}$	volumetric flow rate ($m^3\ s^{-1}$)
$\dot{q}_v$	critical volumetric flow rate at real-size scale ($m^3\ s^{-1}$)
$\dot{Q}$	convective heat release rate (W)
S	fire source section (m^2)
T	local temperature (K)
T^*	dimensionless temperature: $T^* = \frac{T - T_\infty}{T_0 - T_\infty}$ (–)
U,V,W	longitudinal, lateral and vertical velocity component ($m\ s^{-1}$)

Greek symbols

$\Delta\rho$	difference of density between longitudinal flow and fire: $\Delta\rho = \rho_\infty - \rho_f$ ($kg\ m^{-3}$)
ΔT	difference of temperature between fire and longitudinal flow: $\Delta T = T_f - T_\infty$ (K)
ρ	density ($kg\ m^{-3}$)

Subscripts and overlines

(*)	relation between real scale (r) and subscale model (m)
0	condition after pre-heating period outside the accesses
∞	longitudinal flow conditions
f	fire flow conditions
m	subscale model
r	real scale

Dimensionless number

Fr	Froude number: $Fr = \frac{\rho}{\Delta\rho}\frac{U^2}{gD_h}$

was also based on the Froude number similitude and the source of fire was an air/butane burner. Smoke spreading was tracked by temperature evolution. A key objective was to determine the ventilation most effectively preventing smoke from spreading into staircases. All results given hereinafter such as the $\dot{q}_v$ critical volumetric flow rate are given in real-size scale.

2. Froude number and similitude

In order to develop the subscale analysis, a Froude number similitude approach has been applied following experimental studies (Wu and Bakar, 2000; Futujota et al., 2012; Tanaka et al., 2015). It represents the ratio between flow inertia and gravitational external forces and is defined as:

$$Fr = \frac{\rho_\infty}{\Delta\rho}\frac{U^2}{gD_h} \tag{1}$$

with ρ_∞ the longitudinal fluid density, $\Delta\rho$ the difference density between longitudinal and vertical flows, U the velocity induced by ventilation system, g the gravity and D_h the hydraulic diameter.

From a similitude viewpoint, conservation between real-case (r) and subscale model (m) is as follows:

$$\frac{\rho_r}{\Delta\rho_r}\frac{U_r^2}{gD_{h_r}} \equiv \frac{\rho_m}{\Delta\rho_m}\frac{U_m^2}{gD_{h_m}} \tag{2}$$

Contrarily to non-thermal approaches such as Vauquelin and Mégret (2002), flames are involved i.e. temperature levels between real and subscale configuration are similar as well as fluid densities ρ_r and ρ_m. Thus (2) becomes:

$$\frac{U_r^2}{D_{h_r}} \equiv \frac{U_m^2}{D_{h_m}} \tag{3}$$

The ratio of the characteristic velocity in real-scale over that in the subscale model exclusively depends only on the scales such as:

$$\frac{U_r}{U_m} \equiv \sqrt{\frac{D_{h_r}}{D_{h_m}}} \Rightarrow L^{*1/2} \tag{4}$$

Consequently, the volumetric flow rate ratio is also directly linked to the scale factor as:

$$\dot{q} = U{\cdot}A = U\ \ cdotL \tag{5}$$

$$\frac{\dot{q}_r}{\dot{q}_m} \equiv \left(\frac{D_{h_r}}{D_{h_m}}\right)^{5/2} \rightarrow \dot{q}^* \equiv L^{*5/2} \tag{6}$$

Convective heat release rate issued from fire can be estimated as:

$$\dot{Q} = \rho c_p \Delta T S W_f \tag{7}$$

where W_f is the vertical flame velocity, S the fire surface and c_p the specific heat capacity. From Froude number similitude, thermo-physical parameters such as density and specific heat capacity are equal and fire power ratio can be written as:

$$\frac{\dot{Q}_r}{\dot{Q}_m} \equiv \left(\frac{D_{h_r}}{D_{h_m}}\right)^{5/2} \equiv L^{*5/2} \tag{8}$$

The Froude number similitude provides parameters depending on the scale ratio such as velocities and convective heat release rate linked to the L^* length ratio. In our case, the L^* ratio was rendered equal to 1/30 in order to fit a laboratory scale set-up. Experiments were carried out following a defined procedure. All the main characteristics are listed in Table 1.

3. Experimental procedure

A 1/30 subscale model of an underground subway station was developed (Fig. 1) with dimensions of 8.4 m × 2.5 m × 2.5 m including ventilation system, characteristic exit areas and tunnel exits. The main part of the experimental set-up was made of glass and aluminum profiles equipped with dedicated insulation. The experimental scale model was representative of a subway station with platforms and railway (Fig. 1 right top corner) connected to tunnels downstream and upstream from the station. Both tunnels had 0.19 m hydraulic diameter and 2.2 m long. Each tunnel was connected at 1.6 m from the station to a reversible ventilation system i.e. extracting/blowing air from/to the subscale model inducing the longitudinal flow.

Two staircases were connected to the subway station, located at the station roof with a 0.1 m × 0.1 m square vertical section (Fig. 2), which

Table 1
Main characteristic parameters of real scale and subscale models.

Characteristic	Real case	Subscale
Length (m)	1	1/30
Hydraulic diameter tunnel (m)	5.58	0.186
Vitesse (m/s)	0.16–3.22	0.03–0.59
Volumetric flow rate (m^3/s)	5–100	1.0×10^{-3}–20.3×10^{-3}
HRR (W)	5.0×10^6	$1.0\text{x}10^3$
Re	6.0×10^4–1.2×10^6	3.7×10^2–7.3×10^6
Fr	0.041–0.223	0.041–0.223