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Safe velocity of on-fire train running in the tunnel

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ABSTRACT

The safety of a running train on fire in a tunnel is a key issue for rescue operations, and the train velocity is mainly related to its safety. In this study, the relationship between the wind velocity and heat release rate (HRR), temperature field around the train, and flame/smoke pervasion rule were investigated under the conditions of variable train velocity, fire location, and fire source location. Beijing Metro was considered as a typical example, in which the safe velocity was estimated to be ~41.83 km h^{-1}. Assuming the occurrence of fire at the center of the train, the numerical simulations of the flow field using the sliding grid of CFD were performed for a full-scale tunnel under different HRRs. When the fire source reached to the target section, the velocities of all the monitoring points rapidly increased. The velocities increased as the train tail arrived at the target section. The velocities at the measuring points increased with the increase in height, excluding the value of the position with a distance of 0.025 m from the tunnel ceiling. The average temperature and concentration of smoke in the annular space between the train and tunnel ceiling had the minimum values when the running train on fire moved with a speed of 45 km h^{-1}. Thus, the safe velocity of a subway train on fire should be managed between 41.83 km h^{-1} and 45 km h^{-1}.

1. Introduction

Tunnel fire is a major threat to life safety (Leitner, 2001 and Kirkland, 2002). This is an interdisciplinary science, involving fluid dynamics, turbulence, chemical kinetics, radiation, and multiphase flow (Emmons, 1971; Quintiere, 1998; Tieszen, 2001). When a subway train is on fire in a tunnel, it is unwise and difficult to stop the train for evacuation and rescue because of the narrow annular space between the tunnel and train (Wang, 2003). Moreover, the concentrated smoke inside the tunnel decreases visibility and increases the degree of evacuation difficulty.

The prevention measures for the disasters of subway train fire (Wang, 2003) by Japan, Germany, and China have the same policy: The subway train on fire in a tunnel should immediately be driven to the next station as a precautionary measure, thus starting the evacuation process as soon as possible. However, no prevention measures have been indicated for the speed of the train on fire.

To date, many research studies have been conducted concerning tunnel fire. Extensive works have been reported in the literatures to address the smoke temperature longitudinal distribution in a tunnel fire (Kunsch, 2002; Gao et al., 2004; Hu et al., 2005, 2007; Colella et al., 2009), as well as the smoke temperature under ceiling (Kurioka et al., 2003; Hu et al., 2006). And that the longitudinal ventilation which has a great effect on the fire heat release rate(HRR) (Oka and Atkinson, 1995; Wu and Bakar, 2000). The interaction between the ventilation air flow and HRR of tunnel fires were conducted by many scholars (Li et al., 2012; Kayili et al., 2011; Ingason and Li, 2010; Roh et al., 2007a; Lemaire and Kenyon, 2006). Although tunnel fires have been extensively studied (Li et al., 2014, 2016; Harish and Venkatasubbaiah, 2014; Roh et al., 2014; Ji et al., 2011; Ahmed et al., 2013; Meng et al., 2014; Tang et al., 2014; Chow et al., 2016; Liu et al., 2016), train fire in a tunnel has been rarely studied. Based on numerical simulations, Qu et al. (2003) concluded that the relative velocity of airflow surrounding the train was below 5 m s^{-1} when the train speed was less than 25 km h^{-1}. Therefore, a subway train on fire should immediately be driven to the next station as slow as possible to avoid relatively high flow of smoke. Yang et al. (2006) also reported similar observations as described earlier. Notably, the aforesaid conclusions do not mention the speed of the subway train on fire.

A running train on fire in a tunnel generates a windy airflow that can increase the burning to a harmful extent. The windy airflow may also decrease the temperature of the combustion below the ignition point, thus decreasing the burning. Carvd et al. (2004) reported that the vertical-forced ventilation increased a large-scale oil pool fire and decreased a small-scale oil pool fire in the tunnel. Carvel and Wang (2001) showed that longitudinal ventilation

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Nomenclature

v_t	train speed (m s^{-1})
v	piston wind speed (m s^{-1})
v_s	average wind speed of the annular space between train and tunnel ceiling (m s^{-1})
A_t	train cross-sectional area (m^2)
A	tunnel cross-sectional area (m^2)
α	A_t/A (–)
L	length of tunnel (m)
L_t	length of train (m)
d_l	length of flame (m)
d_s	hydraulic diameter of the annular space between train and tunnel (m)
d	hydraulic diameter of tunnel (m)
ξ_t	resistance coefficient of tunnel excluding the annular space between train and tunnel (–)
λ	frictional drag coefficient (–)
K	piston effect coefficient (–)
ξ	local resistance coefficient between station and tunnel (–)
ξ_1	local resistance coefficient between tunnel and annular space* (–)
ξ_2	local resistance coefficient between annular space* and tunnel (–)
T_f	average temperature of hot smoke in the annular space between train and tunnel (K)
T_t	average temperature of airflow in the annular space between train and tunnel (K)
ΔT_r	difference in temperature when air flows through before and after the fire
k	air thermal conductivity (W m^{-1} K^{-1})
Nu	Nusselt number (–)
Pr	Prandtl number (–)
Re	Reynolds number (–)
υ	kinematic viscosity (m^2 s^{-1})
q_f	heat loss due to convection (kW)
q_r	heat loss caused by airflow (kW)
Δq_a	incremental heat release rate caused by the increased airflow velocity
β	convective heat transfer coefficient (–)
Cp	specific heat (kJ kg^{-1} K^{-1})
ρ_0	ambient density (kg m^{-3})
Q_v	heat release rate for airflow velocity of v (kW)
Q_0	heat release rate for airflow velocity of $v = 0$ (kW)
φ	combustion efficiency of fuel (–)
$\dot{m}$	mass loss rate (g s^{-1})
ΔH	calorific value of fuel (kJ g^{-1})

Subscripts

m	model
f	full-scale

Note

*	annular space between train and tunnel

significantly affected the extent of fire, and the optimal ventilation velocity was used to control the smoke.

In this study, a series of model experiments and numerical simulations were carried out on the safe velocity of an on-fire train running in a tunnel. The relationships between the train speed and heat release rate (HRR), temperature field, oxygen concentration, and smoke pervasion rule were investigated. Based on the comparisons between the model experiments and numerical simulations, the safe velocity of a running train on fire in a tunnel was obtained. This provides a new guideline for evacuation.

2. Airflow velocity around fire

A subway train with a speed of v_t can cause a piston-like wind effect and a forward-direction air-stream with a speed of v as shown in Fig. 1. Owing to the running subway train, the average wind velocity of the annular space between the train and tunnel ceiling is considered as v_s. The relative speed of wind velocity around the train is $v_{sr} = v_t + v_s$. As the fire source moves in the forward-direction with the train, the average relative wind velocity of fire in the annular space is considered as v_{sr}. Using the continuity and Bernoulli equations, the mathematical relations for estimating the piston speed caused by a running train (Jin and Chen, 1983) can be expressed as follows:

$$v_t A_t = vA + v_s(A - A_t) \tag{1}$$

$$v_s = (\alpha v_t - v)/(1 - \alpha) \tag{2}$$

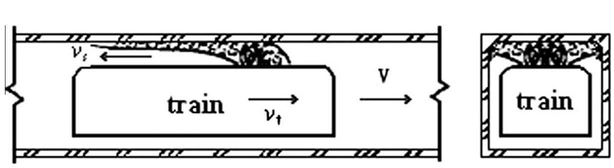

Fig. 1. A train on fire while moving in the forward direction in a subway.

$$v_{sr} = (v_t - v)/(1 - \alpha) \tag{3}$$

$$\xi_t = \xi + 1 + \lambda(L - L_t)/d \tag{4}$$

$$K = (\xi_1 + \xi_2 + \lambda L_t/d_s)/(1 - \alpha)^2 \tag{5}$$

The following relationships can be derived for the onward estimation of the resistance coefficient when fluid flows through pipes (Zhang, 1999):

$$\xi_1 = 0.5[1 - (A - A_t)/A] \tag{6}$$

$$\xi_2 = [1 - (A - A_t)/A]^2 \tag{7}$$

Using Eqs. (1)–(5), the piston-like wind speed can be expressed as follows:

$$v = v_t \Big/ \left[1 + (\xi_t/K)^{1/2}\right] \tag{8}$$

Based on Eqs. (3) and (6)–(8), the following relationship can be developed to estimate the average relative wind velocity of the annular space between a train and tunnel:

$$v_{sr} = \frac{(\xi_t/K)^{1/2}}{\left(1 + (\xi_t/K)^{1/2}\right)(1 - \alpha)} v_t \tag{9}$$

or,

$$v_{sr} = \frac{(\xi_t/K)^{1/2}}{(1 - \alpha)} v \tag{10}$$

3. Effect of airflow on fire intensity

An airflow can be heated by three forms of heat transfer, i.e., convection, conduction, and radiation, when it flows with v_{sr} through a combustion zone. Thus, an airflow may decrease the fire temperature and fire intensity. Moreover, the oxygen volume, contact area, and contact probability of an airflow between the fuel