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Water spray flow rate effect on smoke temperature distribution under the ceiling in tunnel fires with longitudinal ventilation

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ABSTRACT

A series of fire tests with various water spray flow rates were conducted in a small-scale longitudinal ventilated tunnel to investigate the influence of flow rates of a water spray system and different longitudinal wind speed on maximum smoke temperature and longitudinal smoke temperature distribution. Then, the test data for the case without the water spray system were compared with previous studies and agreed well with previous model which overestimates smoke temperature of the cases with the water spray. Results show that the maximum smoke temperature decreases and the longitudinal smoke temperature decays faster with the increase of water spray flow rate. Thus an improved model for maximum smoke temperature is proposed by introducing a modified coefficient λrepresenting the water spray flow rate effect. It was found that longitudinal smoke temperature decays exponentially and the decay coefficient increases with increasing water spray flow rate. Therefore considering the effect of water spray flow rate, a modified coefficient K_{down} is introduced into the exponential model to predict the longitudinal smoke temperature distribution.

1. Introduction

Tunnel fires can produce a large amount of hot smoke which accumulates beneath the ceiling and reaches more than 500 °C injuring occupants inside and damaging the structural stability of the tunnel (Li and Ingason, 2012), thus leading to catastrophic casualties and loss of property (Vuilleumier et al., 2002). So, the maximum smoke temperature along the tunnel ceiling has received extensive attention in tunnel fire protection research (Kurioka et al., 2003; Hu et al., 2006; Li et al., 2011). Kurioka et al. (2003) conducted a series of large scale tunnel fire experiments and established an empirical equation for the maximum smoke temperature. Hu et al. (2006) further verified the application of this empirical equation by comparing with their full scale experimental data. Li et al. (2011) analyzed the maximum smoke temperature beneath the tunnel ceiling theoretically through an axisymmetric fire plume theory and proposed a theoretical equation with the necessary empirical coefficients obtained from experimental data. Similarly, longitudinal smoke temperature distribution along the ceiling has been studied extensively recently (Alpert, 1972; Ji et al., 2011; Delichatsios, 1981; Wang et al., 2017a, 2017b; Hu et al., 2007). Firstly, Alpert (1972) correlated the radial smoke temperature beneath an unconfined ceiling by a power function and Zhang et al. (2014, 2018a, 2018b) improve the unconfined ceiling theory based on Alpert's work. Based on Alpert's empirical formula, Ji et al. (2011) proposed a simple method for smoke temperature distribution under the ceiling in a subway station. Delichatsios (1981) studied the smoke temperature between two beams which decreases exponentially with the ceiling distance. Kurioka et al. (2003) verified the application of the empirical formula in exponential form in the prediction of smoke temperature distribution under a tunnel ceiling. Further, some researchers investigated the smoke temperature distribution beneath a tunnel ceiling concerning the point extraction and longitudinal ventilation (Hu et al., 2006; Tang et al., 2017; Mei et al., 2017), inclined tunnel (Huo et al., 2015; Zhong et al., 2016), natural smoke exhaust shafts (Wang et al., 2016; Fan et al., 2014), and different fire location (Zhou et al., 2017; Tang et al., 2017) and attempted to develop a global model involving the exponential empirical formula. In sum, two types of typical models, i.e., the power model and the exponential model were used to describe the smoke temperature distribution under a tunnel ceiling widely. Due to the restriction effect of construction walls and the heat convection effect of ventilations, the

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Nomenclature

b	radius of the fire source (m)
C_O	CO concentration beneath the ceiling at the flame centerline (ppm)
C_L	scale ratio in the small-scale model 1:10
c_p	specific heat capacity of the ambient gas (J/(kg °C))
H_{ef}	height between fuel source and the ceiling (m)
K	decay coefficient
K_{down}	modified coefficient of longitudinal smoke temperature distribution
Q	water spray flow rate (L/min)
Q_f	water spray flow rate in the full-scale model (L/min)
Q_m	water spray flow rate in the small-scale model (L/min)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}_c$	convective heat release rate (kW)
$\dot{Q}_f$	heat release rate in the full-scale model (kW)
$\dot{Q}_m$	heat release rate in the small-scale model (kW)
r	ceiling distance away from the flame centerline (m)
T_∞	temperature of the ambient gas (K)
T_f	Smoke temperature in the full-scale model (K)
T_m	Smoke temperature in the small-scale model (K)
$\Delta T_{\max}$	maximum smoke temperature rise beneath the ceiling (K)
$\Delta T_{r,\max}$	maximum ceiling smoke temperature rise at the longitudinal direction r m from the fire source (K)
v	longitudinal ventilation velocity (m/s)
v_f	longitudinal ventilation velocity in the full-scale model (m/s)
v_m	longitudinal ventilation velocity in the small-scale model (m/s)
v'	dimensionless longitudinal ventilation velocity
Greek symbols	
ρ_∞	density of ambient gas (kg/m^3)
λ	modified coefficient of maximum smoke temperature correlation

exponential coefficients of tunnel ceiling jet temperature models are smaller than that of unconfined ceiling jet, which indicates smoke temperature decays slowly in a confined space.

Some studies (Tang et al., 2013a, 2013b, 2017; Chang et al., 2017; Sun et al., 2016; Ingason et al., 2016; Li et al., 2013) have been reported on the influence of water spray system on tunnel fires. Tang et al. (2013a, 2013b, 2017) investigated the downward smoke layer displacement and critical velocity caused by a water spray through small-scale tunnel fire tests. Two full-scale tunnel fire experiments were conducted by Chang et al. (2017) to estimate wall cooling performance of the spray system. Sun et al. (2016) tested the effectiveness of a water system in blocking fire-induced smoke and heat in a reduced-scale tunnel. Furthermore, Ingason et al. (2016) and Li et al. (2013) investigated and measured the suppression of a water system on tunnel fire sources. All above analyzed the change of smoke layer, heat release rate and wall temperature induced by a water spray system in tunnel fires qualitatively and quantitatively simply. However, the effects of a water spray system on the smoke temperature distribution under a tunnel ceiling have not been involved.

Therefore, this paper focuses on the influence of a water spray system, especially its water yield, on the maximum smoke temperature and smoke temperature distribution beneath the ceiling in tunnel fires to develop new correlations.

2. Description of the experiments

The experiments were conducted in a small-scale tunnel model in 1:10 which is 20 m long (L), 1 m wide (W) and 0.615 m high (H) as shown in Fig. 1. According to Froude scale law used widely in former research (Atkinson and Wu, 1996; Tilley et al., 2012; Ko and Hadjisophocleous, 2013), all the parameters considered in the study were set by the scale ratio as shown in Table 1. To avoid heat damage to the tunnel model, the floor of the tunnel was made of stainless steel, the side windows and roof of the tunnel were made of 8 mm tempered glass.

Propane gas was used as fuel to provide a relative stable heat release rate through a porous gas burner with inner size of 0.2 m × 0.2 m. The flow rate of the fuel was metered via a rotameter with measurement

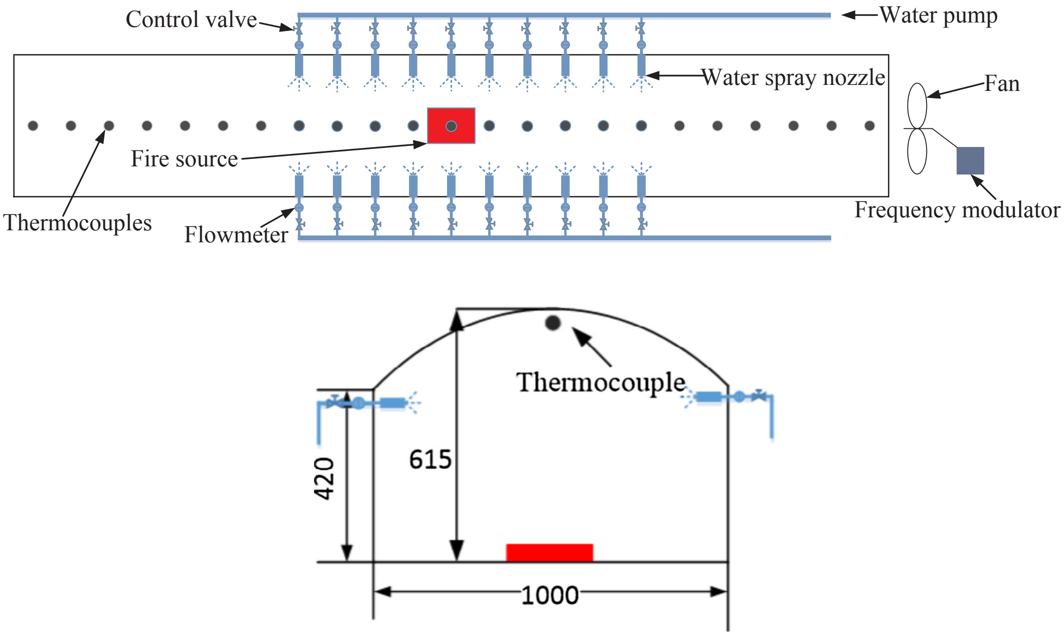

Fig. 1. Schematic of the small-scale tunnel model (mm).