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Research Paper

Effect of ceiling extraction system on the smoke thermal stratification in the longitudinal ventilation tunnel

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HIGHLIGHTS

- Smoke thermal stratification was investigated in a 72 m long model tunnel.
- The coupling effect of ceiling extraction and longitudinal ventilation considered.
- A modified *Fr* was proposed to describe the influence of ceiling extraction.
- Proposed correlation was to be applicable with and without ceiling extraction.

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ABSTRACT

Poisonous and harmful smoke is one of the most important factors in the life-threatening in tunnel fires. In the event of fire, the effective control of fire growth and smoke sinking is crucial for personnel security in tunnel. The aim of this work is to study the smoke thermal stratification with ceiling extraction in a longitudinal ventilated tunnel. A series of experiments were carried out in a 1/6 scale model tunnel [72 m (length) × 1.5 m (width) × 1.3 m (height)]. Four thermocouple trees are used to measure vertical temperature profile. The heat release rate, ceiling extraction velocity and longitudinal forced air flow velocity were considered. It was found that: (a) the smoke temperature below the tunnel ceiling decreased and the thermal stratification stability reduced with the increasing of ceiling extraction velocity; (b) the measured temperatures ratios $\Delta T_{cf}/\Delta T_h$ versus $\Delta T_{cf}/\Delta T_{avg}$ with and without ceiling extraction are in good agreement with Nyman and Ingason's work; (c) with the coupling effect of ceiling extraction and longitudinal forced air flow, a modified Froude number was proposed to describe the influence of ceiling extraction, and the relation between the smoke thermal stratification and the modified Froude number agree well with Nyman and Ingason's model.

1. Introduction

Tunnel fire accident caused a lot of personnel casualty and property. Extensive works have been done to study on tunnel fire-induced smoke movement [1–7], including the effect of longitudinal wind [8–12]. In recent years, the following three parameters become the favor of many researchers, such as, the maximum temperature profile [13–17], smoke back-layering length [18–20] and critical wind speed [21–23]. It was found that effective smoke control [24–26] and maintenance of the smoke layer stability [27–30] are crucial for tunnel fire prevention.

For the study of smoke thermal stratification stability, Ingason et al. [27] established the relational model between the smoke thermal stratification and the oxygen concentration by studying the smoke temperature and gas concentrations in a tunnel fire. Ellison and Turner [28] proved that the entrainment coefficient of the buoyant flow depended on Richarson number. When $Ri > 0.8$, the buoyant flow stratification was stable; When $Ri < 0.8$, the buoyant flow stratification became unstable. The ceiling-jet thickness, the vertical temperature and velocity distribution were investigated by Oka [29] through conducting experiments in a horizontal tunnel with natural ventilation. Yang et al. [30] investigated the relation of the fire-induced buoyant flow stratification with Froude number and Richardson number in a horizontal channel with longitudinal ventilation. Newman [31] divided the smoke thermal stratification patterns into three regimes: At Region I ($Fr < 0.9$), the buoyant flow stratification was stable, where buoyancy dominates temperature

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Nomenclature

Fr	Froude number
g	gravitational acceleration (m/s^2)
H	ceiling height (m)
Ri	Richardson number
ΔT_{avg}	temperature difference between the average temperature T_{avg} and the ambient temperature T_a
ΔT_{cf}	temperature difference between the ceiling temperature T_c and the floor temperature T_f
ΔT_h	temperature difference between the ceiling temperature T_c and the ambient temperature T_a
T	smoke temperature below the tunnel ceiling (K)
T'	the arithmetic average temperature (K)
Ta	ambient temperature (K)
T_{avg}	average temperature in the cross-section
T_f	floor temperature (K)
u	longitudinal forced air flow velocity (m/s)
u_{avg}	average "hot" longitudinal velocity (m/s)
V	ceiling extraction velocity (m/s)
Greek symbols	
ρ	smoke density (kg/m^3)
ρ_a	ambient density (kg/m^3)

stratification. At Region II (0.9 < Fr < 10), governed by large Froude number, some vortexes existed at the interface, there is a strong competitive between the ventilation velocity and the fire-induced buoyancy. At Range III (Fr > 10), the buoyant flow and the air flow had no obvious stratification. Nyman and Ingason [32] presents results from a validation of correlations proposed by Newman [31] and model experiments performed by Ingason [33], the large scale Runehamar tunnel [34,35] tests and the Memorial tunnel fire tests. It was found the smoke thermal stratification and Froude number don't entirely agree well with Newman' work, and after further work, a modified model between the temperature stratification and the Froude number is presented on the basis of the previous researches [33,34]:

$$\frac{\Delta T_{cf}}{\Delta T_{avg}} = 0.62 \cdot Fr^{-1.58} \tag{1}$$

$$\frac{\Delta T_{cf}}{\Delta T_h} = 0.67 \cdot \frac{\Delta T_{cf}}{\Delta T_{avg}}^{0.77} \tag{2}$$

In recent years, with the development of the tunnel ventilation and smoke exhaust technology, the collaborative ventilation design strategy combining longitudinal ventilation and ceiling extraction system is going to be more and more common in tunnel fires in recent years, especially in long and large cross section tunnels. For the study of the combining ventilation design strategy [36–38], Chen and Hu et al. [37,38] studied the effect of ceiling extraction on ceiling temperature decay and buoyant smoke back-layering flow length in a tunnel fire, and developed models for describing them. It must be noted that, as the ceiling extraction exhaust out part of the fire-induced smoke, and it must affect the smoke thermal stratification stability, but the effect of ceiling extraction on the smoke thermal stratification has not been reported. The goal of this work is to clarify and characterize the effect of the ceiling extraction on the smoke thermal stratification in a tunnel with combination of ceiling extraction and longitudinal forced air flow.

2. Theoretical model

Nyman and Ingason [32] studied the smoke thermal stratification in tunnel fires with longitudinal ventilation only based on the relation between the smoke thermal stratification and the Froude number. The Froude number can be expressed as:

$$Fr = \frac{u_{avg}}{\sqrt{\frac{\Delta T_{cf}}{\Delta T_{avg}} gH}} \tag{3}$$

where u_{avg} is the average "hot" longitudinal velocity:

$$u_{avg} = uT_{avg}/T_a \tag{4}$$

where u is the longitudinal forced air flow velocity, T_{avg} is the average temperature of downstream, the average temperature is calculated as the average between 1.1 m and 0.2 m (one ceiling temperature and one floor temperature), T_a is ambient temperature.

With the effect of ceiling extraction, a part of the heat is exhausted out by the extraction opening, the mass flow rate of extraction can be calculated by [37,38]:

$$\Delta \dot{m} = \rho VS \tag{5}$$

where V is the ceiling extraction velocity, S is extraction opening area, ρ is the smoke density.

$$\frac{\rho}{\rho_a} = \frac{T_a}{T} \tag{6}$$

The ceiling extraction will induce longitudinal air flows moving from both sides of the tunnel toward the fire source. The induced air flow velocity [37,38] can be expressed as:

$$v_{induced} = \rho VS/2A\rho_0 \tag{7}$$

Eq. (3) is further modified by a non-dimensional factor accounting for these ceiling extraction velocities as follows:

$$Fr' = \frac{(u + \rho VS/2A\rho_0)T_{avg}/T_a}{\sqrt{\frac{\Delta T_{cf}}{\Delta T_{avg}} gH}} \tag{8}$$

3. Experimental

A series of smoke spread experiments are conducted in a reduced-scale model tunnel (1:6) with dimensions of 72 m (length) × 1.5 m (width) × 1.3 m (height). The experimental setup is shown in Fig. 1. The experimental device was designed based on Froude Modeling to simulate the smoke spread and heat transmission driven by buoyancy. The floor of the tunnel is made of steel plates covered with high temperature resistant material, while the ceiling and the sidewalls are made of reinforced transparent glass in order to allow for a better view of the smoke transport phenomenon during the experiments, the detailed description of Tunnel experimental facility can be found in previous works [37–42]. Two propane gas burners were used as fire source to provide steady heat release rate. The dimensions of the burner is 0.5 m (length) × 0.25 m (width) × 0.15 m (height).

Four thermocouple trees which used type K sheathed thermocouples were used to collect the vertical temperatures from the height of 0.1 m to that of 1.2 m with interval of 0.1 m, which were positioned at the distance of 3 m (Location A), 6 m (Location B), 10 m (Location C) and 13 m (Location D) from the fire source as shown in Fig. 1.