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Experimental investigation on transverse ceiling flame length and temperature distribution of sidewall confined tunnel fire

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ABSTRACT

This paper presents an experimental investigation on the transverse ceiling flame length and the temperature distribution of a sidewall confined tunnel fire. The experiments were conducted in a 1/6th scale model tunnel with the fire source placed against the sidewall, 0 m, 0.17 m and 0.35 m above the floor, respectively. Experiments of fire against a wall without a ceiling, 0.35 m above the floor in a large space, were also conducted as a control group. Results shows that for small heat release rate (HRR), the flame is lower than the ceiling and extends along the sidewall. With the increase of HRR and elevation of burner height, the flame gradually impinges on the ceiling and spreads out radially along it. The flame impingement condition and the flame shapes of the wall fire with and without ceiling are presented. From the viewpoint of the physical meaning of flame impinging on the ceiling, the horizontal flame length should be a function of the unburned part of the fuel at the impinging point. Based on the proportional relation between the flame volume and HRR, the effective HRR (Q_{ef}) at the ceiling is determined and the effective dimensionless HRR, Q^{*}_{ef} is defined to correlate the horizontal ceiling flame length. Additionally, predictive correlations of transverse ceiling temperature distribution are proposed for the continuous flame region, the intermittent flame region and the buoyant plume region under the ceiling, respectively.

1. Introduction

In a tunnel fire, for small heat release rates (HRR), the flame height is lower than the ceiling, in this condition the spreading toxic smoke is the most fatal factor in fires [1]; while for large HRR, the flame impinges on the ceiling and extends along the tunnel ceiling, owing to the confinement tunnel space, the ceiling extension flame can significantly enhance the risk of fire propagation and lead to a much larger fire [2]. Thus, it is important to thoroughly investigate the key parameter of ceiling flame length, especially for fire adjacent to or flush with a sidewall of a tunnel.

You and Faeth [3] investigated the ceiling flame length and ceiling temperature distribution when a turbulent fire impinged upon a horizontal ceiling, both unconfined and confined ceilings were considered. In their study, the radial flame extensions were correlated in terms of free flame height, and due to the reduced oxygen concentration within the ceiling layer, the flame lengths under confined ceiling were longer that those under an unconfined ceiling. Lattimer et al. [4] studied the flame length for configurations including fire in corridor/tunnel and an unconfined ceiling. Results showed that flame length was more strongly dependent on the HRR in the corridor configuration than in the unbounded ceiling configuration. Ingason et al. [5] proposed a simple theoretical model for the flame length in tunnel fires with different ventilation conditions, and a large amount of experimental data relevant to the flame length was used to validate the model. Ji et al. [6] conducted a set of experiments on sidewall fires in a small-scale corridor-like structure and established a correlation for prediction the longitudinal length of ceiling jet flame by taking into account the effects of heat release rate, the effective ceiling height and the burner configuration. In our prior research [7], we presented an experimental investigation on the flame shape and length under a channel ceiling and quantified the total flame extensions using dimensional analysis. However, in these previous studies, the ceiling flame lengths were always correlated with the total HRR, nevertheless, from the viewpoint of the physical meaning of flame impinging on the ceiling, the ceiling flame length should be a function of the unburned part of the fuel at the impinging point [8] rather than the total HRR which produces both the vertical flame height and the horizontal flame length. Specifically, when the fire was immediately adjacent to the sidewall in the confined tunnel space, the air entrainment process was

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Nomenclature

a	coefficient
b	coefficient
c_p	specific heat (kJ/kg K)
D	equivalent diameter of fire (m)
g	gravity acceleration (m/s^2)
H	ceiling clearance above fire (m)
L	flame height (m)
r	distance from the sidewall (m)
r_f	ceiling flame length (m)
s	base area of flame volume (m^2)
T	temperature (K)
ΔT	excess temperature (K)
V	flame volume (m^3)
Q	heat release rate of fire (kW)
Q_{ef}	effective heat release rate at ceiling (kW)
Q^*_{ef}	effective dimensionless heat release rate at ceiling
z	along edge (m)

Greek

ρ	density (kg/m^3)
∞	ambient property

Subscripts

fmax	maximum value
favg	average value
f	flame property

blocked to a larger extent, leading to longer ceiling flame lengths.

Therefore, two series of experiments with fires against tunnel sidewall and against a vertical wall without ceiling (serving as control group) were conducted to investigate the transverse ceiling flame extension as well as the ceiling temperature distribution. Such tunnel sidewall fires occur in many realistic tunnel fire scenarios, especially in two-lane tunnels. The experimental study can be used to estimate the radiation heat transfer to the surroundings and evaluate the risk of fire propagation.

2. Experimental apparatus

In order to investigate the wall-fire behavior, including the flame extension and temperature distribution, with and without a ceiling, two series of experiments were conducted. The first series investigated a fire against a wall without a ceiling, 0.35 m above the floor in a large space. Fireproof board was used as the wall material. The second series concerned the fire against a tunnel sidewall. This series of experiments was conducted in a 1/6th scale model tunnel with dimensions of 6 m long, 2 m wide and 0.88 m high. The burner heights were changed as 0 m (on the floor), 0.17 m and 0.35 m above the floor to account for the enhancing influence of the ceiling. 20 mm thick fireproof boards were used to make the top, bottom and one sidewall of the tunnel, the other sidewall was constructed of 10 mm thick fire-resistant glass to observe the experimental phenomena. The density of the fireproof boards is 870 kg/m^3, their heat capacity is 1130 J/kg K and the heat conduction is 0.175 W/m K. The schematic of the experimental apparatus is shown in Fig. 1.

A 0.15 m square porous gas burner was used with propane as fuel. The fuel supply rate and thus the HRR were controlled by a flow meter. The heat of combustion of propane was 46.45 kJ/g [9] and complete combustion was assumed for estimating HRR. 8 different fire powers were used with HRRs of 15.94, 26.57, 39.85, 53.13, 66.42, 79.71, 92.99 and 106.28 kW, respectively. Each case was repeated three times. More details can be found in [7].

Flame behaviors were recorded from the front view and side view using two digital cameras (DV). The vertical and horizontal flame extensions were determined using a commonly used image processing method [10,11]. The basic idea of this method is to transform the RGB images from the video to pseudo-gray ones, which has been shown to give better performance in flame image recognition. Based on the definition by Zukoski [12], the maximum and average flame height/length is determined as the height/length at which the intermittencies are 0.05 and 0.5, respectively. Moreover, for the sidewall fire in tunnel, temperatures were measured with K-type stainless steel-sheathed thermocouples of 1 mm diameter. As shown in Fig. 1b, a sequence of 21 thermocouples were placed 0.01 m under the ceiling, spanning from 0.01 to 1.99 m from the sidewall with an interval of 0.1 m. The

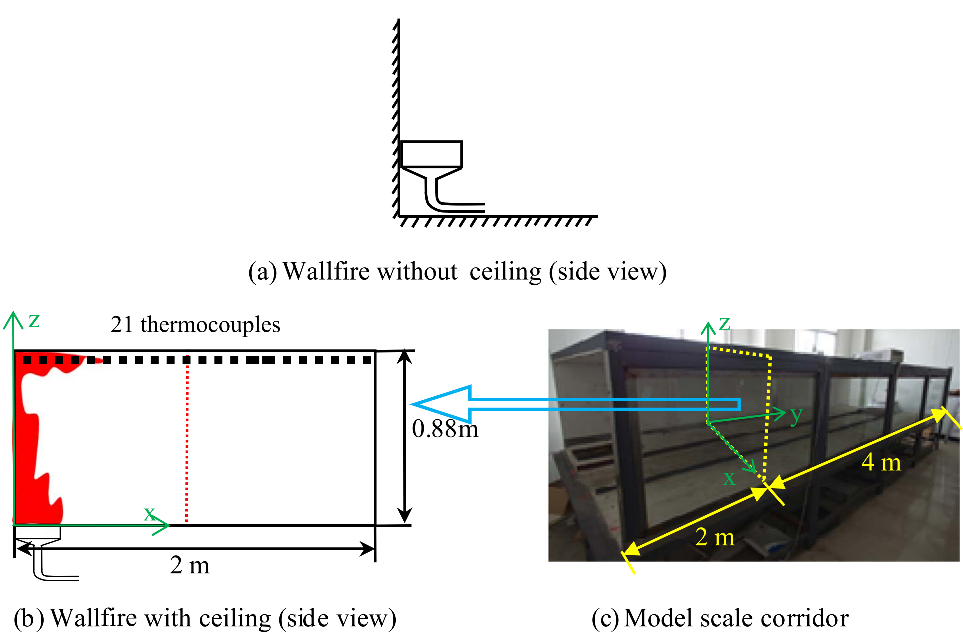

Fig. 1. Geometrical arrangement of the experiments.