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An investigation of the detailed flame shape and flame length under the ceiling of a channel

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Abstract

This paper presents an experimental investigation on the flame shape and length under the ceiling of a channel, and altogether 48 experiments with four experimental setups were performed. The experimental setups include fires in the open space, flush with a wall without ceiling, at the longitudinal centerline of a channel and flush with the sidewall of a channel. Results showed that the flame extending under the ceiling presented a circular shape when the fire is located at the longitudinal centerline of channel, whereas for fire placed flush with sidewall, it is a half ellipse. As heat release rate (HRR) increases, the long axes of the ellipse changes from perpendicular to the sidewall plane to parallel to it, resulting from the competition between air entrainment enhancement of generated vortices and air entrainment restriction of the corner structure above fire source. Additionally, the total flame extension as a lump of the vertical flame height and horizontal flame length is quantified using dimensional analysis. The total flame extensions for fire at the longitudinal centerline are proportional to 2/5 power of dimensionless heat release rate $\dot{Q}_H^*$, while for fire flush with sidewall, the total flame extensions in longitudinal and transverse directions are proportional to 1/2 and 2/5 power of $\dot{Q}_H^*$, respectively. The critical (transient) dimensionless heat release rate can be calculated as 0.60, under which the longitudinal and transverse flame lengths are identical.

Keywords: Flame length; Flame shape; Channel fire; Sidewall; Ceiling jet

1. Introduction

When a rising flame impinges on a ceiling, it will be deflected and spread out along the ceiling radially. During this process, the relatively small cone-shaped vertical flame will be re-shaped into a disk of horizontal flame, which dramatically increases the heat flux in the flame region and enhances the risk of fire propagation [1–4]. However, compared to the numerous studies on free axisymmetric vertical flames, the knowledge of horizontal flame extension under the ceiling is quite insufficient.

You and Faeth [1] calculated the flame length under a ceiling in terms of the free flame height without the ceiling and put forward a predicting formula to address the flame extension under a ceiling. Babrauskas [2] developed procedures for approximate calculation of flame lengths when part of the flame extended along the ceiling. Hinkley et al. [3] conducted an experimental investigation on flames spreading beneath both

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combustible and non-combustible ceilings. They indicated that a combustible ceiling lining results in longer flames than a non-combustible one with similar thermal properties. Ding and Quintiere [4] presented a simple integral model for horizontal flame lengths under a ceiling and attempted to obtain approximate solutions to predict the flame length. However, in these former studies, fire sources were always placed in unconfined environments with approximately symmetrical horizontal flame extensions under ceilings. Asymmetrical flame extensions generated by the fire source confined in a long, narrow structure have rarely been addressed.

Therefore, four series of burning experiments, with fire sources located in unconfined and confined environment, were conducted to analyze the detailed flame shape under the ceiling of a channel. Simplified correlations are proposed to quantify the magnitude of flame extension in longitudinal and transverse directions, which will be conducive to determine the radiation heat transfer to surrounding objects and estimate the risk of fire propagation.

2. Experimental details

The four series of experiments with different setups were fire in the open space (series A), flush with a vertical wall without ceiling (series B), at the longitudinal centerline of channel (series C) and against the channel sidewall (series D). In series A and B, the fires were placed 0.35 m above the floor. In series C, the fire was placed on the floor. In series D, the heights of fire were chosen as 0 m, 0.17 m and 0.35 m above the floor to account for the situations with the top part of vehicles or goods on fire in the channel-like structure. The schematic diagram of the experimental apparatus is shown in Fig. 1.

The model scale channel was 6 m long, 2 m wide and 0.88 m high with scale ratio of 1:6. 20 mm thick fireproofing boards were used to make the top, bottom and one side walls of the channel, the other side was made up of 10 mm thick fire-resistant glass to provide the experimental observation.

A 0.15 m square porous gas burner was used with propane as fuel. The fuel supply rate and the heat release rate were controlled by a flow meter. The heat of combustion of propane was 46.45 kJ/g [5] and complete combustion was assumed in the estimation of HRR. In each series of experiments, 8 different fire powers were used with HRR of 15.94, 26.57, 39.85, 53.13, 66.42, 79.71, 92.99 and 106.28 kW. Each case was repeated three times to assure its reliability and repeatability.

Flame behaviors were monitored from the front view and side view by two digital cameras (DV) with a frequency of 25 frames per second. In series C and D, one camera was located at the left end of the channel to record the transverse flame development and the other camera was pointed to the fire-resistant glass to record the longitudinal flame development. The vertical and horizontal flame extensions were determined by image processing method developed by Yan et al. [6]. The basic idea of this method is to transform the RGB images from the video to pseudo-gray ones, which has been proved with better performance in flame image recognition in confinement spaces. Besides, in this research, the average flame height/length is determined as the height/length at which the intermittency is 0.5, i.e., the height/length exceeding which flame appears half the time [7]. Error analysis and hypothesis testing have been conducted at the 0.05 level of significance, and the standard deviation/averaged value for flame extension is smaller than 5%, which confirms the accuracy of the data.

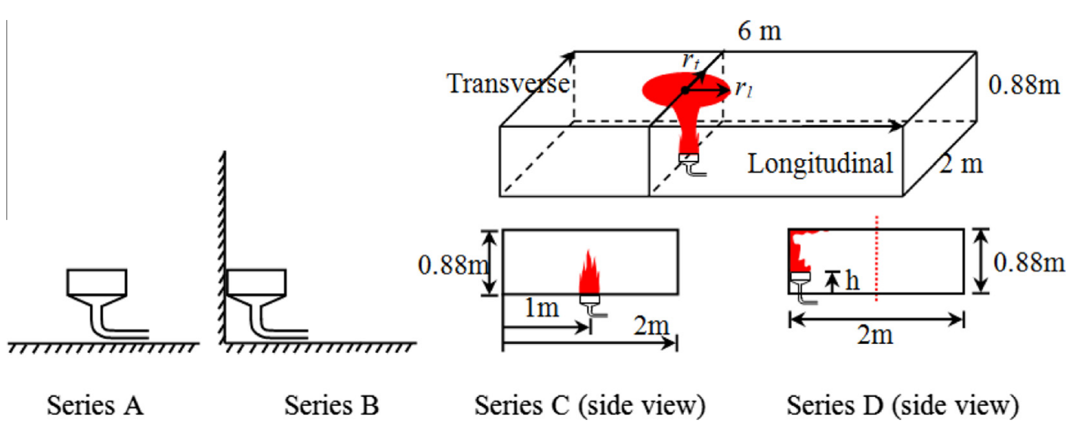

Fig. 1. Geometrical arrangement of the experiments.