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A study on the maximum temperature of ceiling jet induced by rectangular-source fires in a tunnel using ceiling smoke extraction

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ABSTRACT

This study analyzes the physics characteristics of the flame plume temperature, induced by a ceiling jet and their coupling with an extraction flow. As it is knows, the maximum increase in the temperature of a ceiling jet is a key parameter for tunnel fire safety. The ceiling maximum temperature has been analyzed and its evolution model has also been correlated in the past. However, those previous suggested correlations had considered the fire source shape is square or circular. Actually the van shape is rectangular, the corresponding fire source may be rectangular, which is necessary to extend it to other conditions of rectangular fire sources. It has also been noted that the smoke transport characteristics changed by the ceiling smoke extraction. The aim of this experimental work is to study the maximum increase in the temperature of a ceiling jet induced by rectangular-source fires with different burner aspect ratios (ranging from 1 to 8.2) in a tunnel, using a ceiling smoke extraction. The effects of different burner aspect ratios on the ceiling maximum smoke temperature increase were studied with and without a ceiling smoke extraction. The change of the burner aspect ratios, the ceiling mechanical extraction rate, and the heat release rate were also analyzed. The evolution characteristics of the ceiling maximum plume temperature rise, considering the different burner aspect ratios, with the change in the aspect ratios of burners without the ceiling extraction were firstly obtained. A new normalized equation of the ceiling maximum plume temperature, through the addition of an impact factor for the ceiling smoke extraction rate, of a ceiling jet induced by rectangular-source fires was established. The results indicated that the new global model can effectively predict experimental data.

1. Introduction

Recently, road and rail tunnels around the world have undergone rapid development. Simultaneously, tunnel fire accident would release a great amount of heat, resulting in huge casualties and property damage due to confined special spatial structures [1,2]. For example, incidents such as the Viamala tunnel fire that occurred in Switzerland in 2006 and the Burnley tunnel fire in Austria in 2007, which resulted in nine and three deaths, respectively. The maximum temperature beneath the tunnel ceiling is an important parameter; since understanding the maximum temperature profile beneath the ceiling is a highly critical variable in terms of tunnel fire safety [3–9].

Many previous studies have focused on the maximum temperature of a ceiling jet in tunnel fires [10–18]. Kurioka et al. [10] conducted a series of model experiments, proposing an empirical mathematical model for the maximum smoke temperature rise. Li et al. [12,13] carried out two series of model-scale experimental tests. i. These authors found, when the non-dimension ventilation velocity is less than 0.19, the maximum temperature under the ceiling is related with the two-thirds power of the non-dimension heat release rate. They also found that the maximum temperature under the tunnel ceiling vary with the $-5/3$ power of the vertical distance between the fire source and the tunnel ceiling. In addition to previous studies carried out on the maximum temperature with a longitudinal ventilation, research has also been conducted on the maximum temperature under various conditions, such as the natural smoke exhausting shafts [15], an inclined tunnel [16], the blockage effects [17], and different transverse fire locations [18].

Previous studies generally assumed that the fire source shape is square or circular, and few works have been developed regarding the maximum smoke temperature of a ceiling jet induced by a rectangular fire. However, in an actual tunnel fire, the fire source shape is usually not unaltered. In the present study, the maximum temperatures of the ceiling jet induced by the fire sources shaped as rectangles of different aspect ratios were studied.

Zhang et al. [19] carried out a series of inclined unconfined ceiling

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Nomenclature

$f(V)$	factor defined in Eq. (10)
$f(V_s)$	factor defined in Fig. 7
H_d	distance from burner face to tunnel ceiling (m)
ℓ_F	full-scale tunnel length (m)
ℓ_M	small-scale tunnel length (m)
n	burner aspect ratios
$\dot{Q}$	heat release rate (kW)
$\dot{Q}_{c,F}$	convective heat release rate of full-scale tunnel (kW)
$\dot{Q}_{c,M}$	convective heat release rate of small-scale tunnel (kW)
S	ceiling exhaust port area (m^2)
T	smoke temperature under the exhaust port (K)
T_a	ambient temperature (K)
ΔT_{max}	maximum temperature rise (K)
$\Delta T_{max,V}$	maximum temperature rise with ceiling extraction (K)
V	ceiling extraction velocity (m/s)
V^*	dimensionless ceiling extraction velocity
V_s	smoke exhaust rate
x_F	full-scale tunnel size
x_M	small-scale tunnel size

Greek letters

α	coefficient of maximum temperature rise
ρ	smoke density under the exhaust port (kg/m^3)
ρ_a	air density (kg/m^3)

Subscripts

F	full-scale
M	model scale

jet experiments induced by the three rectangular-source gas burners with different aspect ratios (n = 8, the burner exit size is 6 mm × 47.5 mm; n = 18, the burner exit size is 4 mm × 71.25 mm, and n = 71, the burner exit size is 2 mm × 142.5 mm). The heat release rates were varied (from 2.40 to 9.60 kW), five source-ceiling heights were considered (0.475 m, 0.57 m, 0.665 m, 0.76 m and 0.855 m) and four inclined angles (5°, 8°, 20°, 30°) were studied in their experiments. It was found by those authors that the ceiling inclined angles have a large influence on the maximum temperature, and that its value is proportional to that of free fire plumes at the ceiling level for a given ceiling inclined angle up to 30°. It is should be noted that, previous studies have not focused on the maximum temperature induced by a rectangular fire source, particularly in a ceiling smoke extraction system. As the mechanical ventilation is widely applied in tunnel or building ceiling, the ceiling smoke extraction system can affect the smoke spread characteristics in tunnel fires [20–24], which will exhaust a part of smoke and heat, and affect the ceiling maximum plume temperature profile. In this study, the aim is to study the evolution characteristics of the maximum plume temperature of a ceiling jet beneath the ceiling induced by a rectangular burner, under the effect of a point ceiling smoke extraction system.

2. Experimental

2.1. Experimental rig

The experiments were carried out in a 1:20 model-scale tunnel with the size of 8 m (length) × 0.34 m (width) × 0.44 m (height) [25]. A schematic diagram of the model tunnel can be found in Fig. 1, where the horizontal distance between the two ceiling exhaust ports (center) is 1 m and the fire source is placed in the middle of the two exhaust ports. Both the ceiling and bottom of the tunnel was equipped with a 0.008 m calcium fireproof plate, in order to resist the high temperature induced by the fire source. The sidewall was constructed by reinforced

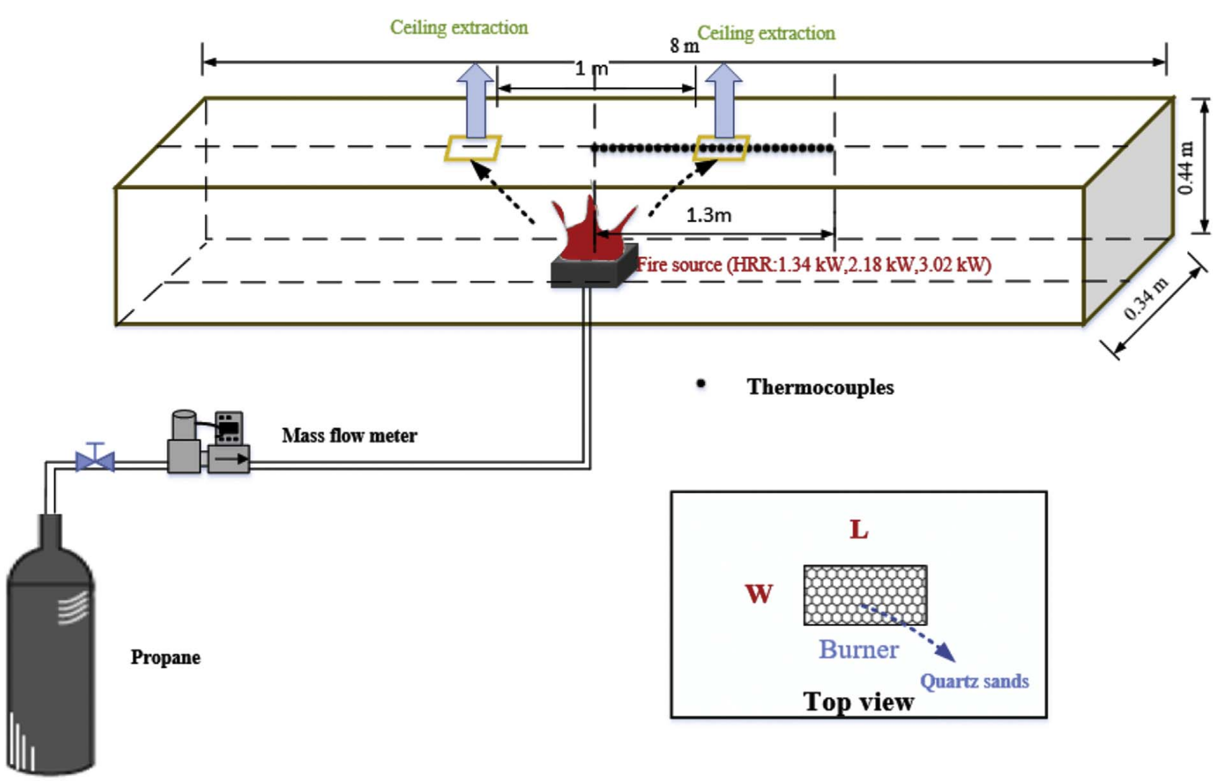

Fig. 1. Schematic diagram of the model tunnel.