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Flame extension lengths beneath a confined ceiling induced by fire in a channel with longitudinal air flow

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ABSTRACT

This paper investigates the length of flame extension for an impinging flame underneath the confined ceiling in a channel with longitudinal air flow. Previous works in this field have been primarily concerned with un-confined ceilings and no forced air flow conditions. Under longitudinal air flow conditions, the flame extension beneath the channel ceiling is non-symmetrical, that is, different in the upstream and downstream directions from the fire source. In this study, experiments were carried out with two channeled ceilings with widths of 1.5 m and 0.5 m. Square porous gas burners of different sizes were employed as the fire source, using propane as fuel, with various heat release rates and source-ceiling heights. The flame extension lengths beneath the ceiling, both upstream and downstream from the fire source, were measured. Their difference as well as their total length was quantified for different magnitudes of forced longitudinal air flow along the channel. Results show that the flame extension lengths beneath the ceiling increases with heat release rate, but decreases with source-ceiling height, channel width, burner size or longitudinal air flow speed. With a longitudinal air flow, the flame extension is longer downstream than upstream. Non-dimensional correlations are proposed for the flame extension lengths (upstream, downstream and their total length), based on the unburnt fuel distribution upstream and downstream, as well as considering air entrainment of the ceiling flow, which further consumes the unburnt fuel along the ceiling. These correlations are shown to fit the data well.

1. Introduction

When the free flame height of a fire is higher than the ceiling height, the flame impinges upon the ceiling and extends for some distance beneath the ceiling. This impinging flame will result in a very high heat flux to the ceiling and an enhanced radiative flux to the lower parts of the surrounding environment [1–3]. This high heat flux may have a significant effect on any combustible materials leading to further ignition, and may also cause physical damage to non-combustible materials. So, the flame extension length beneath the ceiling is an important parameter to be quantified and modeled. The behavior of the impinged flame may be divided into two broad scenarios: (i) for an unconfined ceiling where the flame extends radially in an axi-symmetrical manner; or (ii) for a confined ceiling, for example, in a long-narrow structure (such as a corridor, tunnel or duct), where the flame is constrained by the side walls and extends along the ceiling in two opposite directions from the fire source.

For the flame extension length beneath an unconfined ceiling, You and Faeth [1] proposed an empirical correlation, which is widely used in practice:

$$r_f/D = 0.502\left[\left(H_f - H\right)/D\right]^{0.957} \quad (1)$$

where r_f is the radial flame extension length beneath ceiling; H_f is the visible flame height (free burning, without the ceiling); H is the source-ceiling height; and D is the diameter of the fire source. Babrauskas [2] reviewed the problem in 1980s. Gross [3] obtained some data with 0.61 m and 0.91 m diameter burners (104–283 kW). Hasemi and Yokobayashi [4] proposed following formula based on a dimensionless fire heat release rate:

$$r_f/D = 2.58\dot{Q}^{*2/5}(H/D)^{2/5} - H/D \quad (2)$$

with

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Nomenclature

c_p	specific heat of air at constant pressure (kJ/kg•K)
d	depth of hot gas layer beneath corridor ceiling (m)
D	diameter of fire source/side dimension of square burner (m)
g	gravitational acceleration (m/s^2)
H	source-ceiling height (m)
H_f	free flame height (m)
ΔH_∞	heat released per kg of air consumed (kJ/kg)
ΔH_{fuel}	heat of combustion of the fuel (kJ/kg)
l_f	flame length beneath the corridor ceiling(m)
l_{fe}	flame extension length along the channel ceiling (m)
$l_{fe,0}$	flame extension length beneath the channel ceiling with no air flow (m)
$l_{fe,upstream}$	flame extension length beneath the channel ceiling for the upstream with air flow (m)
$l_{fe,downstream}$	flame extension length beneath the channel ceiling for the downstream with air flow (m)
$\dot{Q}$	heat release rate (kW)
r_f	radical flame extension length beneath ceiling (m)
T_∞	ambient air temperature (K)
ΔT_f	flame temperature rise above ambient air temperature (K)
u_a	longitudinal air flow speed (m/s)
u_e	characteristic velocity of the ceiling flow after impingement (m/s)
$\dot{V}_{fuel}$	fuel volume flow rate (m^3/s)
W	channel width (m)

Greek symbols

ρ_∞	ambient air density (kg/m^3)
$\Delta\rho_f$	density difference between flame and ambient air (kg/m^3)
θ	flame tilt angle (degree)

Subscripts

fe	flame
p	constant pressure
∞	ambient

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty T_\infty c_p g^{1/2} D^{5/2}} \tag{3}$$

where $\dot{Q}$ is the heat release rate; ρ_∞ is the ambient air density; T_∞ is the ambient air temperature; c_p is specific heat capacity of air at constant pressure; and g is the acceleration due to gravity. The data in Ref. [4] was further correlated non-dimensionally [5] using source-ceiling height H for normalization rather than source dimension D. Ding and Quintiere [6] also proposed another non-dimensional correlation based on a theoretical analysis to predict the flame extension length beneath the ceiling using source dimension D for normalization:

$$r_f/D = 1.62\dot{Q}^{*2/5} \tag{4}$$

More recently, Zhang et al. [7,8] proposed correlations of flame

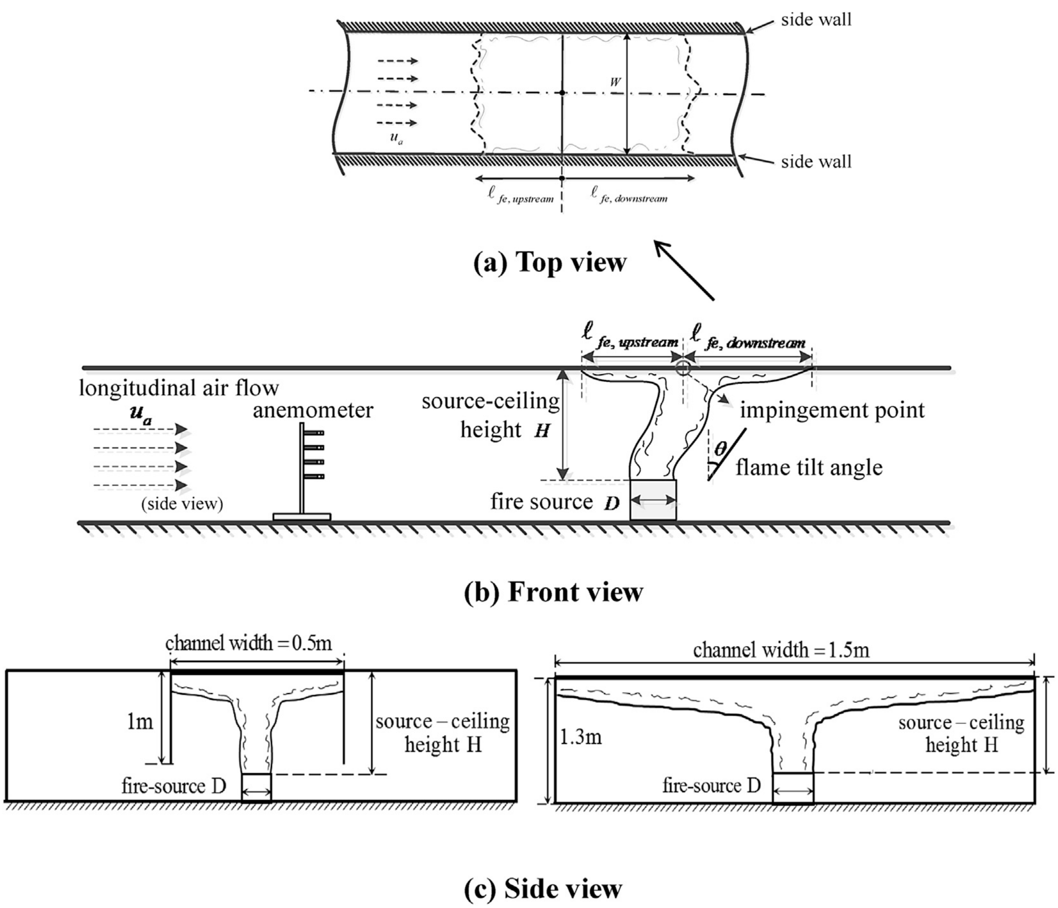

Fig. 1. Experimental setup.