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Flame extension lengths beneath an inclined ceiling induced by rectangular-source fires

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ABSTRACT

The flame extension length beneath an inclined ceiling has not been studied in the past, and therefore no data or analysis is reported in the literature. Experiments were carried out in this work to measure both of the flame extension lengths in the upward and the downward directions beneath an inclined ceiling of different angles induced by rectangular fire sources with various heat release rates and source-ceiling heights. Results showed that the flame extension length was larger in the upward direction than that in the downward direction, which was physically explained as attributed to the non-symmetrical distribution of un-bunt fuel in the two directions after impingement. A new global equation was proposed to correlate the flame extension lengths in both directions by using modified non-dimensional heat release rates accounting for this non-symmetry. This work provided supplementary results over previous knowledge and correlations about flame extension beneath a flat ceiling.

1. Introduction

Flame is deflected then extends beneath the ceiling when flame region directly impinges upon a ceiling in a compartment fire. The flame extension length is a significant parameter in assessment of fire hazards owing to the increased heat flux upon the ceiling in the flame extension region [1–4]. In view of its importance, researches on this issue have been carried out in early years [1–7], which are primarily focused on flat horizontal ceilings.

For flame extension beneath a horizontal ceiling induced by axisymmetric-source fires, You and Faeth [4] gave an empirical formula to describe the flame extension length based on measured experimental data (heat release rates ranged from 0.36 to 7.89 kW):

$$r_f/D = 0.502[(H_f - H)/D]^{0.957}, \tag{1}$$

where H_f is the free flame height, H is the source-ceiling height, D is the fire source diameter, and r_f is the radical flame extension length beneath the ceiling. On the basis of scaling analysis, Ding and Quintiere [5] suggested the following correlation by employing a non-dimensional heat release rate ($\dot{Q}_D^*$) using source diameter (D) as characteristic length:

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

in which $\dot{Q}_D^*$ is expressed as:

$$\dot{Q}_D^* = \frac{\dot{Q}}{\rho_\infty c_P T_\infty \sqrt{g} D^{5/2}}. \tag{2b}$$

Later, Lattimer [6] proposed another non-dimensional correlation similar to that proposed by Ding and Quintiere:

$$r_f/H = 3.1\dot{Q}_H^{*2/5} - 1, \tag{3a}$$

Lattimer chose the source-ceiling height (H) as characteristic length and the non-dimensional heat release rate ($\dot{Q}_H^*$) is defined as:

$$\dot{Q}_H^* = \frac{\dot{Q}}{\rho_\infty c_P T_\infty \sqrt{g} H^{5/2}} \tag{3b}$$

where $\dot{Q}$ is heat release rate of the fire source, ρ_∞ is the ambient air density, c_p is the specific heat of air at constant pressure, T_∞ is the ambient temperature, g is the gravitational acceleration. More recently, Zhang et al. [7] proposed a semi-empirical correlation for horizontal flame extension length and temperature profile in thermal impinging flow induced by a round fire source.

However, it is noted that all of the above works and correlations are only for a horizontal ceiling. Actually, there are many buildings having inclined roofs [8–10] for which the existing correlations are

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Nomenclature

C_1	parameter defined in Eq. (7)
c_p	specific heat of air at constant pressure (kJ/(kg K))
D	diameter of axi-symmetric source (m)
D_h	hydraulic diameter of rectangular fire source (m)
Fr	Froude number
g	gravitational acceleration (kg m/s^2)
H	source-ceiling height (m)
H_f	free flame height (m)
L	length of rectangular-source burner (m)
$\dot{m}$	unburned fuel mass contained in impingement zone
$\dot{m}_{up}$	unburned fuel mass in upward direction after impingement
$\dot{m}_{down}$	unburned fuel mass in downward direction after impingement
P	probability of flame presence
q	flow rate of the fuel (m^3/h)
$\dot{Q}$	heat release rate of fire source (kW)
$\dot{Q}_D^*$	non-dimensional heat release rate defined in Eq. (2b)
$\dot{Q}_H^*$	non-dimensional heat release rate defined in Eq. (3b)
$\dot{Q}_{Hm}^*$	non-dimensional heat release rate defined in Eq. (6)
$\dot{Q}_{Hm}^{**}$	non-dimensional heat release rate defined in Eqs. (11a) and (11b)
r_f	flame extension length beneath ceiling (m)
$r_{f\text{-}up}$	flame extension length in the upward direction beneath the ceiling (m)
$r_{f\text{-}down}$	flame extension length in the downward direction beneath the ceiling (m)
Ra	Rayleigh number
Re	Reynold number
T_∞	ambient air temperature (K)
u	velocity at the impingement point (m/s)
U	fuel flow velocity at nozzle exit (m/s)
V_f	volume of a free flame (m^3)
V_{fu}	flame volume portion intercepted by the ceiling (m^3)
W	width of the rectangular-source burner (m)
z	height above fire source (m)

Greek symbols

β	thermal expansion coefficient
θ	inclination angle of ceiling
ν	kinematic viscosity
ρ_∞	ambient air density (kg/m^3)
ℓ_x; ℓ_y	dimensions of the flame cross-section at impingement in x-(y-) direction (m)

Subscript

c	combustion
$down$	downward
f	flame
h	horizontal
i	inclined
P	constant pressure
up	upward
∞	ambient

no longer applicable. For this reason, Oka et al. [8–10] studied the temperature, ceiling flow thickness and velocity profiles beneath an inclined ceiling recently. However, their research focused on the scenarios that flame tip does not reach the ceiling just resulting in a plume impingement.

In summary, there is still no work reported for flame extension length beneath an inclined ceiling. It can be anticipated that the flame extension lengths will be different in the two directions, namely upward or downward along the inclined ceiling with respect to the impingement point.

So, experiments were carried out in this work to measure both of the flame extension lengths in the upward and the downward directions beneath inclined ceilings with different inclination angles, fire source heat release rates, source aspect ratios and source-ceiling heights. A new global equation was then proposed to correlate the flame extension lengths in the two directions.

2. Experiments

Figure 1 depicts a schematic diagram of the experimental setup. A smooth fire-proof plate with good heat resistance performance [size of 1.5 m (W) × 2 m (L), thickness of 0.02 m, low thermal conductivity of 0.035 W/(m K)] was employed to simulate the ceiling. The inclination angle and height of ceiling could be adjusted for different experimental conditions.

Three rectangular burners made of stainless steel with exit dimensions of 2 mm × 142.5 mm, 4 mm × 71.25 mm, and 6 mm × 47.5 mm were employed as fire sources, with relatively larger aspect ratio of 1:71, 1:18 and 1:8, respectively. In all the experiments, these burners were placed with its longer side perpendicular to the inclination direction (as shown in Fig. 1). This setup was to highlight the non-symmetrical distribution of the ceiling flow after impingement in the upward and the downward directions. Propane with high purity (>95%) was used in our experiments. The supply rates were monitored and controlled by a mass flow rate meter (with accuracy of 0.01 L/min). The heat release rates were designed in a range 9.0–53 kW in order to have turbulent flames.

Five source-ceiling heights (0.38 m, 0.48 m, 0.57 m, 0.68 m and 0.78 m) and five inclination angles (0°, 5°, 10°, 15°, 20°) were considered in the experiments. More higher inclination angles were not considered because inclined roofs usually do not have very large angles; however, the inclination angle effect on flame extension length was remarkable as shown in the next section even for these relatively limited inclination angles. For all of the experimental scenarios, only the cases with direct flame impingement and extension were considered. Both the visible free flame heights without ceiling and the flame extension lengths beneath the ceiling were recorded by a CCD camera whose sensor size is 8.5 mm with 3 Megapixels (25 fps). The tested conditions are summarized in Table 1. Each case was repeated 3 times. Hydraulic diameters of rectangular fire sources were selected as characteristic length in calculation of Reynolds and Froude numbers. The method proposed in [11] to quantify the turbulence of the flame (not that at the source) based on the Ra number ($Ra = \frac{g\beta\dot{Q}H^2}{\rho C_p \nu^3}$) was also used here, as the buoyant flow turbulence was growing with height. Yih [11] found a Ra criteria (9×10^9) for dividing the buoyant flow as laminar or turbulent. The Ra numbers of You and Faeth's experiments [4] ranged in 1.3×10^{11} to 4.04×10^{12} for the jet fire tests and they claimed their experimental scenarios were turbulent. The Ra numbers of our experiments (at ceiling height H) were ranged in 8.16×10^{12} to 1.82×10^{14} and the scenarios were confirmed to be turbulent as also confirmed by our direct visual observations.

3. Results and discussion

Figure 2 shows typical instantaneous views of flame extension photos obtained from 6 mm × 47.5 mm burner for different inclination angles 0°, 5°, 10°, 15° and 20° with the same source-ceiling height ($H = 0.38$ m) and same heat release rate ($\dot{Q} = 12$ kW).