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Temperature profile beneath an inclined ceiling induced by plume impingement of gas fuel jet flame

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ABSTRACT

Temperature profile of thermal impingement flow beneath sloped ceiling induced by non-isotropic gaseous fuel jet flame has not been studied before and therefore no data are available in the literatures. Experiments were carried out in this work to measure the temperature distribution in both upward and downward directions beneath the inclined ceiling induced by gaseous fuel jet flame. Different inclination angles, various heat release rates and diverse source-plate heights were considered. Results show that the influence of inclination angle has opposite impacts on the temperature rise for upward flow and downward flow respectively and burner dimension has little effect on the temperature attenuation characteristics while the inclined direction is perpendicular to long side of fire source. The experimental data were compared with correlations predicted by predecessors' researches and it was observed that the experiment data of upward were consistent with the former correlations while an apparent discrepancy can be found along the downward direction. The influence of buoyancy component force parallel to inclined ceiling was discussed and simply reflected by the cosine value of inclination angle. New relatively uniform correlations were proposed to predict the temperature decay profiles by combing the effects of heat release rates, inclination angles and source-ceiling heights.

1. Introduction

Significant number of researches have been carried out to investigate the thermal flow characteristics induced by impingement of a gaseous fuel jet (e.g. [1–3]) in recent years. Temperature profile of thermal ceiling jet is a significant parameter which can provide guidance for building fire risk assessment, fire protection design and even for numerical verification [4,5].

Most of the fires occurred in our real world can be approximately defined as two types according to the geometry of fire source: axisymmetric fire source, rectangular-source and line-source fire (non-isotropic source fire). Fire source geometry should be an essential factor in fires, which can affect many profiles in fires [6–11], such as flame height, the axial temperature and velocity of the thermal plume.

A larger number of previous studies have been focused on axisymmetric source [12–25]. For example, Hu et al. [12] researched the centerline temperature decay profile of circular jet flame plume. Then, they investigated the temperature profile of a thermal ceiling jet flow impingement upon a horizontal plate induced by an axisymmetric source fire [13], in which a correlation is finally proposed to predict the temperature distribution. Kurioka et al. [14] developed an empirical formula for maximum temperature of the smoke layer in a tunnel fire by employing square fire sources. Li et al. [16] proposed a correlation to predict the maximum gas temperature beneath the tunnel ceiling based on axisymmetric fire plume theory. Bart [19] quantified the influence of the global chimney effect in an inclined tunnel fire. Kashef et al. [21] researched the effect of nature ventilation on the ceiling temperature distribution and smoke diffusion in horizontal thermal ceiling tunnel induced by axisymmetric source.

In contrast, much less works have been conducted for line source and rectangular source fires [26–28]. For example, Zhang [27] conducted experiments to investigate the flat ceiling temperature profiles and flame extension length under the ceiling for ceiling jets driven by line fire plumes and proposed a correlation to predict the temperature decay along the flat ceiling. Tang et al. [28] analyzed the physics characteristics of the flame plume temperature, induced by a ceiling jet and their coupling with an extraction flow, and proposed new normalized equation of the ceiling maximum plume temperature of a ceiling jet induced by rectangular-source fires.

However, the literatures mentioned above are all focused on

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Nomenclature

b_c	characteristic radius (m)
c_p	specific heat of air at constant pressure (kJ/(kg·K))
C	non-dimensional constant in Eq. (5)
C'	constant in Eq. (4a)
g	gravitational acceleration (kg·m/s^2)
H	source-ceiling height (m)
L	length of rectangular-source burner (m)
$\dot{Q}$	heat release rate of the fire source (kW)
$\dot{Q}^*$	non-dimensional heat release rate $\left(\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} H^{5/2}}\right)$
$\dot{Q}^*_{mod}$	non-dimensional heat release rate $\left(\dot{Q}^*_{mod} = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} L W^{3/2}}\right)$
r	travelling distance from the fire source along the plate (m)
T_∞	ambient air temperature (K)
ΔT	temperature rise at radial position r from impingement origin (K)
ΔT_p	temperature rise at ceiling height along the plume center line (K)
W	width of the rectangular-source burner (m)

Greek symbols

θ	inclined angle of ceiling (°)
ρ_∞	ambient air density (kg/m^3)
Δ	difference between variables
ξ	non-dimensional constant in Eq. (5)

Subscript

down	downward direction
up	upward direction
∞	ambient

horizontal thermal ceiling flow. The results obtained from these works can not directly used to predict the temperature distribution in an inclined ceiling jet flow which extensively exists in our constructions [29–33]. Oka et al. [29] investigated the temperature decay profile along inclined ceiling and gave a correlation for upward flow in the case of flame height being much less than ceiling height, which gives:

$$\frac{\Delta T_{up}}{T_\infty} \Big/ \dot{Q}^{*2/3} = \left(0.188 + 0.313\frac{r_{up}\cos\theta}{H}\right)^{-4/3} \tag{1}$$

However, no correlation was established for the downward flow in this work. Actually, there were hardly any correlation can be found in the former literatures for the temperature attenuation along downward direction. The only one can be found was that conducted by Kung et al. [34], which gave empirical correlations for both upward and downward flows as following:

$$\frac{\Delta T_{up}}{\Delta T_p} = \exp\left[(0.12\sin\theta - 0.42)\left(\frac{r_{up}}{b} - 1\right)^{0.7}\right] \quad r_{up}/b \geqslant 1 \text{ and } 0° \leqslant \theta \leqslant 30° \tag{2a}$$

$$\frac{\Delta T_{down}}{\Delta T_p} = \frac{r_{down}(0.15\sin\theta + 0.11)}{b} + 0.97 - 0.06\sin\theta \quad r_{down}/b < 0 \text{ and } 0° \leqslant \theta \leqslant 30° \tag{2b}$$

But there are still some limitations in Kung's work [34]. While the buoyancy component force has a negative effect on the downward flow to prevent the flow movement, temperature attenuation in downward direction might be divided into distinctly different region, as has also been proven in former work [29]. However, with only two measured locations arranged in downward direction, the measured temperature data might be insufficient to comprehensively describe the temperature profile along downward direction.

Besides, it is also noticed that above research work focus on temperature decay profile along inclined ceiling is limited in one-dimensional axisymmetric fire source-driven thermal ceiling flow. Temperature profile of thermal impingement flow beneath sloped ceiling induced by non-isotropic fire source has not been studied before, and the applicability of previous correlation in such non-isotropic source-induced flow is still unknown. In this work, we would like to extend the knowledge of temperature decay profile under the sloped

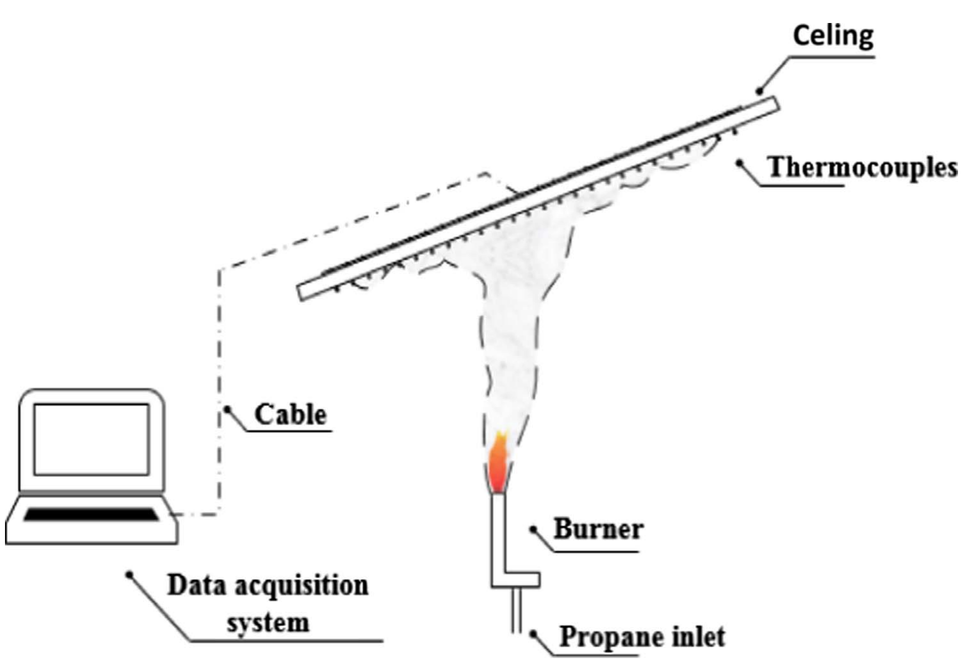

Fig. 1. Experimental setup.