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Predicting heat fluxes received by horizontal targets from two buoyant turbulent diffusion flames of propane burning in still air

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ABSTRACT

An analytical method to estimate the heat fluxes received by horizontal targets from two buoyant turbulent diffusion flames was proposed. Two identical square gas burners with side length of 15 cm were used as the fire sources with propane burning in still air. The heat release rate (HRR) and burner edge spacing were changed in experiments. Heat fluxes received by four external horizontal targets were measured. In cases with one burner or two burners with zero spacing, there is one single flame and the vertical centerline temperature distribution were divided into four zones including core zone, constant zone, intermittent flame zone and plume zone. Based on the established piecewise function for predicting the flame temperature, the cuboid flame model with hierarchical temperatures was proposed to determine the flame emissivity, the mean flame temperature of the model and the corresponding blackbody emissive power. The results showed that when the HRR of single flame ranges from 10.8 kW to 64.8 kW, the flame emissivity of 15 cm square burner ranges from 0.125 to 0.387, and the absorption coefficient ranges from 0.99 m^{-1} to 3.62 m^{-1}. At a given HRR, the flame emissivities of two burners with zero spacing and infinite spacing are nearly identical, suggesting that the influence of spacing on flame emissivity is marginal. For two burners with spacing higher than zero, by assuming that the flame radiative fraction of propane is 0.3 and the flame emissivity is equal to that of the single flame, the flame radiative heat fluxes received by external targets are calculated by modeling the flame shapes as two right or tilted cuboids. The comparison validates that the calculations using the proposed cuboid models for both one and two flames agree well with the experimental results.

1. Introduction

The radiant heat flux from flame is one of the most important parameters governing the fuel surface heating, fire sustenance and spread hazards in free space [1–2]. As for the flame radiation characteristics, many studies have been focused on single fire cases. However, it should be recognized that most of the devastating and uncontrollable fire accidents are erupted along with multiple fires burning. Two or more nearby fires burning simultaneously is termed as multiple fires. The interaction of multiple fires will lead to flame tilt and even merge together due to the restriction of air entrainment, which has a great impact on the burning rate, flame shape, and heat transfer from flames to surroundings [3–5]. Due to the superposition effect of thermal radiation from multiple fires, the possibility of ignition and flame spread between adjacent discrete combustibles is dramatically increased. The information of flame radiative heat flux is very useful in fire and combustion researches for estimating the heat transfer from flames to nearby targets, fire spread and ignition hazards, safety separation distances between combustibles, activation of thermal detectors and extent of damage from fires [1,2]. However, the recent review of multiple fires by Vasanth et al. [6] reveals that in spite of the significance of heat transfer between multiple fires and external objects, very limited studies have been concerned with this subject. This work attempts to bridge the knowledge gap.

In general, the radiative heat transfer is dependent on three physical parameters including flame temperature, absorption coefficient of the flame and flame shape [7–8]. It is widely assumed that the flames are homogeneous (constant average absorption coefficient) and isothermal (constant flame temperature) in the literature [7–13]. Modak [9] reported that the assumption of uniform

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Nomenclature

a	horizontal distance from the edge of cuboid to the target in Eq. (18)
A_f	flame surface area (m^2)
b	length of the rectangular in Eqs. (18) and (23)
D	burner diameter or square length (m)
D_{eq}	burner equivalent diameter in Eq. (19) (m)
E_b	blackbody emissive power (kW/m^2)
F	geometrical view factor
H	flame height (m)
J	parameter in Eq. (19)
K	parameter in Eq. (19)
L_c	continuous flame height (m)
L_i	intermittent flame height (m)
l_m	mean beam length (m)
L_m	mean flame height (m)
M	parameter in Eq. (19)
N	parameter in Eq. (19)
P	perimeter of flame base (m)
$\dot{Q}$	heat release rate (kW)
$\dot{q}''$	surface heat flux (kW/m^2)
$\dot{Q}_{total}$	total heat release rate of two burners (kW)
R	distance from the flame center to the target in Eq. (20) (m)
S	burner edge spacing (m)
T	gas temperature (K)
T_∞	ambient temperature (K)
V_f	flame volume (m^3)
W	flame width (m)
W_A	total flame width induced by burner A (m)
z	height above the burner surface (m)
ΔT	temperature rise (K)
ΔT_r	temperature rise due to radiation error (K)

Greek symbols

α	angle related to the point source model in Eq. (20) (°)
α_f	flame absorptance
ε_f	flame emissivity
θ	flame tilt angle (°)
κ	absorption coefficient (m^{-1})
σ	Stephan–Boltzmann constant ($W/(m^2K^4)$)
τ_f	flame transmittance
χ_{rad}	flame radiative fraction

Subscript

A	burner A
B	burner B
c	cylinder
f	flame
H	horizontal
max	maximum
rad	radiation
V	vertical

properties of flame is quite satisfactory for medium (< 0.4 m dia.) scale fires in flame radiation analyses. However, different flame temperatures and absorption coefficients were assumed arbitrarily in former studies [7–13]. To obtain more accurate results, it is required to determine the flame temperature and absorption coefficient using experimental methods. Flame and plume temperatures have been widely studied by former researchers. The axisymmetric fire plume above the fire surface was conventionally divided into three zones [14], the continuous flame zone where the temperature is roughly constant, the intermittent flame zone and the plume zone where the temperature decreases with increasing height. Similar expressions for estimating vertical temperatures within the three zones were established through experiments [14–20]. It is worth noting that the flame emissivity rather than absorption coefficient is usually determined to estimate the flame radiation intensity. Raj and Prabhu [21] summarized total 6 methods to calculate the flame emissivity in the literature.

Basically, there are two flame shape models to evaluate the flame radiation to external targets, i.e. the point source model [7] and the solid flame model [22]. Modak [7] reported that the point source model can well predict the flame radiation received by remote targets with a horizontal distance between the target and the fire center larger than 2.5 times the fire diameter, while it is unsuitable for cases of increasing optical thickness and decreasing distance between target and fire. The solid flame model is based on the assumption that the flame shape is a prism surrounding the entire luminous flame and the non-luminous flame does not contribute significantly [22]. To calculate the radiative heat flux using the solid flame model, it is required to know the flame surface area and the view factor between flame and target, both of them are dependent on the information of flame shape. For the fire with a circular shape or rectangular shape with aspect ratio (ratio of fire length to width) close to 1, the cylindrical flame model is basically assumed. Hasemi and Nishihata [23] indicated that for large HRRs, the effects of fire size and shape are negligible, while for relatively low HRRs, the fire shape effect is found to be considerably significant for aspect ratio greater than 2. At this time, the unsuitable assumption of cylindrical flame model for rectangular burners will cause large errors on predicting the view factor and flame surface area and the resultant flame radiation. Fortunately, cuboid flame model provides an alternative way to calculate the radiative heat fluxes from fires with large aspect ratios. Based on the current rectangular burner shape, the cuboid rather than cylindrical flame model is adopted to calculate the flame radiation.

As extensive studies have been done on flame radiative heat flux to external targets under the condition of a single fire, very limited studies have been reported on the subject of multiple fires. Markstein [24] explored the effects of fuel flow rate and burner spacing on radiative properties and indicated that the total radiative power of two interacting flames is identical to 2 times of the single flame case regardless of the spacing. Weng et al. [25] conducted 2 by 2 and 3 by 3 array wood crib fires and calculated the flame radiation to external targets by assuming the merged flames as a cylindrical and black-body homogeneous emitter. The overall trend of the flame radiative heat flux calculated by their model is similar to that obtained in experiments, while the calculated peak radiative heat fluxes are always higher than the experimental results. The error might be induced by the assumption of the single fire model regardless of the actual flame shape formed by multiple fires with a spacing.

This work aims to extend the previous analysis [5] to study the flame radiation property. Former work [5] was mainly focused on the flame merging behaviors and the impact of air entrainment on mean flame height. The main contribution of this work is that it establishes suitable flame models to estimate the radiative heat fluxes received by external targets from both single and two interacting buoyant diffusion flames. The comparison validates that the accuracy of the proposed cuboid flame model in predicting the flame radiative heat flux is much higher than the traditional cylindrical flame model and point source model. A further aim of this paper is to provide experimental results from two buoyant diffusion flames that can be applied for validation of numerical simulations.