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Experimental study and analysis on the interaction between two slot-burner buoyant turbulent diffusion flames at various burner pitches

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ABSTRACT

This paper investigated the interaction of two slot-burner buoyant turbulent diffusion flames at various burner pitches. Experiments were conducted by employing two identical slot burners (length: 142.5 mm; width: 2 mm) using propane as fuel at various fuel exit velocities. Results showed that with an increase in burner pitch, the interaction of the two flames made a transition from merging to non-merging, resulting in a complex non-monotonic evolution of flame height. An analytical model was developed to characterize the critical burner pitch for flame merging, which was found to be proportional to the free flame height, or have a 2/3 power law dependence on the fuel exit velocity. As a result of their interaction, the flame merging point height increased till the two flames separated with the increase in burner pitch. Meanwhile, the flame height was shown to first decrease, then increase and finally approach the free flame height with the increase in burner pitch. A scaling non-dimensional formula was finally proposed, based on the analysis of the change in air entrainment into the flame from the space between the two burners with burner pitch variation. This proposed formula was shown to well correlate the above transitions based on a newly defined non-dimensional heat release rate using an “effective” entrainment perimeter as a characteristic length, which includes the burner width and length as well as the additional flame base “extension” due to the change in burner pitch.

1. Introduction

The interaction between multiple diffusion flames is a fundamental combustion problem. The burner pitch has a great influence on their interaction hence the air entrainment and flame shape [1,2]. A decrease of burner pitch will lead to flame merging, which causes a considerable increase of flame height [3,4]. Furthermore, the interaction of adjacent flames is also effected by burner geometry and diffusion-flame type (laminar or turbulent, and momentum- or buoyancy-controlled) due to a changed air entrainment mechanism.

In the past decades, numerous works have been conducted on the interaction of multiple diffusion flames. However, most of them [3–11] focused on axisymmetric burners to investigate the effects of fuel type, diffusion-flame type, the number of burners, array pattern and burner pitch. Weng et al. [3] and Kamikawa et al. [4] investigated the influences of burner pitch and fuel supply rate on the flame height of propane square burners in square arrays. Similar works had also been reported for burner arrays of liquid-fuel circular pools and gaseous-fuel square pools [5,6] as well as a solid fuel (wood crib) [7]. Delichatsios [8] proposed a global model for the flame height of square propane burner arrays at various burner pitches. Putnam and Speich [9] investigated the heights of buoyant turbulent flames for different numbers of jets in different polygon array patterns by using identical porous cylinder burners. Additionally, there were also researches on the interaction of multiple laminar diffusion flames [e.g., 2,10,11]. For example, Hirasawa et al. [2] experimentally explored the interaction between two micro-flames established on circular burners at various burner pitches.

The employment of axisymmetric burners is appropriate when studying burner arrays (almost square arrays) concerning the effect of burner pitch on the interaction of such multiple group flames, as three-dimensional effects (or a change in three-dimensional air entrainment with burner pitch) control the interaction. However, when basically investigating the interaction of two diffusion flames, it is noted that it is the buoyancy-induced side entrainment

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Nomenclature

d	additional flame base “extension” [m]
D	burner pitch [m]
D_c	critical burner pitch [m]
Fr	Froude number based on flame height
Fr_f	flame Froude number
g	gravitational acceleration [m/s^2]
Gr	Grashof number
ΔH	heat of combustion [kJ]
L	length of slot-burner [m]
N	number of total sampling flame frames
N_m	number of merging flame frames
P	“effective” entrainment perimeter [m]
P_m	flame merging probability
$\dot{Q}$	total heat release rate [kW]
$\dot{Q}_L^*$	non-dimensional heat release rate of slot-burner per unit length
$\dot{Q}_P^*$	non-dimensional heat release rate for one burner of two interaction flames
S	air to fuel mass stoichiometric ratio
T_∞	ambient air temperature [K]
$\overline{\Delta T_{f,a}}$	flame temperature rise [K]
U_a	buoyancy induced flow velocity [m/s]
U_f	fuel exit velocity [m/s]
W	width of slot-burner [m]
Z_f	flame height [m]
$Z_{f,0}$	free flame height [m]
$Z_{f,m}$	flame merging point height [m]
Greek symbols	
$\mathfrak{D}$	diffusion coefficient [m^2/s]
ρ	fuel density [kg/m^3]
ρ_∞	ambient air density [kg/m^3]
ν_∞	kinematic viscosity [m^2/s]
ξ	mixture fraction
Subscripts	
f	flame
m	merging
∞	ambient

flow between the two diffusion flames that controls the interaction of the two flames. The interaction of two slot burner flames is essentially a two-dimensional phenomenon, while three-dimensional effects cannot be neglected when employing two axisymmetric flames. In other words, for an axisymmetric burner, its entrainment comes from all the surroundings (three-dimensional). So, when two axisymmetric burners move closer, besides the change of the side entrainment which should be only considered to understand basically the interaction of the two flames, the entrainment from the front direction is also significant and might also change with burner pitch variation in some manner. This is not most appropriate to resolve the interaction of two diffusion flames, which is a result of a change in side entrainment with burner pitch variation. However, for a slot-burner, the entrainment is dominantly from the side direction, and that from the front direction is negligible (two-dimensional). So, employing slot-burners is more appropriate to purely investigate and resolve the interaction of the two diffusion flames, which is caused basically by the change of side entrainment with burner pitch variation. Two slot-burner flames interacting with each other are thus ideal for studying the fundamental mechanism of two flame interaction.

A relevant work had been reported for two rectangular burners (width/length; W/L = 1:2) by Thomas et al. [1] in early years investigating the effect of burner pitch on merged flame height; however, the correlation of flame height against burner pitch was not thoroughly studied. The only work on slot burners was carried out recently by Kuwana et al. [12] studying the effects of burner pitch and fuel exit velocity on the interaction of two laminar micro diffusion flames produced by two identical micro-slot burners. They proposed an analytical model to predict the critical burner pitch for merging of these laminar diffusion flames. Although the interaction of two laminar slot-burner flames was previously studied, that of two buoyant turbulent slot-burner flames has never been studied. On the other hand, flames during fires are generally buoyancy-controlled and turbulent, and their interaction changes the characteristics of the fires (e.g., flame shapes and resultant heat flux to the surroundings). There is still no work reported yet about such an interaction between buoyant turbulent diffusion flames of slot burners, despite the fact that its air entrainment mechanism differs significantly from that of laminar micro-slot diffusion flames [13–15].

So, in this paper, experiments were carried out to study the flame interaction between two slot-burner buoyant turbulent diffusion flames at various burner pitches. The critical burner pitch for flame interaction and merging, as well as the evolution of the flame height with burner pitch were quantified. Analytical models were derived to characterize these quantities and transitions.

2. Experiments

The experimental setup is schematically shown in Fig. 1(a). Two identical slot burners were employed; the length of the burners is 142.5 mm, while the width is 2 mm and the burner pitch (D), defined as the distance between burner centerlines, ranged from 0.004 m to 1.004 m. The burners were located with its bottom being 0.4 m above the ground. Practically, a fire source (burning surface) can be either at the ground level or at a certain height above the ground, for example, a desk or table on fire with its top surface burning. The ground will have some effect on the entrained flow near the ground level around the flame for the fire source with the burning surface being at the ground level. The basic idea of placing fire sources above the ground is to allow that the buoyancy-effect is freely and effectively presented to examine its role on the flame interaction and merging trend, where the ground effect can be avoided. With an increase in the burner pitch, the evolution of the interaction between the two flames resulted in transition from a merged flame (at relatively small distance) to non-merged separate flames (at relatively large distance). Propane was used as the fuel with its supply rate controlled by a flow rate meter with the accuracy of 0.01 L/min. The fuel supply rates and hence fuel exit velocities at the burner portal were controlled to be identical for the two burners, varying from 0.23 m/s to 0.70 m/s for each burner. The flame here is designed to be buoyancy-controlled based on the calculated Fr number using burner width (W) as the characteristic length [16,17]. Delichatsios [16] showed that the flame is buoyancy- or momentum-controlled depending on the flame Froude number defined as $Fr_f = \frac{U_f}{(gd)^{1/2}(S+1)^{3/2}(\rho/\rho_\infty)^{1/4}(\overline{\Delta T_{f,a}}/T_\infty)^{1/2}}$. The Fr_f calculated for the present experiments using burner width (W) as the characteristic length (replacing d in above definition) ranged between 0.0127 and 0.0381, which were all much less than 0.1 indicating that the experiments were in the buoyancy-controlled regime. Furthermore, Roper et al. [17] showed that a flame is buoyancy-controlled if the value of Fr defined by $Fr = \frac{{U_f}^2}{g(\overline{\Delta T_{f,a}}/T_\infty)H}$, where H is flame height, is much less than unity. The Fr number calculated by this definition for the present experiments is approximately from 0.0064 to 0.0298, further confirming that the flames