Mutual Interactions of Two Methane Premixed Flames in Extremely Lean Combustion

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1 Introduction

Lean combustion is generally considered as a timely solution for the more stringent environmental regulations and concerns in the new century. However, the instability associated with lean flames significantly refrains the lean combustion techniques from being widely accepted as a major combustion technique for general applications. Combustion enhancement to improve instability in lean condition through interaction with adjacent flames in the burner array or matrix is usually adopted. Premixed flat flame burner has been used to provide good array-type flames which are burning right on top of the burner outlet for intensive heating purpose without excessive heat leakage of hot gas to the ambient. In this study of the mutual interaction of premixed flames in lean condition, the equivalent ratio and the pitch distance between dual-pore array burners are the important parameters in the design for optimal performance of the burner. And a broader range in lean side was found.

To simplify the problem of mutual interactions of premixed flames and to ease of theoretical analysis and experimental study, we used two rectangular slot burners to investigate the effects of the pitch distance between two burners in terms of temperature distribution, flame structure and operation range of this interacting premixed flames. Early studies by Kimura and Ukawa [1] and Singer [2] revealed the combustion characteristics of the two-dimensional rectangular burner. Wagner and Fergusen [3] studied the flow field and geometrical characteristics of a Bunsen burner. The flow field characteristics of single and two interacting jet flows were also investigated [4-5]. Menon and Gollahali [6-7] studied the interaction of multiple jet flames in still air and crossflow. Roper [8] reported the interactions of two laminar jet diffusion flames. Recently, Seigo et al. [9] studied the flame characteristics low load rich-lean flame burner. The above review shows that most past research efforts were invested on the interactions of the jet diffusion flames and studies on interactions of premixed flames have been very scarce, especially for lean conditions.

In order to enhance the performance of this existing array burner we would like to closely study the mutual interactions of two lean premixed flames issued from two rectangular slot burners in terms of operating range, flame temperature, flame cone shape, flame interacting pitch distance, equivalence ratio and flow velocity by theoretical, experimental and numerical methods.

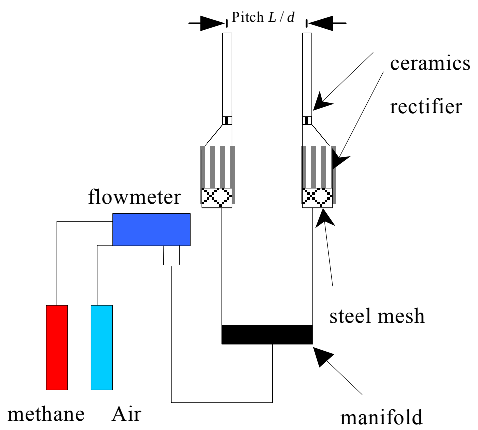

Fig. 1 Experimental Device

2 Experimental and Mathematical methods

2.1 Experimental set up and method

The experimental apparatus is shown in Fig. 1. The dimension of burner's exit is 5 mm(called d or 2w) ×50 mm slot, and the thickness of aluminium burner's wall is 1 mm. The height of burners is 160 mm. Besides, stainless steel mesh and ceramics rectifier are used to straighten the flow field, and the flow at the vicinity of burner's exit is a fully developed velocity profile verified by pito-tube. Methane and air, metered by electronic flowmeter, are premixed and guided to a manifold where the mixture is divided equally to two injections. Dimensionless L/d = 2～6 (d is the width of the burner and d=2w; L is the distance between two burners' central line) are investigated in mean inlet flow velocities ranging from 0.7 to 3 m/s and equivalent ratio φ is around 0.75～1.38. The temperature distributions are measured by thermocouples, and the flame structures are captured by digital CCD camera.

2.2 Numerical simulation

To model numerically the laminar pre-mixed methane twin flames, the relevant governing equations are solved using commercial package CFD-ACE. An orthogonal, non-uniform grid system is used for solving the discretized equations with a control volume formulation in accordance with the SIMPLEC algorithm. All of the governing equations are solved using the second-order scheme. Input of the molecular transport data is obtained from the CHEMKIN package and both Skeletal and GRI Rev. 3.0 package are used for comparisons.

2.3 Theoretical model

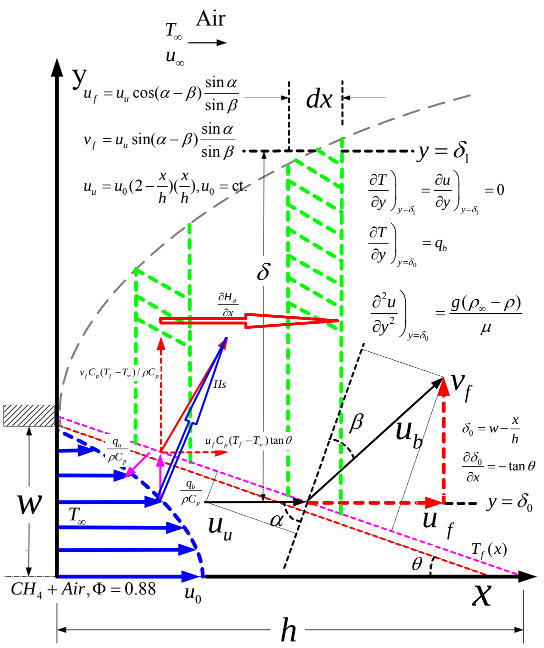

Fig. 2 Combustion generated flow field and thermal diagram

Continuity equation:

$$\frac{\partial u}{dx}+\frac{\partial v}{dy}=0 \quad \text{---------------------------------} \quad (1)$$

X-direction momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=v\frac{\partial^2 u}{\partial y^2}+\frac{1}{\rho}(B_x-\frac{dp}{dx})= \quad \text{-----------} \quad (2)$$

$$v\frac{\partial^2 u}{\partial y^2}+\frac{1}{\rho}(-\rho g+\rho_\infty g)$$

Y-direction momentum equation

$$\frac{dp}{dy}\approx 0 \quad \text{--} \quad (3)$$

Energy Equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{dy}=\alpha\frac{\partial^2 T}{\partial y^2} \quad \text{------------------------} \quad (4)$$

$$u=u_\infty \;,\; T=T_\infty \quad \text{-----------------------------} \quad (5)$$

$$\frac{\partial u}{\partial y}=\frac{\partial T}{\partial y}=0 \quad \text{------------------------------------} \quad (6)$$

These equations are subjected to the following boundary conditions.

At y= δ_1 and y= δ_0

$$u=u_f(x)\;,\; v=v_f(x) \quad \text{-----------------------} \quad (7)$$

$$\frac{\partial^2 u}{\partial y^2}=\frac{g}{\mu}(\rho_\infty-\rho) \quad \text{------------------------} \quad (8)$$

and assuming

$$T=T_f=(T_2-T_1)(3\xi^2-2\xi^3)+T_1\;,\;\xi=x/h \quad \text{--------} (9)$$

in which T_2 and T_1 mean the highest and lowest flame temperature respectively. Using the mass conservation law to transfer the incoming unburned velocity $u_u = u_u(x)$ into burned gas velocity u_f and v_f and u_0 is assuming to be 1.5 times of average inlet flow speed $\bar{u}$. That means

$$u_u=u_0(2-\xi)(\xi),\; u_0=1.5\bar{u} \quad \text{---------} \quad (10)$$

$$u_f=u_u\cos(\alpha-\beta)\frac{\sin\alpha}{\sin\beta},\quad \alpha+\theta=\frac{\pi}{2} \quad \text{---} \quad (11)$$

$$\frac{\rho_u}{\rho_b}=\frac{ctn\beta}{ctn\alpha}=\frac{\tan\alpha}{\tan\beta} \quad \text{------------------------} \quad (12)$$

$$v_f=u_u\sin(\alpha-\beta)\frac{\sin\alpha}{\sin\beta} \quad \text{---------------------} \quad (13)$$

By Assuming Pr=1.0 the momentum boundary layer thickness and thermal one are the same and boundary condition as shown in the Fig. 2. So it is possible to simplified the following models for velocity and temperature with single dimensionless y-directional variable η = y/ δ and integrate the governing equations along the y-direction from y=δ_0 to y=δ_1 and found a set of non-linear O.D.E. for further analysis.

Set $\delta = \delta_1 - \delta_0$ effective boundary layer

$$u = \frac{u_f}{2}(2-\eta)(1-\eta) + \frac{u_B}{4}\eta(1-\eta)^2 + \frac{u_\infty}{2}\eta(3-\eta^2) \text{ ------ (14)}$$

in which buoyancy driven velocity is named as u_B.

$$u_B = U_B\delta^2 = \frac{g\rho_\infty\beta(T_f - T_\infty)\delta^2}{\mu} = \frac{g(\rho_\infty - \rho)\delta^2}{\mu} \text{ ------ (15)}$$

$$\frac{T - T_\infty}{T_f - T_\infty} = 1 + 3\eta^2 + 2\eta^3 + q_d\eta(1 - 2\eta + \eta^2) \text{ ------- (16)}$$

and let $u_c = \cos(\alpha - \beta)\dfrac{\sin\alpha}{\sin\beta}\bar{u}$ -------------------(17)

Non-linear O.D.E Momentum

$$\left[\frac{5}{480}U_B{}^2\delta^4 + \left(\frac{3}{80}u_\infty + \frac{1}{10}u_f\right)U_B\delta^2 + \left(\frac{2}{15}u_f{}^2 - \frac{9}{120}u_f u_\infty - \frac{39}{280}u_\infty{}^2\right)\right]\frac{d\delta}{dx} + \left[\frac{1}{30}U_B\delta^3 + \frac{4}{15}u_f\delta - \frac{9}{120}u_\infty\delta\right]u_c\frac{2}{h}\left(1 - \frac{x}{h}\right) \text{ (18)}$$

$$= \frac{g\delta}{\rho}(\rho_\infty - \rho) - \frac{\mu}{\rho\delta}\left(\frac{u_B}{4} - \frac{3u_f}{2} + \frac{3}{2}u_\infty\right) + (u_f{}^2 - u_\infty u_f)\tan\theta + v_f(u_f - u_\infty)$$

Non-linear O.D.E Energy:

$$\frac{\partial}{\partial x}\left\{(T_f - T_\infty)\delta\left[\frac{19}{120}u_f + \frac{4}{105}u_B + \frac{137}{70}u_\infty\right] + q_b\left[\frac{1}{24}u_f + \frac{1}{420}u_B + \frac{19}{420}u_\infty\right]\right\} = \frac{q_b}{\rho C_p} + (T_f - T_\infty)(v_f + u_f\tan\theta) \text{ --------- (19)}$$

Using 2nd order Runge-Kutta method with Fortran 99 program the O.D.E. sets can be solved and plotted in Fig.5.

3 Results

3.1 Effect of pitch distance

In Fig. 3 it shows that flame cone angle obviously tilts while flame pith varies from L/d=2, 3, 4 and 5 from the lowest one all the way to the upper one. The left column shows (Y) the concentration of OH by CFD. The operation range is shown in Fig. 4. Single flames remain stable within solid black and red lines but twin flame L/d=3 case is in blue and L/d=4 is in dark red dash line. The operation ranges are abroad in the twin flames.

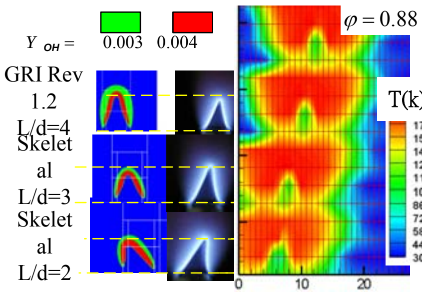

Fig. 3 Two burner flame shape comparison of CDF [OH],photo and temperature images.

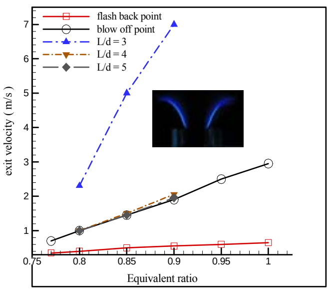

Fig. 4 flame operation ranges. (Solid lines: Single and dash ones: Twin flames)

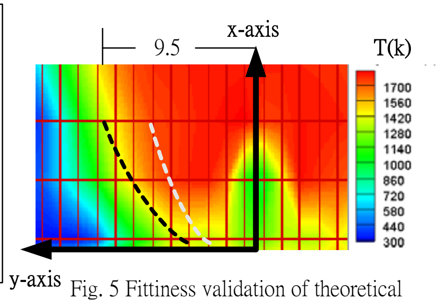

Fig. 5 Fittiness validation of theoretical Analysis

3.2 Result of theoretical analysis

The results of theoretical analysis are plotted on top of temperature profile measured by thermal couples in Fig. 5. The grey dot line represents the momentum boundary layer and the black dot line represents the thermal one by taking Pr. number back to 0.7 instead of 1.0.

From this result we have momentum boundary layer at point of flame cone tip is 6.7 mm and thermal one is 9.5mm. Therefore if the pitch of two flames is shorter than two times of thermal boundary layer thickness which is 9.5 mm in this case then they will become an interacting couple. Fig. 3 shows the temperature profiles started to overlap some where between L/d=2 and 3.

3.3 Effect of equivalence ratio

In Fig. 6 shows the height of the flames varying with the equivalence ratio from 0.6 to 1.38. The mass fraction of OH is depicted from lean towards rich ascendingly along with the equivalence ratio from 0.6 to 0.8. There is an interesting phenomenon happened between equivalence ratio 0.7 and 0.75 as shown in Fig 6. That is the outboard flame blown-off and the inboard one remains on. It means twin-flame burners has a better feature to consume leaner mixtures than single flame burners.

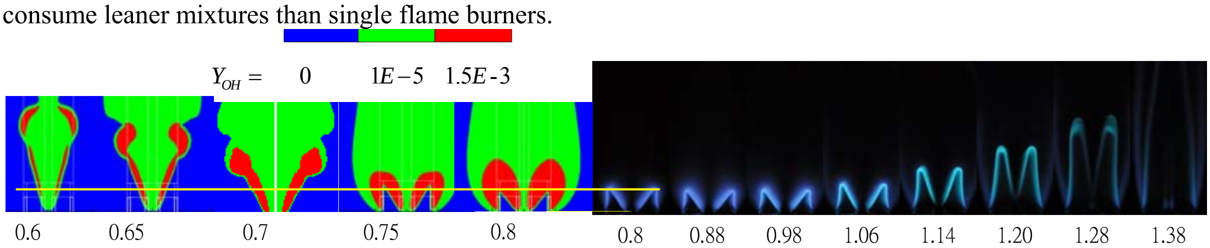

Fig. 6 The road map of equivalent ratio from 0.6 all the way to 1.38 by CFD-ACE simulation (from 0.6 to 0.8) and the lab experimental (from 08. to 1.38, L/d=2.0, $\overline{u}$ =1 m/s) results are shown.

4 Conclusions

The combustion enhancement through mutual interaction of two lean premixed flames issued from two rectangular slot burners is studied by theoretical, experimental and numerical methods. The operating range of the burners can be greatly expanded beyond the blown-off boundary of the single jet flame with flames stabilized by mutual interaction on the inboard side when the separation distance L/d is smaller than 3, which corresponds to the apparent contact of the inboard post flame thermal boundary layers. The results, counter-verified by theoretical, experimental and numerical methods, show that as the separation distance between the two slot burners is decreased, the heat loss will be reduced by convection to the ambience on the inboard side and the intense of combustion heat will be centralized between the two offset flame sheets if the separation distance is smaller than certain threshold.Besides, this twin-flame burners can also burn a mixture as lean as φ =0.6.($\overline{u}$ =1 m/s)

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