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ON THE CHARACTERISTICS OF PARTIALLY-PREMIXED DIFFUSION FLAME IN A STRAINED FLOW FIELD

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The characteristics and extinction of the partially-premixed diffusion flame are studied both experimentally adopting counterflow burner system and theoretically using matched asymptotic expansion techniques. Results show that the partially-premixed diffusion flame exists at high rate of strain when the degree of partial premixing is low. The results for the practical partially premixed diffusion system indicate that the partially premixed diffusion flame plays an important role in charaterizing the turbulent flames.

Key Words: Partially-Premixed Diffusion Flame, Premixed Flame, Diffusion Flame, Flame Stretch

NOMENCLATURE

B : Frequency factor
c : $1-|\gamma|$
c_p : Specific heat
D : Nozzle diameter
D_i : Mass diffusivity of i-th species
Da : Damkohler number($B\sigma/k$)
E_a : Activation energy
k : Thermal conductivity
L : Nozzle distance
Le_i : Lewis number($k/\rho c_p D_i$)
m : Heat loss factor
Q : Heat of combustion per unit mass of fuel consumed
R : Universal gas constant
T : Nondimensional temperature
T_a : Activation temperature(E_a/R)
T_{ad} : Adiabatic flame temperature
V : Nozzle exit velocity
Y : Mass fraction
y_r : $Y_{Op}/\epsilon_p Le_O$

Greek Symbols

γ : Heat loss parameter for diffusion flame
δ_0 : Reduced Damkohler number for diffusion flame
ϵ : Small parameter(T_f^2/T_a)
ζ : Inner stretched coordinate
η : Similarity variable
θ : Perturbed temperature
χ : Flame stretch
λ_m : Partial premixing parameter
ξ : Inner stretched coordinate
ρ : Density
σ : Stoichiometric oxidizer to fuel mass ratio
ϕ_1, ϕ_2 : Defined in Eq.(1)
ω : Reaction rate

Subscripts

d : Diffusion flame
E : Extinction
F : Fuel
f : Flame
i : Species($i=O, F$)
m : Partially-premixed diffusion flame
N : Nitrogen
O : Oxidizer
p : Premixed flame
$\pm\infty$: Boundaries

1. INTRODUCTION

Partially-premixed diffusion flame(PPDF) plays an important role in understanding the structure and character of turbulent flames. Examples are the lift-off of the diffusion flames where the fuel is partially premixed with the oxidizer near the flame stabilization point reacting with the oxidizer forming a partially-premixed diffusion system(PPDS), and the premixed burner system with primary and secondary air supply such that the fuel rich premixture interact with the secondary air(Peters, 1984).

Turbulent flames can be frequently modeled as an ensemble of laminar flamelets when the turbulent scale is large compared with the flame thickness. In the modeling of such a flame, the stretched laminar flame especially the flame stabilized in the counterflow system can best be suited in identifying the turbulent flame characters such as the flame extinction(Peters, 1986).

Two different types of the flame structures can be conceived in the PPDS. One is the two distinct flame structures consisting of a premixed flame and a diffusion flame and the other a merged flame, that is the PPDF. The structure and extinction of these flames have been studied both theoretically and experimentally(Hamins et al., 1985 ; Seshadri et al.,

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1985) where the PPDF is assumed to exist at high stretch rate.

Recently the existence of the PPDF is tested theoretically by comparing the respective extinction criteria of the premixed, diffusion and the PPDF and expermentally(Kim and Chung, 1988 ; Law et al., 1989). Under the mixture strengthes studied, it was found that the PPDF does not exist even at high stretch.

Thus the purpose of this study is to identify the conditions of the existence of the PPDF in both experimentally using counterflow system and theoretically using matched asymptotic expansion techniques. Experimental results are presented in the next section followed by the theoretical predictions.

2. EXPERIMENT

2.1 Experimental Methodology

The counterflow system consists of two nozzle burners set up vertically with area ratio 1/80, nozzle diameter of 14mm and separation distance of 14mm. At the rim of the main nozzle, another nozzle with ϕ 18mm is installed through which the nitrogen is supplied forming inert curtains to eliminate the effect of the ambient air. Water-jacket near the nozzle prevents overheat, and the upper burner surface was covered with cooling coils to eliminate the burner heating due to buoyancy.

Flow rate was monitored by rotameters calibrated from the wet-test gas meter. The fuel, oxygen and diluent nitrogen was separately controlled and mixed in the mixing chamber, and supplied to the burner through the diverging, settling and converging sections to have uniform exit velocities. To prevent flashbacks and enhance the uniformity of the exit velocity profiles, 4 brass meshes were installed at various locations in the burner.

The partially-premixed diffusion system was made by supplying fuel diluted with nitrogen through the lower burner and lean premixture of fuel and oxidizer diluted with nitrogen through the upper burner.

The mass fraction of each species supplied through the upper and lower bunners can be specified using the following three parameters,

$$\phi_1 \equiv \frac{Y_{F-\infty}+Y_{F\infty}}{Y_{O\infty}/\sigma}$$
$$\phi_2 \equiv \frac{Y_{F\infty}}{Y_{O\infty}/\sigma} \qquad (1)$$
$$Y_{N,tot} \equiv Y_{N-\infty}+Y_{N\infty}<2$$

where Y is the mass fraction, subscripts F, O, N respectively indicate fuel, oxygen, and nitrogen, subscripts $\pm\infty$ the upper and lower freestream respectively, σ the stoichiometric oxidizer to fuel mass ratio. Hence ϕ_1 indicates the equivalence ratio of the total system and ϕ_2 that of the premixture side.

Fuel used was LPG(C_3H_8 : 97.8%) where it was assumed a propane in determining ϕ_1, ϕ_2 and $Y_{N,tot}$. In order to study the effect of stretch, nozzle exit velocities were simultaneously increased for given concentrations, and the flame thickness(visual thickness) and location were measured using cathetometer.

2.2 Experimental Results

For the total equivalence ratio ϕ_1 of 1.0, 1.8 and 3.6, ϕ_2 and flame stretch were varied to observe the flame behaviors. If the $Y_{N,tot}$ is fixed then the extinction stretch varies significantly depending on (ϕ_1, ϕ_2) and the flame becomes unstable for exit velocities higher than 50cm/sec. Hence $Y_{N,tot}$ was adjusted to have the similar stretch rate at extinction for various (ϕ_1, ϕ_2)

(a)

(b)

Fig. 1 Direct photographs of flames($\phi_1=1.0$, $\phi_2=0.3$, $Y_{N,tot}=1.62$), (a) $V=21$cm/sec, (b) $V=34$cm/sec(near extinction)

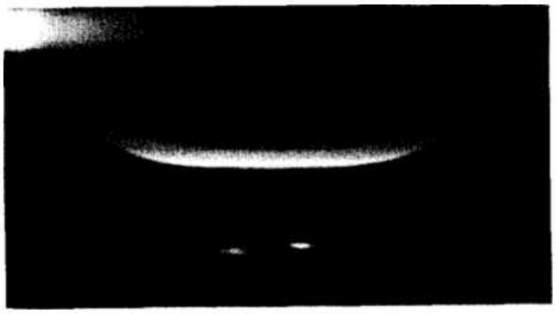
Typical flame configurations for low fuel loading of $\phi_1=1.0$ and $\phi_2=0.3$ are shown in Fig. 1. For lower rate of strain ($V=21$cm/sec), the diffusion flame[lower flame in Fig. 1(a)] and the premixed flame [upper flame in Fig. 1(a)] are distinctively separated. This character remains up to the extinctions, meaning that the two flames are still distinguishable for the high stretch near extinction[Fig. 1(b)].

For high fuel loading of $\phi_1=3.6$, $\phi_2=0.3$, Fig. 2 shows that at low stretch the two flames are distinguishable however at high stretch the two flames are merged having a single reaction zone by forming the PPDF.

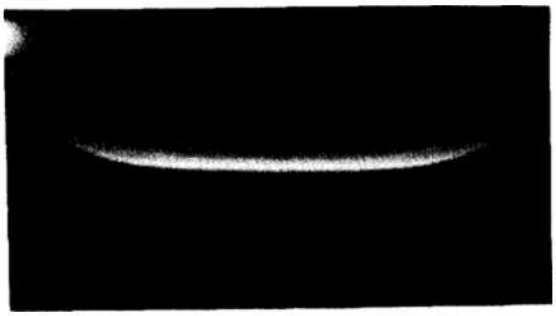
The flame locations and flame thickness variations with the flame stretch are shown in Figs. 3 and 4. For low fuel loading ($\phi_1=1.0$), the two flames remains its separateness up to the extinction. Even though the two flames are quite close near extinction it can be distinguishable from the colors and the thin dark zone between the flames.

As the fuel loading increases($\phi_1=1.8$, $\phi_2=0.3$), two flames are very close for wide range of the exit flow velocities. However since the two luminous zones are still distinguishable and the total luminous zone thickness near extinction is comparable to the sum of the two luminous zones, two distinct reaction zones exit.

The general characters of these flames show that the



(a)



(b)

Fig. 2 Direct photographs of flames($\phi_1=3.6$, $\phi_2=0.3$, $Y_{N,tot}=1.60$), (a) $V=20$cm/sec, (b) $V=43$cm/sec(PPDF near extinction)

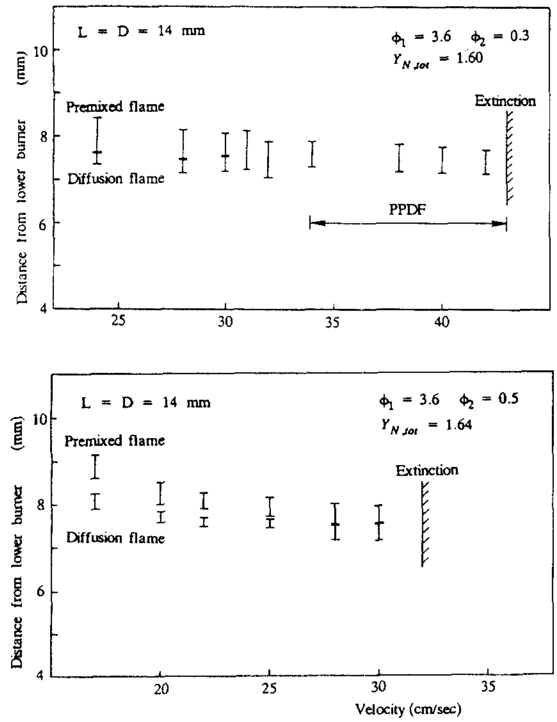


Fig. 4 Characteristics of flame locations with stretch for high fuel loading

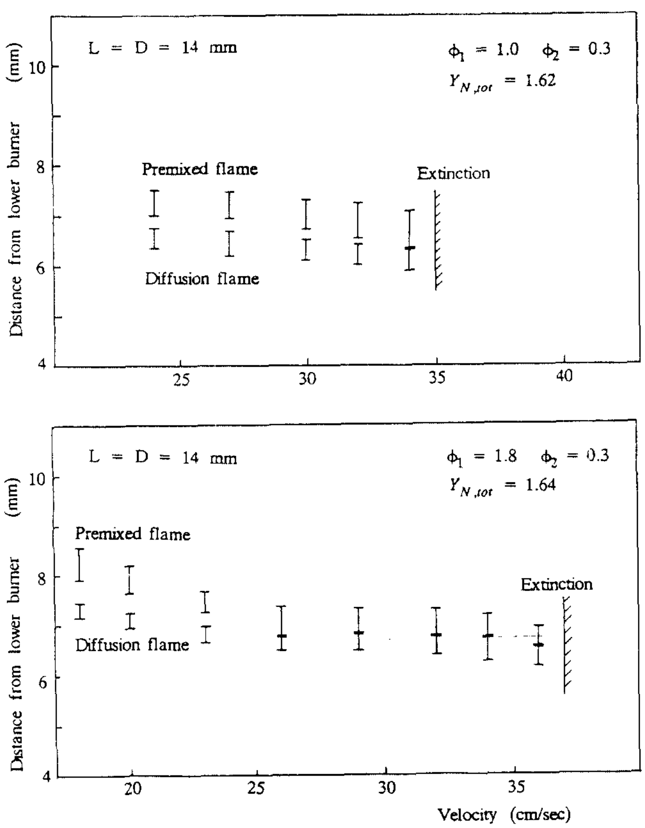


Fig. 3 Characteristics of flame locations with stretch for low fuel loading

diffusion flame location is less sensitive to the stretch than that of the premixed flame since the premixed flame adjusts its position complying the flame speed to that of the flow velocity. Another character is the extinction mode that the flames are extinguished in a single stage meaning that the merged flame or PPDF does not exist for low fuel loading(Law et al., 1989).

For high fuel loading of $\phi_1=3.6$ as shown in Fig. 4, the two flames are indistinguishable in high rate of stretches for low premixed flame strength of $\phi_2=0.3$. The visual zone thickness in such a case is almost the half of the total visual zone thicknesses when the two flames are apart. This verifies the existence of the PPDF that the reaction occurs in a single merged region. In such a case, the extinction occurs in two stages that one of the binary flames extinguishes first and then the meged flame persist until the complete extinction of the whole system occurs. If the premixed flame strength increases to $\phi_2=0.5$ then the extinction occurs in a single stage.

Based on these, it was found that when the fuel concentration in the fuel stream is sufficiently high and its concentration in the premixture stream is lean enough then the single merged reaction zone structure of the PPDF exists.

3. THEORETICAL PREDICTIONS

Theoretical derivations of the structures and extinction criteria follow that of Kim and Chung(1988) and Law et al. (1989), hence only brief calculation procedures will be presented here.

The governing equations for counterflow system with Arrhenius reaction and incompressible assumptions are(Jain and Mukunda, 1968)

$$\frac{d^2T}{d\eta^2}+\eta\frac{dT}{d\eta}=\omega$$
$$\frac{1}{Le_i}\frac{d^2Y_i}{d\eta^2}+\eta\frac{dY_i}{d\eta}=-\omega,\ i=O,F \tag{2}$$
$$\omega=-Da\,Y_OY_F\exp(-T_a/T)$$

with the boundary conditions of

$$T=T_\infty,\ Y_F=Y_{F\infty},\ Y_O=Y_{O\infty}\ ;\ \eta\to\infty$$
$$T=T_{-\infty},\ Y_F=Y_{-\infty},\ Y_o=0\ ;\ \eta\to-\infty \tag{3}$$

where $Y_{F\infty}< Y_{O\infty}$ to have possible binary flame structures. Here one should analyze the three flame stuctures of the diffusion flame and premixed flame for the binary flame situation and the merged flame structure. For the binary flame situation, the flame sheet solutions can be obtained by assuming the complete consumption of the fuel and oxidizer at the diffusion flame sheet and the complete consumption of the fuel only for the premixed flame sheet. Then the flame temperatures of T_p and T_d and diffusion flame location η_d and the oxidizer concentration at the premixed flame sheet Y_{Op} can be expressed as a function of the premixed flame location η_p.

Through the premixed flame structure analysis, the η_p can be related to the Damkohler number. In the thin reactive-diffusive zone of the premixed flame, the structure can be determined by two parameters of the concentration at the flame $y_r\equiv Y_{Op}/\epsilon_pLe_O$ and the downstream heat loss parameter m which is the ratio of the downstream heat loss to the total heat generation at the flame. Then inner governing equation reduced to(Kim and Chung, 1988 ; Law et al., 1989)

$$2(2+y_r)\frac{d^2\theta}{d\xi^2}=\theta(\theta+y_r)\exp[-(\theta+m\xi)] \tag{4}$$

$$\frac{d\theta}{d\xi}\to0\ ;\ \xi\to\infty,\ \frac{d\theta}{d\xi}\to-1\ ;\ \xi\to-\infty \tag{5}$$

where θ is the perturbed temperature and ξ the stretched inner coordinate.

Using the correlation of the $m(\theta+\xi)_{-\infty}$(Kim and Chung, 1988) which contains the relation between the Damkohler number and η_p, we can determine the flame characteristics as functions of the Damkohler number.

The diffusion flame structure can be seperately analyzed based on the above mentioned flame sheet solutions. The important parameters in determining the inner structure of the diffusion flame are the properly reduced Damkohler number δ and the ratio of the heat transferred toward the equilibrium side to the total heat generation $(1-|\gamma|)/2$. Then the inner governing equation becomes(Linan, 1974 ; Chung and Law, 1983).

$$\frac{d^2\theta}{d\zeta^2}=(\theta-\zeta)(\theta+\zeta)\exp\{-\delta_o^{-1/3}(\theta+\gamma\zeta)\} \tag{6}$$

$$\frac{d\theta}{d\zeta}\to1\ ;\ \zeta\to\infty,\qquad \frac{d\theta}{d\zeta}\to-1\ ;\ \zeta\to-\infty \tag{7}$$

Since the equation is nonlinear, there exist a minimum Damkohler number for given γ below which no solution exists, such that it can be indentified as a extinction Damkohler number. The extinction criteria then is (Linan, 1974)

$$\delta_{a,E}=e\{c-c^2+0.26c^3+0.055c^4\} \tag{8}$$

where $c=1-|\gamma|$. Thus the extinction Damkohler number for the diffusion flame can be found independently with premixed flame chracteristics for the binary flame situation. Analysis of the merged flame is similar to that of the diffusion flame. It started from the assumption of the complete consumption of the fuel and oxidizer at the flame sheet. Thus the flame location and flame temperature can be found from the flame sheet solution. The inner structure analysis then provides the extinction criteria. The inner governing equation reduced exactly to the same form as Eq.(6) with proper modification in the boundary conditions due to the partial premixing which are represented as

$$\frac{d\theta}{d\zeta}\to1\ ;\ \zeta\to\infty$$
$$\frac{d\theta}{d\zeta}\to-1+\lambda_m\ ;\ \zeta\to-\infty \tag{9}$$

where λ_m is the parameter related to the partial premixing. Then the extinction criterion for this flame is modified as (Peters, 1984)

$$\delta_{m,E}=\delta_{a,E}(1+\lambda_m/2)^2 \tag{10}$$

To check the validity of the theoretical predictions, calculations were made for the same conditions of $(\phi_1,\ \phi_2,\ Y_{N,tot})$ as that of Figs. 3 and 4. The stoichiometric oxidizer to fuel mass ratio and the Lewis numbers of the fuel and oxidizer are selected to comply with the propane/oxygen/nitrogen system as $\sigma=3.636$, $Le_F=1.5$, $Le_o=1.0$ with the physico-chemical parameters of $c_p=1.0$kJ/kg·K, $Q=5.0\times10^4$kJ/kg fuel, $E_a=$ 46kcal/mole.

The theoretical results of the flame locations and temperatures for $\phi_1=1.0$, $\phi_2=0.3$ are shown in Fig. 5. Here for the binary flame configuration η_d is relatively constant compared to that of η_p with the stretch variations through Damkohler number. As the stretch increases(or Damkohler number decreases) the premixed flame approaches to the diffusion flame. At high stretch the premixed flame shows a turning point behavior from which we can identify the extinction criteria for the premixed flame.

The diffusion flame extinction criteria from Eq.(8) can be calculated. For $Le_i=1$, the diffusion flame location in η coordinate is unchanged such that there exists single extinction criteria for the diffusion flame since the heat transfer from the flame to the fuel and premixed side is unaltered by the stretch. However for $Le_i\neq1$, the diffusion flame location is changed by the change of the premixed flame location which is a function of the Damkohler number. Hence the heat transfer parameter of the diffusion flame $|\gamma|$ is varied by the stretch. As a consequence the extinetion Damkohler number of the diffusion flame varies with the system Damkohler number Da. The dash-dot arrow indicates that for a given Damkohler number (vertical line) the two flame locations were identified. The extinction Damkohler numbers for the diffusion flame from Eq.(8) are marked by the horizontal dash-dot line. Hence at the crosspoint(marked as*) of η_p and extinction Damkohler numbers $Da_{d,E}$, the diffusion flame is expected to be extinguished.

In this case since the turning point Damkohler number of

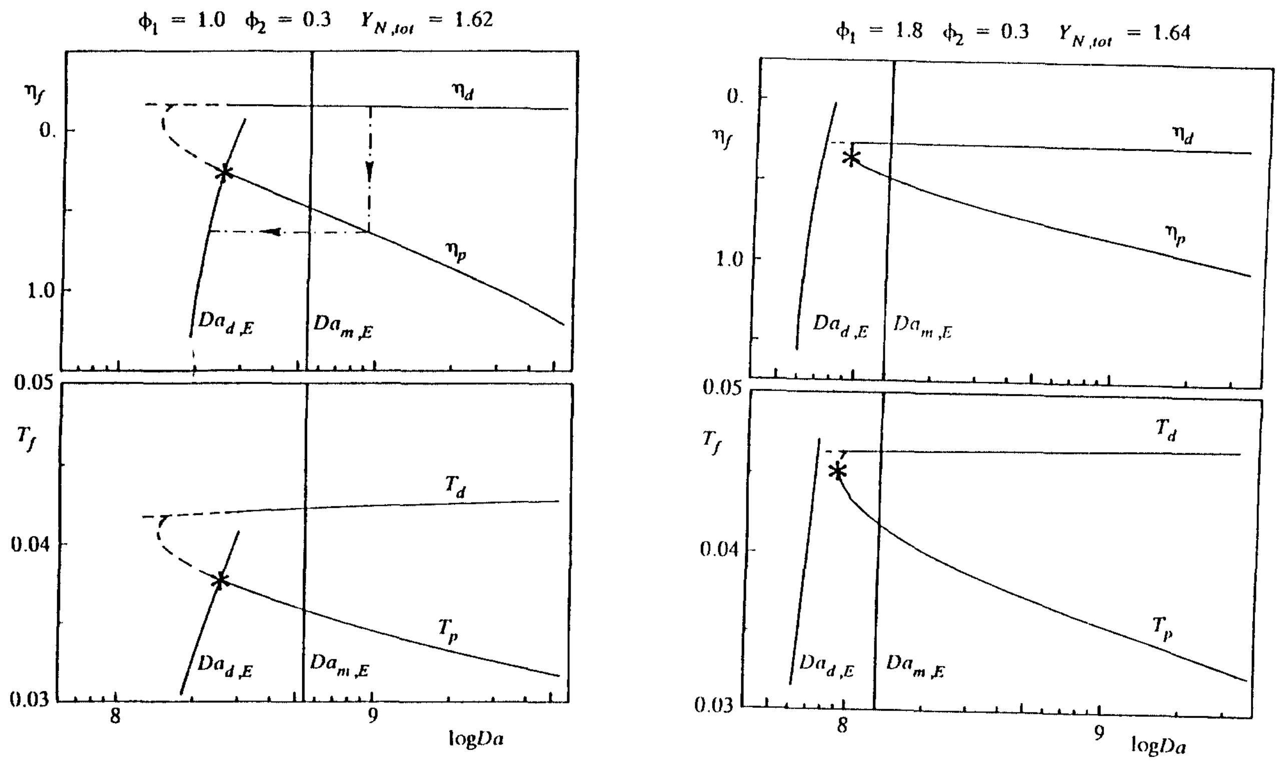


Fig. 5 Flame location and temperature variations with Damkohler number($\sigma=3.636$, $Le_f=1.5$, $Le_0=1.0$)

the premixed flame is smaller than the diffusion flame extinction Damkohler number, the diffusion flame is expected to be estinguished first. The diffusion flame extinction causes the destruction of the binary flame configuration. Then two possible scenarios can be possible. One is the complete extiction of the whole system and the other the persistence of the merged flame(or PPDF). The merged flame location is the cross point of η_d and η_p where the oxidizer and fuel are both completely consumed and having single reaction zone structure. The extinction criteria for such a flame can be identified from Eq.(10) which is marked as a vertical line indicating $Da_{m,E}$. Since $Da_{m,E}>Da_{d,E}$, the merged flame can not exist such that the extinction of the diffusion flame causes the complete extinction of the system. Hence the extinciton occurs in a single stage. This agrees with the experimental results.

For (ϕ_1, ϕ_2, $Y_{N,tot}$) = (1.8, 0.3, 1.64), the extinction Damkohler number of the premixed flame from the turning point is larger than $Da_{E,d}$ hence the premixed flame will be extinguished first. Since the merged flame extinction Damkohler number is larger than that of the premixed flame turning point, the extinction of the system occurs in a single stage meaning that no merged flame structure exists.

For high fuel loading of (ϕ_1, ϕ_2, $Y_{N,tot}$) = (3.6, 0.3, 1.64), Fig. 6 shows that the diffusion flame and the premixed flame collide as the stretch increases for the binary flame configuration. Then only the sigle flame structure of the merged flame is possible. Since $Da_{m,E}$ is smaller than the Damkohler number when the two flames collide, the partially-premixed diffusion flame could exist in this situation. This substantiate the experimental observation of Fig. 4(b). For increased premixed flame strength ($\phi_2=0.5$), again the merged flame structure could not exist.

This theoretical studies together with the experiments show that the merged flame structure in the partially-premixed system could exist only for certain concentration ranges. That is only for high values of ϕ_1 and low values of ϕ_2, which means that the diffusion flame strength is high while the premixed flame strength is weak for the merged flame to exist.

To demonstrate this further, we fix the ϕ_1 and $Y_{N,tot}$ as 3.6 and 1.6 respectively and only vary ϕ_2. Fig. 7 shows the extinction Damkohler numbers of the premixed flame and the merged flame. Here the diffusion flame extinction Damkohler numbers are smaller than $Da_{m,E}$ and $Da_{p,E}$ for the whole range of ϕ_2. The shaded area is the domain of the possible existence of the merged flame, that is for $\phi_2\leq0.45$.

Since the theoretical results can correctly predict the experimental results, we have extended the calulations to the practically important conditions of (ϕ_1, ϕ_2, $Y_{N,tot}$) whether the merged flame plays a significant role in determining the flame characteristics. These are the systems of the pure fuel interacting with the lean premixture and the oxygen interacting with the rich premixture. The importance of these situations can be explained as follows.

Turbulent diffusion flame can be frequently modeled as an ensemble of the laminar diffusion flamelets in the straining flow fields. If there is a locally excessive stretch then this flamelet will be extinguished. Subsequently the fuel will leak through this region thereby mixing with the oxidizer supplied from the other side. This mixture interacting with the fuel will form a partially-premixed diffusion system. The converse is also the same when the leaked oxidizer mixed with the fuel to form a rich premixture and interacting with the oxidizer.

Another system of practical interest related to the

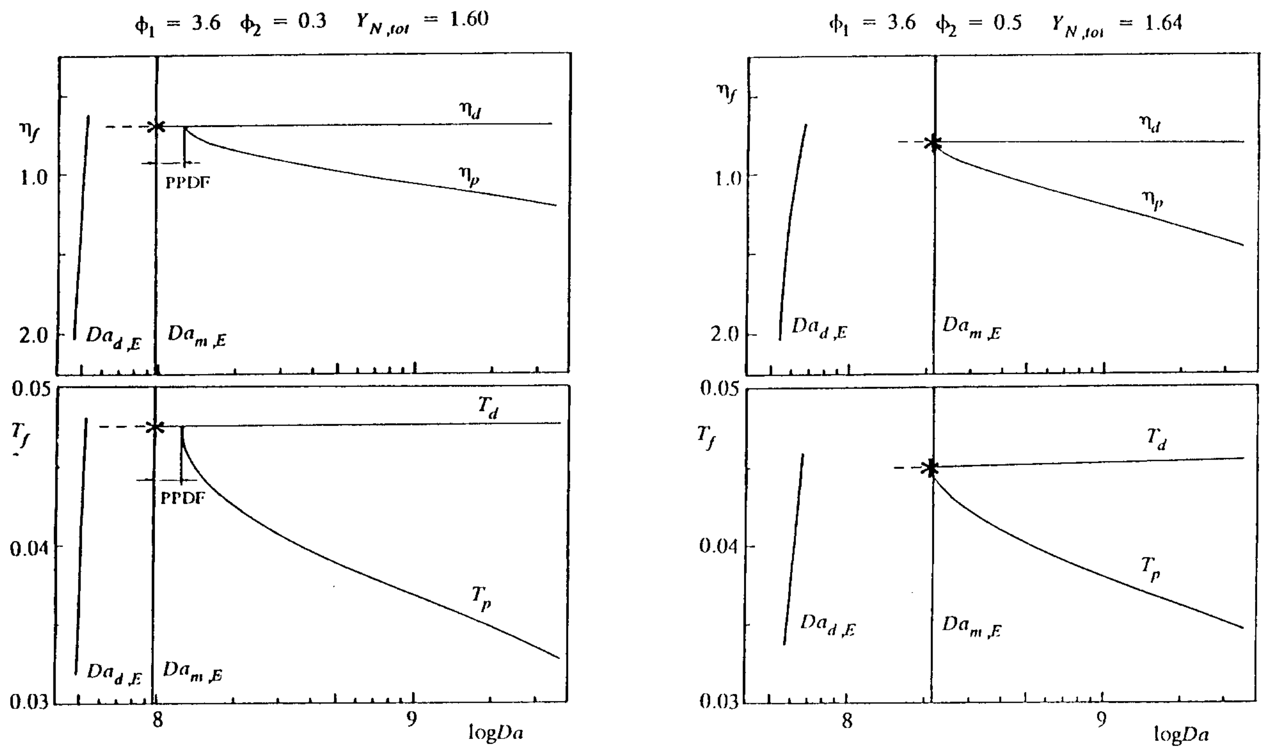


Fig. 6 Flame location and temperature variations with Damkohler number(σ=3.636, Le_f=1.5, Le_o=1.0)

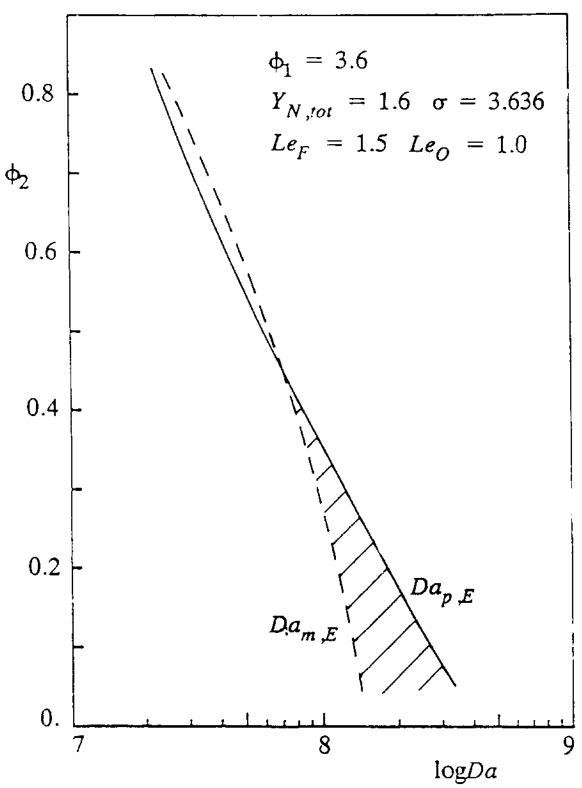


Fig. 7 Variations of extinction Damkohler numbers with equivalence ratio of premixed side(σ=3.6, $Y_{N,tot}$=1.6)

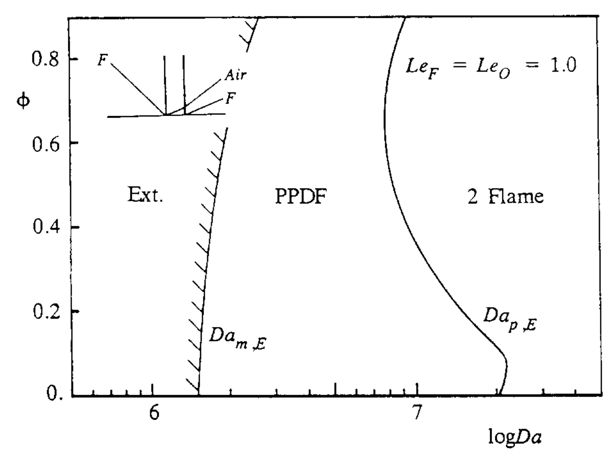


Fig. 8 Extinction characteristics of fuel-fuel/air system

partially-premixed diffusion system is the burner system with primary and secondary air supply. The primary air mixed with the fuel forms a lean premixture, which would interact with the secondary air such that partially premixed diffusion interaction is expected to occur. Thus we have tested such cases to identify the importance of the merged flame(PPDF) for characterizing the turbulent flame structures.

Figure 8 shows the extinction behaviors for the PPDS of the interaction of pure fuel and lean premixture composed of fuel and air. To demonstrate overall characteristics, Lewis numbers are assumed to be unity and propane was considered as a fuel. Here ϕ is the equivalence ratio on the premixed side. For the whole range of ϕ tested($0<\phi<0.9$), it was found that $Da_{p,E}>Da_{m,E}>Da_{d,E}$ such that the merged flames always exist at high stretch and extinction occurs in two stages. This result shows that PPDF is important in characterizing the turbulent flames.

The results for the interaction of air and fuel partially premixed with air are shown in Fig. 9. Here extinction

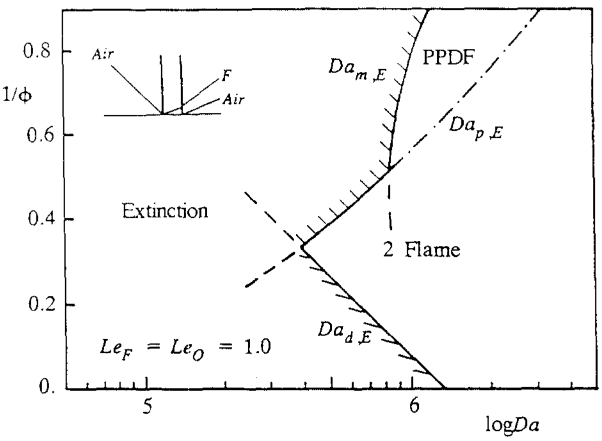


Fig. 9 Extinction characteristics of air-air/fuel system

dynamics is more complex than that of Fig. 7. For the low degree of premixing, say $1/\phi<0.3$, then $Da_{m,E}>Da_{d,E}>Da_{p,E}$ such that the diffusion flame extinction destorys the binary flame structure and extinction is expected to occur in a single stage.

For the intermediate degree of premixing of $0.3<\phi<0.5$, since $Da_{m,E}>Da_{p,E}>Da_{d,E}$ that the binary flame extinction due to the extinction of the premixed flame will lead to the complete extinction of the system. For the high degree of premixing of $1/\phi>0.5$, $Da_{p,E}>Da_{m,E}>Da_{d,E}$, hence after the breakdown of the binary flame configuration due to the extinction of the premixed flame. merged flame structure exists such that extinction occurs in two stages. The results of Figs. 7 and 8 demonstrate that the partially-premixed diffusion flame has an importance in the trubulent flame characteristics.

4. CONCLUDING REMARKS

The existence of the PPDF was tested both experimentally and theoretically. Experimental results show that PPDF would exist at high rate of stretches when the degree of premixing is low. Theoretical results can correctly predict this flame behaviors.

Extension of this analysis to the practical PPDS shows that the PPDF will play an important role in characterizing the burning rate and extinction of the turbulent flames.

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