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A Study of the Effect of Flame Stretch on Flame Speed

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화염 스트레치가 화염전파속도에 미치는 영향에 관한 연구

정 석 호

Key Words; Stretch(스트레치), Preferential Diffusion(확산선호도), Premixed Flame(예혼합화염), Flame Speed(화염속도).

초 록

비균일 접선속도장에 기인한 화염스트레치 인자와 확산선호도가 예혼합화염의 전파속도에 미치는 영향을 연소가스와 예혼합기의 대향류 유동장을 모델로 하여 접합 점근 전개 방법을 이용하여 일반적인 Lewis 수 및 기체팽창을 고려하여 해석하였다. 이 결과 스트레치가 작은 경우에는 확산선호도에 따라 화염특성이 급격히 변화하는데 이는 곡률을 가진 자유전파화염의 특성과 동일하며 스트레치가 큰 경우에는 확산선호도에 관계없이 화염전파속도는 감소하는 특성을 보여주었다. 또한, 화염스트레치의 실험적 측정 및 이론적 해석에 있어서의 정의 및 화염스트레치의 영향에 관한 현상적 설명에 대하여 재검토 하였다.

Nomenclature

a : Strectch of the potential flow field
A : Defined in Eq.(29)
b : Constant
B : Frequency factor
B^* : Defined in Eq.(30)
c : Constant
C_p : Specific heat per unit mass
D : Damköhler number
$\mathscr{D}$: Diffusivity
E_a : Activation energy
f : Stream function
H : Function defined in Eq. (12)
k : Geometry factor
Le : Lewis number($=\lambda/\rho c_p\mathscr{D}$)
m, n : Constants
Q : Heat of combustion
R^0 : Universal gas constant
s : Similarity variable
S_f : Flame speed

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S_f^0 : Laminar flame speed
T : Temperature
T_a : Activation temperature
u : Transverse velocity
U : Transverse velocity of potential field
v : Normal velocity
V : Normal velocity of potential field
x : Transverse coordinate
y : Normal coordinate
Y : Mass fraction

Greek Symbols

β : Perturbed mass fraction
Δ : Reduced Damköhler number
ε : Small parameter of expansion
η : Similarity variable
θ : Perturbed temperature
κ : Stretch factor
λ : Thermal Conductivity
μ : Viscosity
ξ : Stretched coordinate
ρ : Density
ψ : Velocity Potential

Superscripts

$\sim$: Dimensional quantity
$+$: Fresh mixture side
$-$: Burnt side

Subscripts

o : Zeroth order
1 : First order
ad : Adiabatic
cr : Critical
f : Flame
in : Inner
out : Outer
s.e. : Stagnation plane extinction
∞ : Upstream condition

1. Introduction

The characteristics of premixed flame are affected by preferential diffusion and flame stretch. The effect of preferential diffusion is due to the differences of the rate of thermal diffusion to that of mass diffusion which is characterized by Lewis number. The mass diffusion to the flame is a source of heat generation by supplying reactant species whereas the thermal diffusion from the flame is a sink of heat. Hence for nonunity Lewis number, the flame behavior is quite different[1].

The flame stretch factor, first proposed by Karlovitz[2], has been generalized by Williams[3] as a time rate of change of flame area. Subsequently, Chung and Law[4] derived an invariant form of flame stretch, identifying two sources of stretch, that is, stretch due to non-uniform tangential flow fields and to curvature of the propagating flame. The understanding of this effect combined with preferential diffusion is essential in combustion modelling and turbulent combustion.

The effect of stretch due to curvature which is manifested by flame propagation in free space has been studied by Matalon and Matkowsky[5] and Clavin and Joulin[6] for small stretch. The stagnation-point flow or counterflow systems where the flame experiences pure tangential stretch, are widley adopted in the literature, however, it is usually in conjunction with the flame extinction. The assumptions of incompressible potential flow and/or near unity Lewis numbers are frequently adopted eg. Buckmaster[7] and Durbin[8], otherwise final results were drawn from numerical calculations as Libby et. al.[9]

The present paper analyzed the counterflow system for general Lewis number and rigorously accounted the gas expansion for small stretch using the matched asymptotic techniques. Several concepts on the effect of stretch has been clarified including the definition of stretch and the phenomenological description of stretch effect.

2. Analysis

2.1. Governing Equations and Boundary Conditions

The momentum, energy and species equations for the counterflow with the assumptions of one-step Arrhenius reaction, constant $\rho\mu$ and C_p, unity Prandtl number, constant Lewis number, and compressible boundary layer formulation are as follows[10].

$$f'''+ff''-\frac{1}{(k+1)}\left\{\left(\frac{\rho_\infty}{\rho}\right)-(f')^2\right\}=0 \quad (1)$$

$$\frac{d^2T}{d\eta^2}+f\frac{dT}{d\eta}=-DY\exp(-T_a/T) \quad (2)$$

$$\frac{1}{Le}\frac{d^2Y}{d\eta^2}+f\frac{dY}{d\eta}=DY\exp(-T_a/T) \quad (3)$$

where ρ is the density, μ the viscosity, C_p the specific heat, T the nondimensional temperature defined as $C_p\tilde{T}/Q$, $\tilde{T}$ the temperature, Q the heat of combustion per unit mass of fuel consumed, T_a the nondimensional activation energy defined as $(E_a/R^0)(C_p/Q)$, E_a the activation energy, R^0 the universal gas constant, Y the stoichiometrically weighted mass fraction of deficient species, Le the Lewis number, D the Damköhler number defined as $B/a(k+1)$, B the frequency factor, k the geometry factor with $k=0$ for two dimensional and $k=1$ for axisymmetric case, a the coefficient in the potential flow expression as

$$U=ax$$
$$V=-(k+1)ay. \quad (4)$$

Here x and y are physical coordinates in the transverse and normal directions respectively (Fig. 1), U and V are that of potential flow velocities.

In the above, f is the stream function defined in terms of velocity potential ψ as

$$\rho ux^k=\frac{\partial\psi}{\partial y},\quad \rho vx^k=-\frac{\partial\psi}{\partial x},\quad \psi=(2s)^{1/2}f(\eta) \quad (5)$$

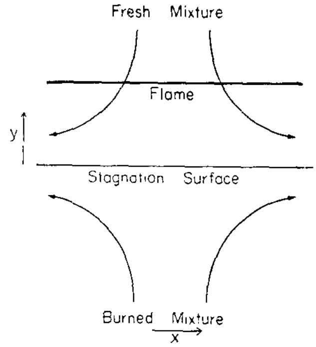

Fig. 1 Schematics of counterflow

where u and v are transverse and normal velocities respectively and similarity variables s and η are defined as

$$s=\rho_\infty\mu_\infty ax^{2(k+1)}/2(k+1),$$
$$\eta=\{\rho_\infty a(k+1)/\mu_\infty\}^{1/2}\int_0^y\left(\frac{\rho}{\rho_\infty}\right)dy \quad (6)$$

where subscript ∞ denotes the upstream condition.

The boundary conditions of the system are

$$f(0)=0,\quad f'(\infty)=f'(-\infty)=1 \quad (7)$$
$$T(\infty)=T_\infty,\quad T(-\infty)=T_f \quad (8)$$
$$Y(\infty)=Y_\infty,\quad Y(-\infty)=0 \quad (9)$$

such that complete consumption of deficient species at the flame and no downstream heat loss are assumed hence T_f is the same as flame temperature.

2.2. Leading Order Solutions

Governing equations of (2) and (3) are solved in the flame sheet limit with the boundary conditions of Eqs. (8) and (9) by specifying T_f at flame location η_f as

$$T_0^+=T_\infty+b_0\int_\infty^\eta Hd\eta$$
$$Y_0^+=Y_\infty+c_0\int_\infty^\eta H^{Le}d\eta \quad (10)$$

for $\eta_f<\eta<\infty$, and

$$T_0^-=T_f \quad (11)$$
$$Y_0^-=0$$

for $-\infty<\eta<\eta_f$, where

$$H(\eta)=\exp\left\{-\int_\infty^\eta f(\eta')d\eta'\right\} \quad (12)$$

$$b_0=(T_f-T_\infty)/\left\{\int_\infty^{\eta_f} Hd\eta\right\},$$

$$c_0=-Y_\infty/\left\{\int_\infty^{\eta_f} H^{Le}d\eta\right\} \tag{13}$$

where superscripts + and − represent upstream and downstream of the flame respectively. The eigenvalues of η_f and T_f will be determined through the higher order analysis.

2. 3. Outer and Inner Expansions

Due to the finite rate kinetics, the reaction zone is broadened such that the temperature and species concentrations should be perturbed from the leading order solutions. The downtream, however, need not be expanded because of the adiabaticity and the complete consumption of the deficient species.

For the upstream convective-diffusive region, the outer expansions subject to the boundary conditions of Eqs. (8) and (9) are

$$\begin{aligned} T_{out}^+&=T_0^++\varepsilon b_1\int_\infty^{\eta} Hd\eta+o(\varepsilon)\\ Y_{out}^+&=Y_0^++\varepsilon c_1\int_\infty^{\eta} H^{Le}d\eta+o(\varepsilon)\end{aligned} \tag{14}$$

where ε is a small parameter of expansion defined as T_f^2/T_a.

The inner diffusive-reactive region is expanded in the neighborhood of η_f as

$$\begin{aligned} T_{in}&=T_f+\varepsilon\theta(\xi)+o(\varepsilon)\\ Y_{in}&=\varepsilon\beta(\xi)+o(\varepsilon)\end{aligned} \tag{15}$$

where ξ is an inner stretched coordinate defined as

$$\xi=(\eta-\eta_f)/\varepsilon. \tag{16}$$

Substituting the inner expansions of Eq.(15) into Eqs. (2) and (3), and collecting the same order terms, we find

$$\frac{d^2\theta}{d\xi^2}=-\Delta\beta\exp(\theta) \tag{17}$$

$$\frac{1}{Le}\ \frac{d^2\beta}{d\xi^2}=\Delta\beta\exp(\theta)$$

where Δ is a reduced Damköhler number defined as

$$\Delta\equiv D\varepsilon^2\exp(-T_a/T_f). \tag{18}$$

The inner governing equation (17) implies the existence of the local Shvab-Zeldovich coupling function in the form of

$$\theta+\beta/Le=m\xi+n. \tag{19}$$

The constants m and n are determined through the matching conditions by expanding outer expansions of Eq. (14) in terms of inner variable ξ using Eq. (16) and by comparing with Eqs. (11) and (15) for $\xi\to\pm\infty$. Thus we find $m=n=0$ and

$$\frac{T_f-T_\infty}{\int_\infty^{\eta_f}\left(\frac{H}{H_f}\right)d\eta}=\frac{Y_\infty}{Le\int_\infty^{\eta_f}\left(\frac{H}{H_f}\right)^{Le}d\eta} \tag{20}$$

which relates flame temperature and flame location. The boundary conditions for inner perturbed temperature become

$$\begin{aligned} &\frac{d\theta}{d\xi}=b_0H_f \text{ as } \xi\to\infty\\ &\theta=0 \text{ as } \xi\to-\infty.\end{aligned} \tag{21}$$

2. 4. Flame Structure Analysis

Using Eq. (19), Eq. (17) becomes

$$\frac{d^2\theta}{d\xi^2}=\Delta Le\theta\exp(\theta) \tag{22}$$

which is solved subjected to the boundary conditions of Eq. (21). Upon integrating Eq. (22), we find

$$\frac{1}{2}\left(\frac{d\theta}{d\xi}\right)^2=\Delta Le(\theta-1)\exp(\theta)+\text{const.} \tag{23}$$

By applying boundary conditions, the constant in Eq. (23) and additional relation of flame temperature and location as

$$2\Delta Le=\left\{\frac{T_f-T_\infty}{\int_\infty^{\eta_f}\left(\frac{H}{H_f}\right)d\eta}\right\}^2 \tag{24}$$

can be determined. Simultaneously solving Eqs. (20) and (24), flame temperature and location can be found as a function of Damköhler number Δ for specified or properly evaluated stream function.

3. Results and Discussions

3.1. Small Stretch Limit

In this section, we will analyze the limiting case for large η_f which corresponds to the small stretch such that direct comparison with the results by Matalon and Matkowsky[5] and Clavin and Joulin[6] for propagating flame is possible.

The flow integral term can be expanded asymptotically as follows

$$\int_\infty^{\eta_f} \exp(-Le\int_\infty^{\eta} f(\eta')d\eta')d\eta = -\frac{1}{Lef(\eta_f)}\exp\left(-Le\int_\infty^{\eta_f} f(\eta)d\eta\right) \times\left\{1-\frac{f'(\eta_f)}{Lef^2(\eta_f)}\right\}, \quad (25)$$

thus

$$\int_\infty^{\eta_f}\left(\frac{H}{H_f}\right)^{Le}d\eta=-\frac{1}{Lef(\eta_f)}\left\{1-\frac{f'(\eta_f)}{Lef^2(\eta_f)}\right\}. \quad (26)$$

Substituting Eq. (26) into Eq. (20) and rearranging

$$T_f=(T_\infty+Y_\infty)+\left(\frac{1}{Le}-1\right)Y_\infty f'(\eta_f)/f^2(\eta_f) \quad (27)$$

where the first term in the parenthesis on the RHS of Eq. (27) is the adiabatic flame temperature T_{ad}. The exponential term in Δ can be expanded as

$$e^{-T_a/T_f}=e^{-T_a/T_{ad}}\left\{1+\frac{T_aY_\infty}{T_{ad}^2}\left(\frac{1}{Le}-1\right)\frac{f'(\eta_f)}{f^2(\eta_f)}\right\}$$

hence Eq. (24) becomes

$$\frac{a(k+1)}{B^*}=\frac{1}{f^2(\eta_f)}\left\{1+A\frac{f'(\eta_f)}{f^2(\eta_f)}\right\} \quad (28)$$

where

$$A\equiv\frac{Y_\infty}{(T_\infty+Y_\infty)}\left(4+\frac{T_a}{T_\infty+Y_\infty}\right)\left(\frac{1}{Le}-1\right)-\frac{2}{Le} \quad (29)$$

$$B^*=\frac{2BLe(T_\infty+Y_\infty)^4}{T_a^2Y_\infty^2}\exp\left\{-\frac{T_a}{(T_\infty+Y_\infty)}\right\} \quad (30)$$

which is the quadratic equation with respect to $f^2(\eta_f)$ and upon solving, we find

$$\sqrt{a}f(\eta_f)=\sqrt{\frac{B^*}{k+1}}\left\{1+\frac{a(k+1)Af'(\eta_f)}{2B^*}\right\} \quad (31)$$

From the variable transformations of Eqs. (5) and (6)

$$\left.\frac{\partial u}{\partial x}\right|_f=af'(\eta_f)\left(1+\frac{1}{\rho_f}\int_0^{y_f}\frac{\partial\rho}{\partial y}dy\right) \quad (32)$$

$$(\rho v)_f=-\sqrt{a(k+1)}f(\eta_f)\sqrt{\frac{\rho_\infty\lambda_\infty}{C_{p\infty}}} \quad (33)$$

where the second term in the parenthesis on the RHS of Eq. (32) vanishes when the flame located in the fresh mixture side of the stagnation plane since the temperature is constant, hence the stretch factor κ is

$$\kappa=(k+1)af'(\eta_f). \quad (34)$$

The flame speed for stretched flame can be defined from the mass consumption rate per unit area at the flame such that

$$(\rho v)_f=-\rho_\infty S_f \quad (35)$$

hence combined with Eqs. (33) and (34),

$$\frac{S_f}{S_f^0}=1+\frac{A}{2}\left(\frac{\lambda_\infty}{\rho_\infty C_{p\infty}}\right)\frac{\kappa}{S_f^{02}} \quad (36)$$

where

$$S_f^0=\sqrt{B^*\frac{\lambda_\infty}{\rho_\infty C_{p\infty}}}$$

(ref. Williams[3]). And Eq. (27) becomes

$$T_f=T_{ad}+\left(\frac{1}{Le}-1\right)\left(\frac{\lambda_\infty}{\rho_\infty C_{p\infty}}\right)\frac{\kappa}{S_f^{02}}. \quad (37)$$

Thus, explicit expression of the dependence of flame temperature and flame speed on stretch factor can be found without analyzing detailed momentum equation. In this expression, the effect of gas expansion is implicitly accounted through the general treatment of stream function. Also these results can be applied for both counter flow and stagnation-point flow systems.

The critical factor that influences flame temperature is the Lewis number in such a way that $T_f \gtreqless T_{ad}$ for $Le \lesseqgtr 1$. The physical reasoning is that Le is the relative indication of thermal to mass diffusivity and these transfers act as a sink and source respectively for diverging positive stretch field of counterflow or stagnation point flow systems.

Depending on the sign of A, the stretch effect is opposite in Eq. (36). Within the assumptions of large activation energy, A vanishes when Le is Le_{cr}, where

$$Le_{cr}=1-\frac{2(Y_\infty+T_\infty)^2}{Y_\infty T_a}<1 \qquad (38)$$

such that for $Le>Le_{cr}(Le<Le_{cr})$, flame speed decreases(increases) compared to planar premixed flame speed.

This result combined with Eq. (37) indicates that as the flame temperature increases(decreases), the flame speed increases(decreases) for positive small stretch except for the range of $Le_{cr}<Le<1$ where flame speed decreases as the flame temperature increases. Even though this range of Lewis number is small since $Le_{cr}=1-2\varepsilon/Y_\infty$, it is an important result since it predicts such a behavior experimentally.

The present dependence of flame speed and temperature on flame stretch is similar to that of curved flame propagation analyses by Matalon and Matkowsky[5] and Clavin and Joulin[6] indicating the universality of these two stretch effect on premixed flame characteristics. One difference of the present results to that of curved propagating flame in the relation of flame speed and stretch is that the present result does not contain the gas expansion term. This difference arises from the definition of flame stretch. Conventionally this was evaluated at free stream or upstream boundary of preheat zone, and presently it is evaluated at the flame, i.e., reaction zone such that the effect of gas expansion is implicitly contained in κ through $f'(\eta_f)$ in Eq. (32). Experimentally one can only measure true stretch through velocity fields measurement at the flame as proposed by Dixon-Lewis and Islam[11], such that it is an important aspect of the present study.

It is of interest to note that for unity Lewis number, Eq. (36) reduces

$$\frac{S_f}{S_f^0}=1-\left(\frac{\lambda_\infty}{\rho_\infty C_{p\infty}}\right)\frac{k}{S_f^{02}} \qquad (39)$$

which coincides with Markstein's[12] intuitive adoption in his flame stability analysis for curved propagating flame if properly evaluate the flame stretch in such a case.

3.2. Fuel Consumption Rate

The fuel consumption rate per unit area of the flame is $-\rho_f\mathscr{D}_f(dY/dy)_f$ and can be calculated using Eqs. (10), (20) and (24) in the leading order for general stretch intensity as

$$\frac{-\rho_f\mathscr{D}_f\left(\frac{dY}{dy}\right)}{\rho_\infty Y_\infty S_f^0}=\left(\frac{T_f}{T_{ad}}\right)^2 \times\exp\left\{\frac{T_a}{2}\left(\frac{1}{T_{ad}}-\frac{1}{T_f}\right)\right\}.$$

For unity Lewis number, the fuel consumption rate per unit area of the stretched flame is always equal to that of planar one-D flame since $T_f=T_{ad}$, implying that the fuel convencted to the upstream boundary of the preheat zone is always transported to the flame by convectional and diffusional transport. The importance of this result is in that the preheat zone thickness which can be defined as the inverse of mass fraction gradient, $1/(dY/dy)_f$ is always constant irrespective of the intensity of blowing, that is, the stretch. The physical reasoning may be simply because the flame is self-adjusted to the new location keeping the thickness constant. Hence explanation of the effect of stretch on steepening the gradient at the flame is inadequate for premixed flames[3].

3.3. Incompressible Case

For the convenience of computation and without losing the physical characteristics of flame we assume the flow field incompressible such that $f(\eta)=\eta$. Then the flame temperature and flame speed relations can be expressed as

$$T_f=T_\infty+\frac{Y_\infty}{\sqrt{Le}}\times\frac{\exp(\eta_f^2/2)\ \mathrm{erfc}(\eta_f/\sqrt{2})}{\exp(Le\eta_f^2/2)\ \mathrm{erfc}(\sqrt{Le/2}\ \eta_f)} \quad (40)$$

$$\frac{S_f}{S_f^0}=\eta_f\left(\frac{T_f}{T_{ad}}\right)^2\exp\left\{-\frac{T_a}{2}\left(\frac{1}{T_f}-\frac{1}{T_{ad}}\right)\right\}\times\sqrt{\pi Le/2}\ \exp(Le\eta_f^2/2)\times\mathrm{erfc}(\sqrt{Le/2}\,\eta_f) \quad (41)$$

and the Damköhler number relation is

$$\frac{a(k+1)}{B^*}=\left(\frac{T_f}{T_{ad}}\right)^4\left(\frac{Y_\infty}{T_f-T_\infty}\right)^2\times\exp\left\{T_a\left(\frac{1}{T_{ad}}-\frac{1}{T_f}\right)\right\}\times\left\{\exp\left(\frac{\eta_f^2}{2}\right)\sqrt{\frac{\pi}{2}}\ \mathrm{erfc}\left(\frac{\eta_f}{\sqrt{2}}\right)\right\}^2 \quad (42)$$

where the *LHS* of Eq. (42) is the inverse of Damköhler number, hence for given η_f, Eqs (40)-(42) can be calculated to determine T_f, S_f/S_f^0 and $a(k+1)/B^*$.

Model calculation is performed for $T_\infty=0.01$, $T_a=0.6$ and $Y_\infty=0.05$. The results are given in Figs. 2~4. Fig. 2 and 3 respectively show the flame speed and location. For small stretch region, flame speed increases(decreases) as the stretch increases for $Le<Le_{cr}(Le>Le_{cr})$, however for large stretch region, the flame speed always decreases.

As the stretch increases for sufficiently large Le, the flame will be extinguished before it reaches the stagnation plane($\eta=0$). The criterion can be found by differentiating the Damköhler number with respect to η_f and applying $\eta_f=0$ which is the case of the curve vertically crossing $\eta_f=0$. The critical Lewis number of stagnation plan extinction $Le_{s.e.}$ is

$$Le_{s.e.}=1+\frac{4(T_\infty+Y_\infty)^2}{Y_\infty T_a} \quad (43)$$

hence for $Le>Le_{s.e.}$ flame will be extinguished by blowing before it reaches the stagnation plane whereas for $Le<Le_{s.e.}$ flame will cross the stagnotion plane having the negative flame speed.

The dotted line in Fig. 2 is from Eq. (39) showing that small stretch expansion result can be used up to relatively large stretch indicating the possibility of usage of Eq. (39) in combustion modelling for near unity Lewis number.

Fig. 4 shows the flame temperature behavior which clearly exhibiting $T_f\gtrless T_{ad}$ for $Le\lessgtr 1$.

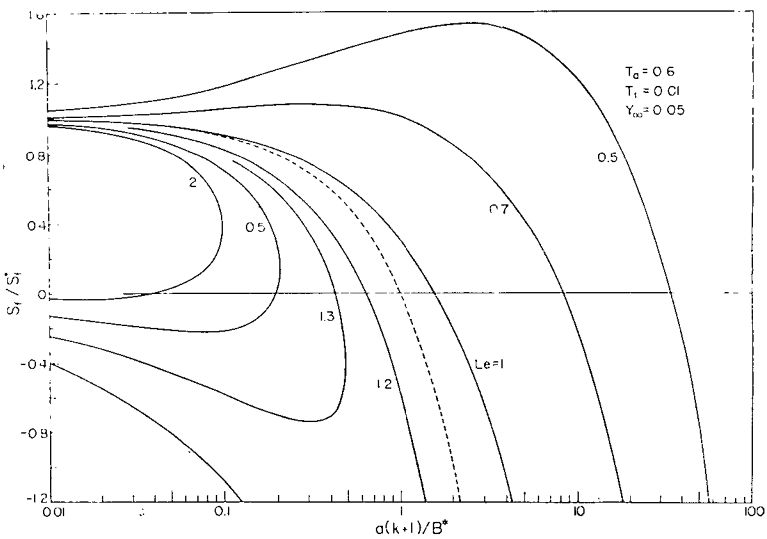

Fig. 2 Flame speed dependence on stretch

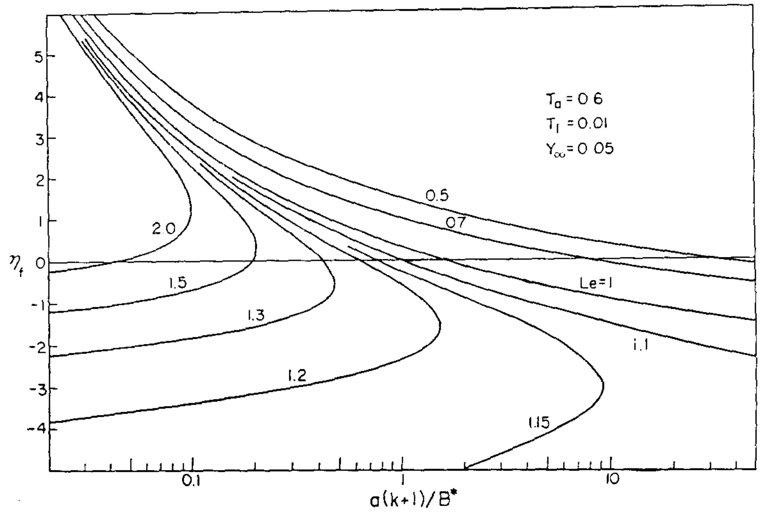

Fig. 3 Flame location as functions of stretch

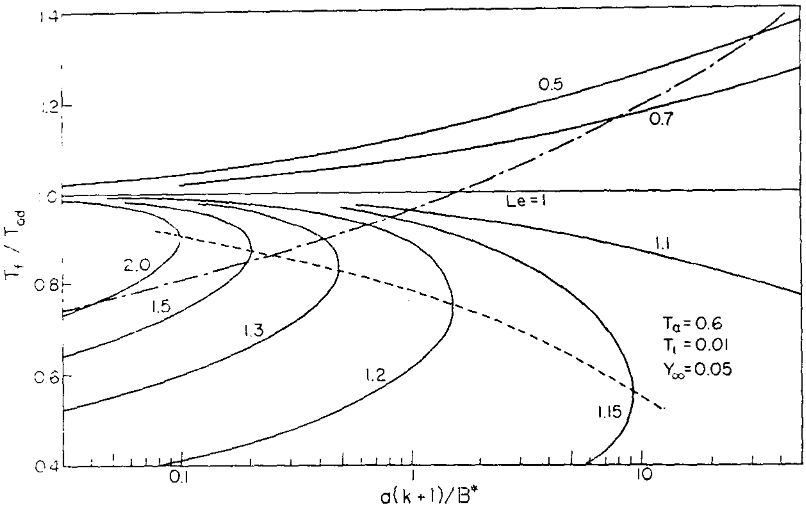

Fig. 4 Flame temperature as functions of stretch
(- - - ; turning point locus,—•— ; locus of flame at $\eta_f=0$)

These criteria of incompressible results can be used as a first approximation for counterflow or stagnation point flow systems frequently adopted in numerous experiments eg. Ishizuka and Law[13], since gas expansion can be considered by properly evaluating stretch.

Finally, Sato and Tsuji[14] numerically studied the stagnation point flow with adiabatic wall for $f(\eta)=\eta$, thus the present asymptotic results for incompressible case can readily be compared. The extinction flame temperature is defined in two ways. For extinction η_f is positive, it is defined at turning points(dotted line in Fig. 4) whereas for extinction η_f is negative, we define it at $\eta_f=0$, i.e. the flame hits the stagnation wall(dash-dot line in Fig. 4). It is clear that there exists minimum extinction flame temperature near $Le=1.45$(i.e., the crosspoint of two lines). This is consistent with that of Sato and Tsuji's results.

4. Concluding Remarks

Premixed counterflow system is analyzed for arbitrary Lewis number including the effect of gas expansion. In the limit of small stretch, the flame behavior is similar to that of curved propagating flame analyses[5,6] implying the universality of general flame stretch definition[3,4].

Two important findings of the present analysis are as follows. First, the flame speed dependence on stretch does not contain the gas expansion term if properly define the stretch, i.e. at the reaction zone which is the only reasonable definition in experiments. Second, the preheat zone thickness does not change by increasing stretch at least for $Le=1$, indicating that the explanation of the effect of stretch based on the steepening the gradient is improper.

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