Transaction of the Korean Society of Mechanical Engineers, Vol. 9, No. 5, pp. 655~662, 1985.

<Original>

Phenomenological Derivation of the Effects of Flame Stretch and Preferential Diffusion on Premixed Flame

Suk Ho Chung*

(Received February 25, 1985)

화염스트레치와 확산선호도가 예혼합화염에 미치는 영향에 관한 현상적 고찰

정 석 호

Key Words: Flame Stretch(화염스트레치), Preferential Diffusion(확산선호도), Flame Speed (화염속도)

초 록

화염스트레치와 확산선호도가 예혼합화염에 미치는 영향을 몇가지 모델에 대해 현상적으로 고찰하였다. 즉, 정상상태의 구형화염, 구형으로 전파되는 화염, 균일유동장내의 곡면화염, 일차원 평면화염, 그리고 확대유동장내에서 스트레치된 평면화염등을 고찰하였으며, 이 해석의 결과는 화염면의 면적 변화율로 정의된 화염스트레치의 제인자들 즉, 비균일 접선속도장과 전파화염의 곡률에 의한 영향들이 공통적 특성을 나타냄을 보여주고 있다. 화염스트레치와 확산선호도가 화염전파속도에 미치는 복합효과는 세가지로 나타나는데 이는 화염온도의 변화에 따른 화학반응강도의 변동, 열 및 물질확산의 강도차이, 그리고 대류 및 확산전달의 방향의 상이함에 기인한다.

Nomenclature

A : Area
C_p : Specific heat
D : Mass diffusivity
E_a : Activation Energy
$\overline{K}$: Nondimensional stretch$(=(\delta/S_f)(1/A)dA/dt)$
Le : Lewis number$(\lambda/\rho DC_p)$
$\vec{n}$: Unit normal vector to the flame
Q : Heat of combustion per unit mass of fuel consumed
r : Radial coordinate
R_f : Flame radius
R° : Universal gas constant
S_f : Flame speed
t : Time
T : Temperature
T_a : Activation temperature$(=E_a/R^\circ)$
v : Velocity
Y : Mass fraction

Greeks

δ : Preheat zone thickness
θ : Half angle
κ : Flame stretch factor$(=(1/A)dA/dt)$
λ : Thermal conductivity
ρ : Density
$\bar{\omega}$: Average reactivity

Superscripts

$\circ$: Planar one-dimensional

* Member, Department of Mechanical Engineering, Seoul National University

$*$: Quantity at upstream boundary of preheat zone

Subscripts

ad : Adiabatic
b : Burnt
eff : Effective
f : Flame
M : Mass
rel : Relative
t : Tangential
T : Thermal
u : Unburned

1. Introduction

The flame stretch factor, originally proposed by Karlovitz[1] is an important element in the understanding of the premixed flame behavior. One typical example of such an effect is manifested in bunsen flame tip at which the flame speed is much higher than that at the side of the cone[2]. The reason being that is the flame tip experiences a strong negative stretch since the direction of tangential flow velocities along the flame centered at the tip, meaning that the rapid change of flow direction in a small region. The importance of the effect of stretch can readily be conceived in conjunction with the turbulent premixed combustion where the flame burst and engulfment within the small eddies will induce high stretch.

The original concept of stretch κ has been generalized by Williams[3] as a time rate of change of flame area, $\kappa=(1/A)(dA/dt)$. Subsequently, Chung and Law[4] derived an invariant form of stretch, identifying two sources of stretch as

$$\kappa=\nabla_t\cdot\vec{v}_t+(\vec{v}\cdot\vec{n})(\nabla_t\cdot\vec{n}), \tag{1}$$

where $\vec{v}$ is the flame velocity, $\vec{n}$ the unit normal vector, and subscript t the tangential direction.

The first term on the RHS of Eq.(1) comes from the non-uniform tangential flow field and the second term from the curvature $(\nabla_t\cdot\vec{n})$ of the propagating $(\vec{v}\cdot\vec{n}\neq 0)$ flame. The steady flame curvature is the subclass of $(\nabla_t\cdot\vec{v}_t)$, implying the curvature alone for steady flame does not guarantee the flame stretch unless$(\nabla_t\cdot\vec{v}_t)\neq 0$ along the flame.

Much of the theoretical efforts are concentrated on the effect of stretch(ref.(5)) however the explanations of the physical mechanisms are either incomplete or unsatisfactory[3,5]. The present paper attempts to clarify the physical reasoning of the influence of flame stretch adopting phenomenological approach for several model situations.

In the next three subsections, steady spherical flame, propagating spherical flame, and curved flame in the uniform flow field are analyzed. These models respectively represent no stretch, strectch due to propagating flame with curvature and stretch due to non-uniform tangential flow field.

In the following two subsections we will consider the combined effects of stretch and preferential diffusion. Effect of preferential diffusion stems from the difference of thermal and mass diffusion characterized by Lewis number Le defined as $\lambda/(\rho C_p D)$ where λ is the thermal conductivity, ρ the density, C_p the specific heat, and D the mass diffusivity.

Mass diffusion is a source of heat at the flame by supplying reactant species whereas thermal diffusion a sink of heat. Hence when $Le\neq 1$, flame behavior could be quite different. To isolate the effect of preferential diffusion from stretch, planar flame propagation is first analyzed. Combined effects are considered adopting planar flame in diverging flow field as a model problem.

2. Analysis and Discussion

Effects of stretch are analyzed phenomenologically assuming the nondimensional stretch factor $\overline{K}$ defined as $(\delta^\circ/S_f^\circ)\ (1/A)dA/dt$ is small, where δ is the preheat zone thickness, S_f the flame propagation speed, and superscript ∘ denotes the planar one-dimensional flame. This small stretch assumption is widely adopted in the literature[6,7].

2.1. Steady Spherical Flame

Steady state spherical flame can be formed by placing a reactant point source at the center (Fig.1). Such a flame does not experience a stretch since $\vec{v}\cdot\vec{n}=0$ and $\nabla_t\cdot\vec{v}_t=0$ in Eq.(1).

The continuity equation is

$$\rho_u v_u A_u=\rho_b v_b A_b \tag{2}$$

where v is the radial velocity and subscripts u and b respectively represent the upstream preheat zone boundary and the flame.

Chemical reaction will be confind to a very thin zone due to the temperature sensitive Arrhenius kinetics where the deficient reactant mass fraction vanishes. Since the temperature is also continuous across the reaction zone[8], the net convectional transports of heat and mass vanish, implying that the chemical heat release by reactant consumption should balance with diffusional transport. Thus, the thermal diffusion-mass diffusion-chemical reaction balance per unit area of the flame with downstream adiabaticity is

$$\lambda\frac{T_b-T_u}{\delta}=\rho D\frac{Y_u}{\delta}Q=Y_u\varpi\delta Q \tag{3}$$

where ϖ is the average reaction rate per unit volume with characteristic temperature of T_b. Here $Le=1$ is implicitly assumed by setting same thermal and concentration boundary layer thicknesses. The upstream mass fraction Y_u in the reaction term of Eq.(3) is the characteristic strength of the concentration on the reaction. The real reaction zone thickness δ_R will be much smaller than δ however $\delta_R\propto\delta$(rigorously $\delta_R=\delta T_b/T_a$[9] where T_a is the activation temperature defined as E_a/R°) due to the temperature sensitiveness of the chemical reaction, and the proportionality constant can be absorbed in ϖ.

By taking a control volume to preheat zone, the energy balance of enthalpy convection and heat release is

$$Y_uQ=C_p(T_b-T_u) \tag{4}$$

hence T_b is the same as adiabatic flame temperature T_{ad}.

Combining Eqs.(3) and (4), the preheat zone thickness is

$$\delta=\sqrt{\frac{\lambda}{C_p\varpi}} \tag{5}$$

Now that the reactant consumed at the flame by diffusion is supplied through convection up to the upstream boundary of the preheat zone such that

$$\rho D\frac{Y_u}{\delta}\ A_b=Y_u\rho_u v_u A_u. \tag{6}$$

Thus from Eqs. (2), (3) and (6), we find

$$\varpi\delta=\rho_b v_b \tag{7}$$

where the RHS is the mass flux at the flame which by definition[10] is $\rho_u S_f$. Therefore,

$$S_f=\frac{1}{\rho_u}\sqrt{\frac{\lambda}{C_p}\varpi}\ ,\quad \delta=(\lambda/\rho_u C_p)/S_f \tag{8}$$

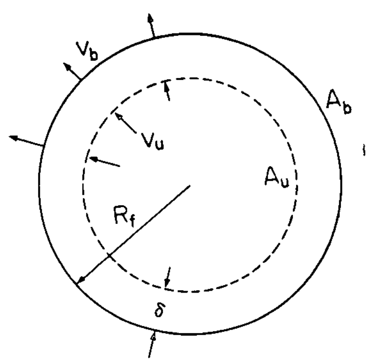

Fig. 1 Schematic of steady spherical flame

Since $\bar{\omega}$ is only a function of flame temperature and $T_b = T_{ad}$, S_f is the same as laminar flame speed S_f^o [11].

This result shows that the steady spherical flame with zero stretch is not affected by curvature alone unless there exists tangential flow nonuiformity, even though $A_b \neq A_u$. This agrees with the theoretical prediction by Frankel and Sivashinsky[12].

2.2. Spherically Propagating Flame

Once the combustible mixture is ignited by an ignition stimulus, the spherical flame will propagate outward. If we set the instantaneous flame radius as $R_f(t)$ then the stretch factor $\kappa = 2\dot{R}_f/R_f$ such that the flame experiences the positive stretch. In such a case we will consider the effect of stretch on flame speed.

Since for deflagration wave, the pressure difference can be neglected such that isobaric situation is considered and the preheat zone thickness is assumed to be small compared to R_f (Fig. 2).

Due to the change of density from ρ_u to ρ_b in the burnt region, the rate of change of mass in the burnt region will be dispersed out such that

$$(\rho_u - \rho_b)\frac{d}{dt}\left(\frac{4}{3}\pi R_f^3\right) = \rho_u \frac{d}{dt}\left(\frac{4}{3}\pi r^3\right) \qquad (9)$$

for arbitrary $r \geq R_f + \delta$. Thus

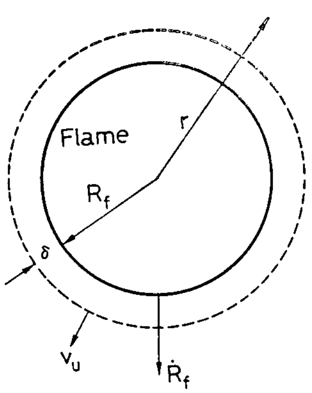

Fig. 2 Schematic of spherically propagating flame

$$\left(1 - \frac{\rho_b}{\rho_u}\right) R_f^2 \dot{R}_f = r^2 \dot{r} \qquad (10)$$

where $\dot{r}$ is the gas velocity.

If we set $\dot{r} = v_u$ at $r = R_f + \delta$ and substitute it to Eq.(10), we find

$$v_u \simeq \left(1 - \frac{\rho_b}{\rho_u}\right)\dot{R}_f\left(1 - \frac{2\delta}{R_f}\right) \qquad (11)$$

The relative velocity of the flame v_{rel} to the gas motion at the upstream boundary of the preheat zone is

$$v_{rel} = \dot{R}_f - v_u = \frac{\rho_b}{\rho_u}\dot{R}_f + \frac{2\delta}{R_f}\dot{R}_f\left(1 - \frac{\rho_b}{\rho_u}\right) \qquad (12)$$

Note that in the limit of no gas expansion, $v_{rel} = \dot{R}_f$ and $v_u = 0$.

Using the reaction-thermal diffusion-mass diffusion balance at the flame of Eq.(3) and the energy conservation of Eq.(4), the preheat zone thickness can again be written as Eq.(5).

Since mass diffused to the flame should balance with mass convected to the upstream boundary of preheat zone at flame fixed coordinate,

$$\rho D \frac{Y_u}{\delta} R_f^2 = Y_u \rho_u v_{rel} (R_f + \delta)^2 \qquad (13)$$

using Eqs.(12) and (3), and noting that $\dot{R}_f$ is the relative velocity of the flame to the stagnant burnt gas thus by definition $\rho_b \dot{R}_f = \rho_u S_f$, the Eq. (13) becomes

$$\frac{S_f}{S_f^o} = 1 - \frac{2\delta}{R_f}\left\{\left(\frac{\rho_u}{\rho_b} - 1\right) + 1\right\} \qquad (14)$$

where use was made of Eq.(8).

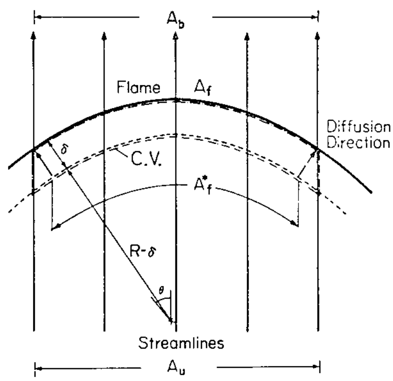

Fig. 3 Schematic of curved flame in uniform flow field

The first term in the bracket on the RHS of Eq.(14) is due to the motion of the upstream by gas expansion and second term to area difference of reaction zone and the upstream boundary of preheat zone. The coefficient of the bracket can be rewritten using $\overline{K}=(2\dot{R}_f/R_f)(\delta/\dot{R}_f)$. Hence the flame speed is influenced by the stretch for propagating spherical flame. In the limit of constant density approximation[9], this phenomenological derivation coincides with the detailed asymptotic analysis[12]. Even considering the gas expansion, the agreement is satisfactory.

The results indicate the decrease of flame speed for present outwardly propagating flame of positive stretch. For inwardly propagating spherical flame, the flame speed is expected to increase.

2.3. Steady Curved Flame in Uniform Flow Field

Near the crest of the steady state curved flame in the uniform flow field is analyzed. This situation closely resembles the tip of the bunsen flame[13] or the inverted flame[14]. In the following, small stretch is assumed, thus $\delta \ll R$ where R is the radius of curvature of the flame near the crest(Fig. 3).

The continuity equation is the same as Eq.(2) with $A_u=A_b$. Diffusion occurs along the maximum gradient i.e., normal to the flame, thus the thermal diffusion-mass diffusion-chemical reaction balance at the reaction zone is the same as Eq.(3). Using the energy conservation of Eq.(4), the preheat zone thickness can be represented as Eq.(5).

By taking a control volume bounded by the upstream boundaries of reaction zone and preheat zone with the sides parallel to streamlines, the reactant species conservation states that the reactant diffusion out of the area A_f where the convective transport vanishes since $Y_u=0$ balances with the convection through the upstream boundary of preheat zone through A_u where diffusion vanishes since the mass fraction gradient vanishes, minus the loss of mass diffusion through the sides of the control volume (i.e., streamlines) where normal projection of mass diffusion to the upstream boundary of preheat zone equals to $(A_f-A_f^*)\rho D Y_u/\delta$, hence

$$\rho D\frac{Y_u}{\delta}A_f=Y_u\rho_u v_u A_u-\rho D\frac{Y_u}{\delta}(A_f-A_f^*). \tag{15}$$

Using Eq.(2) with $A_u=A_b$, $\rho_u v_u=\rho_b v_b=\rho_u S_f$ at the crest, thus by rearranging

$$S_f=\frac{1}{\rho_u}\overline{\omega}\delta\frac{2A_f-A_f^*}{A_u} \tag{16}$$

The areas are $A_f=R_1R_2(4\theta_1\theta_2)$, $A^*_f=(R_1-\delta)(R_2-\delta)(4\theta_1\theta_2)$ and $A_u=R_1R_2$ $(4\sin\theta_1\ \sin\theta_2)$ where R_1, R_2 and θ_1, θ_2 are two princincipal radii of curvature and half angles of A_f. Therefore using $S_f^\circ=\sqrt{(\lambda/C_p)\overline{\omega}}/\rho_u$, Eq.(16) becomes

$$\frac{S_f}{S_f^\circ}=1+\left(\frac{\delta}{R_1}+\frac{\delta}{R_2}\right), \tag{17}$$

in the limit of $\theta\to 0$.

Since the stretch factor $\kappa=-S_f(1/R_1+1/R^2)$[15], the flame speed increases by negative stretch (i.e., compression). The experimental verification can be found in Mizumoto[16] and Lewis and von Elbe[2].

At the tip of the inverted flame, the flame speed is expected to decrease based on the present result and the experimental proof can be found in Kawamura[14].

2.4. Effect of Preferential Diffusion on Planar Premixed Flame.

In this section, we will consider the effect of preferential diffusion characterized by nonunity Lewis number for planar premixed flame and will compare the results with that of unity

Le case. When the rate of thermal diffusion is different to the rate of mass diffusion, the thermal boundary layer thickness δ_T will be different from the concention boundary layer thickness δ_M (Fig. 4), hence it should be accounted in the analysis.

The continuity equation is

$$\rho_u v_u = \rho_T v_T = \rho_M v_M = \rho_b v_b \equiv \rho_u S_f^\circ(Le) \tag{18}$$

where $S_f^\circ(Le)$ is the laminar flame speed for general Lewis number.

Due to the temperature sensitivity of the chemical reaction, the characteristic thickness of reaction will be δ_T, Also the reaction zone does not feel the free stream mass fraction Y_u, rather it feels the effective concentration Y_{eff} at δ_T of $Y_{eff} = Y_u \delta_T / \delta_M$ which is the characteristic intensity of concentration in reaction rate. This implies that the flame behaves as if fresh mixture mass fraction of Y_{eff} and unity Lewis number with preheat zone thickness of δ_T. Thus thermal diffusion-mass diffusion-reaction balance can be written as

$$\lambda \frac{T_b - T_u}{\delta_T} = \rho D \frac{Y_u}{\delta_M} Q = Y_{eff} \bar{\omega} \delta_T Q \tag{19}$$

and with the energy conservation of $Y_u Q = C_p (T_b - T_u)$, we find

$$\frac{\delta_T}{\delta_M} = Le, \quad \delta_T = \sqrt{\frac{\lambda}{C_p \bar{\omega} Le}} \tag{20}$$

The reactant diffused to the flame comes from mass convection, hence

$$\rho D \frac{Y_u}{\delta_M} = Y_u \rho_u \ S_f^\circ(Le) \tag{21}$$

thus combining with Eq.(20), we find

$$S_f^\circ(Le) = \sqrt{Le}\, S_f^\circ(Le=1) \tag{22}$$

where $S_f^\circ(Le=1) = \sqrt{\bar{\omega}\lambda / C_p} / \rho_u$. Note that $\bar{\omega}$ will be the same for both $Le=1$ and $Le \neq 1$ since the flame temperature is the same for both cases. This result coincides with that of the rigorous asymptotic theory(17).

2.5. Combined Effect of Stretch and Preferential Diffusion for Tangentially Stretched Flame

Thus far we have considered several stretched flame with $Le=1$ and unstretched flame with $Le \neq 1$. However in most cases, the premixed flame is stretched and $Le \neq 1$. And recent theoretical analyses show the interesting behaviors for stretched, $Le \neq 1$ flame. To ellucidate the physical reasoning underlying it, we will consider stretched planar flame in diverging flow field accounting the effect of preferential diffusion(Fig. 5). Such a flame can be observed in stagnation point flow or counterflow systems(18).

The continuity equation is

$$\rho_b v_b A_b = \rho_T v_T A_T = \rho_M v_M A_M \tag{23}$$

By taking the control volume bounded by the flame, preheat zone boundary and streamlines, the energy conservation states that the difference of enthalpy convection at flame and thermal

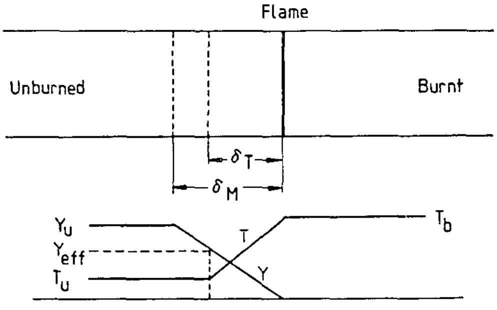

Fig. 4 Schematic of planar one-dimensional flame for nonunity Lewis number.

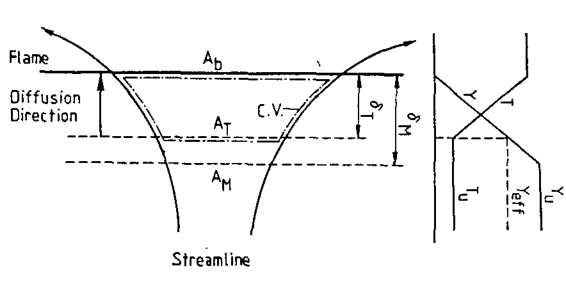

Fig. 5 Schematic of stretched planar flame in diverging flow field.

boundary plus thermal diffusion out along the streamlines balance with the heat generation by convective and diffusive transport of the reactant species to the flame area A_b. The transport along streamlines is equal to the product of diffusion intensity i.e., the normal gradient to the flame and the projected area, hence

$$C_p(\rho_b v_b A_b T_b - \rho_T v_T A_T T_u) + \lambda \frac{T_b - T_u}{\delta_T}(A_b - A_T) = \{\rho_M v_M A_M Y_u + \rho D \frac{Y_u}{\delta_M}(A_b - A_M)\} Q. \quad (24)$$

hence by rearranging

$$C_p(T_b - T_u)\left\{1 + \frac{\lambda}{C_p \rho_u} \frac{1}{\delta_T S_f} \frac{A_b - A_T}{A_b}\right\} = Y_u Q\left\{1 + \frac{\rho D}{\rho_u} \frac{1}{\delta_M S_f} \frac{A_b - A_M}{A_b}\right\} \quad (25)$$

Note that the flame stretch factor $\kappa = (1/A)(dA/dt)$ is

$$\kappa = \frac{A_b - A_T}{A_b} \frac{S_f}{\delta_T}$$

where δ_T / S_f is the characteritsic time of the area change. Since the second term in the curly brackets in Eq. (25) is the correction term, we only need to consider the leading order. Thus $S_f \simeq S_f^\circ$, $\delta_T \simeq \delta_M \simeq \delta$ and $A_T \simeq A_u \simeq A_M$, hence

$$C_p T_b = (C_p T_u + Y_u Q) + Y_u Q\left(\frac{1}{Le} - 1\right) \times \frac{\lambda}{\rho_u C_p} \frac{\kappa}{S_f^{\circ 2}} \quad (26)$$

This relation states that the flame temperature increases(decreases) for $Le < 1$ ($Le > 1$) from the adiabatic flame temperature for positive stretch.

The reaction rate for stretched flame with $Le \neq 1$ will be different from $Le = 1$ since the flame temperature is affected by stretch which will affect the reaction probability of Arrhenius factor, thus we set the reaction rate as $Y_{eff} \bar{\omega}_s \delta_T A_b Q$ where $\bar{\omega}_s$ is for stretched nonunity Lewis number. The thermal diffusion-mass diffusion-reaction balance at the flame can be written as Eq. (19) with $Y_{eff} = Y_u \, \delta_T / \delta_M$. Using Eq. (26) we find

$$\delta_T = \sqrt{\lambda / (C_p \bar{\omega}_s \, Le)}$$

$$\frac{\delta_T}{\delta_M} = Le\left\{1 + \left(\frac{1}{Le} - 1\right) \frac{\lambda}{\rho_u C_p} \frac{\kappa}{S_f^{\circ 2}}\right\} \quad (27)$$

Since the term in the RHS of Eq. (24) is the total reactant species supplied to the flame, hence it should equal to Eq. (19). Thus, we find

$$\rho_M v_M = \bar{\omega}_s \delta_T (\delta_T / \delta_M) \quad (28)$$

Using Eq. (23) and the definition of $\rho_b v_b \equiv \rho_u S_f$

$$S_f = \frac{1}{\rho_u} \bar{\omega}_s \delta_T \left(\frac{\delta_T}{\delta_M}\right)\left(1 - \frac{A_b - A_M}{A_b}\right) \quad (29)$$

Again $(A_b - A_M)/A_b$ is the correction term such that it can be expressed in terms of flame stretch factor as in Eq. (26).

The Arrhenius reaction term is proportional to $\exp(-T_a/T_b)$, and for present case $T_b \neq T_{ad}$, hence using Eq. (26)

$$\frac{\bar{\omega}_s}{\bar{\omega}} = \frac{\exp(-T_a/T_b)}{\exp(-T_a/T_{ad})} = 1 + \frac{T_a Y_u Q}{C_p T_{ad}^2}\left(\frac{1}{Le} - 1\right)\bar{K}. \quad (30)$$

By substituting Eqs. (26) and (30) into Eq. (29), we find

$$\frac{S_f}{S_f^\circ(Le)} = 1 + \bar{K}\left[\frac{T_a Y_u Q}{2 C_p T_{ad}^2}\left(\frac{1}{Le} - 1\right) + \left(\frac{1}{Le} - 1\right) - 1\right] \quad (31)$$

where $S^\circ_f(Le) = \sqrt{Le} \, \sqrt{\bar{\omega}\lambda / C_p} / \rho_u$. The terms in the bracket indicate three combined effects of stretch. The first term is the effect of stretch on flame temperature which modifies the Arrhenius chemical reaction probability. The second term is due to the difference of thermal to concentration boundary layer thickness or the difference of thermal to mass diffusion intensity, meaning the slopes of temperature and concentration profiles at the flame. The third term stems from the pure divergence of flow field that is the differences in the bulk convectional and diffusional directions. The Eqs. (26) and

(31) of the dependence of flame temperature and flame speed on stretch and preferential diffusion, coincide with the detailed asymptotic analysis[6].

3. Concluding Remarks

Several geometries of the stretched flame are phenomenologically analyzed including the effect of preferential diffusion. The geometries considered are the steady spherical flame, propagating spherical flame, curved flame in uniform flow field, planar premixed flame propagation and tangentially stretched flame in diverging flow field.

For unity Lewis number, the effect of the different types of stretches are all the same, meaing the unified concept of stretch of $(1/A)\,dA/dt$.[3,4]

For non-unity Lewis number, the effect of stretch is three folded. These are due to flame temperature variation, difference of diffusional intensities, and different directions of convectional and diffusioal transport.

Acknowledgement

This work has been supported by the Hyundai Research Fund.

References

(1) Karlovitz, B., Denniston, D.W., Knapschaefer, D.H., and Wells, F.H., "Studies on Turbulent Flames", Fourth Symposium(Int'l) on Combustion, pp. 613~620, Williams and Wilkins, 1953

(2) Lewis, B. and von Elbe, G., *Combustion, Flames and Explosions of Gases*, Academic Press, NY, 1961

(3) Williams, F.A., "Analytical and Numerical Methods for Investigation of Flow Fields with Chemical Reactions, Especially Related to Combustion", AGARD Conference Proceedings No. 164, 1975

(4) Chung, S.H. and Law, C. K., "An Invariant Derivation of Flame Stretch", *Combust. Flame*, Vol. 55, pp. 123~125, 1984

(5) Law, C.K., "Dynamics of Stretched Flames", Invited paper, Eastern Section Meeting, Combustion Institute, Dec., 1984

(6) Chung, S.H., "A Study of the Effect of Flame Stretch on Flame Speed", Trans. KSME. Vol. 9, pp. 250~258, 1985

(7) Clavin, P. and Joulin, G., "Premixed Flames in Large Scale and High Intensity Turbulent Flow", *J. Physique-Letters*, Vol. 44, pp. 1~12, 1983

(8) Chung, S.H. and Law, C.K., "On the Flame-Sheet Assumption and Flame Temperature Determination in Combustion Modeling", *Combust. Sci. Tech.*, Vol. 35, pp. 297~310, 1984

(9) Buckmaster, J.D. and Ludford, G.S.S., *Theory of Laminar Flames*, Cambridge, 1982

(10) Dixon-Lewis, G. and Islam, S.M. "Flame Modelling and Burning Speed Measurement", Nineteenth Symposium(Int'l) on Combustion, pp. 238~291, Combustion Institute, 1982

(11) Williams, F.A., *Combustion Theory*, Addison-Wesley, p. 98, 1965

(12) Frankel, M.L. and Sivashinsky, G.I., "On Effects due to Thermal Expansion and Lewis number in Spherical Flame Propagation", *Combust. Sci. Tech* Vol. 31, pp. 131~138, 1983

(13) Sivashinsky, G.I., "Structure of Bunsen Flames", *J. Chem. Phys.*, Vol. 62, pp. 638~643, 1975

(14) Kawamura, T., Asato, K., and Mazaki, T., "Reexamination of the Blowoff Mechanism of Premixed Flames-Inverted Flames", *Combust. Flame*, Vol. 45, pp. 225~233, 1982

(15) Matalon, M., "On Flame Stretch", *Combust. Sci. Tech.*, Vol. 31, pp. 169~181, 1983

(16) Mizumoto, M., Personal Communications, 1984

(17) Bush, W.B. and Fendell, F.E., "Asymptotic Analysis of Laminar Flame Propagation for General Lewis Numbers", *Combust. Sci. Tech.*, Vol. 1, pp. 421~428, 1970

(18) Ishizuka, S. and Law, C.K., "An Experimental Study on Extinction and Stability of Stretched Premixed Flames", Nineteenth Symposium(Int'l) on Combustion, pp. 327~335, Combustion Institute, 1983