

< Combustion Application >

* Ignition, Flammability, Extinction

- Ignition is the event that initiates any combustion process and usually involves heat transfer into a flammable mixture to increase the mixture temperature to the point where a self-sustaining chemical reaction can occur (i.e., the reaction will continue after the ignition source is removed)

⇒ Heat transfer, Active radical production.

- A mixture is flammable if a self-sustaining combustion wave or explosion (homogeneous combustion) will occur upon ignition.

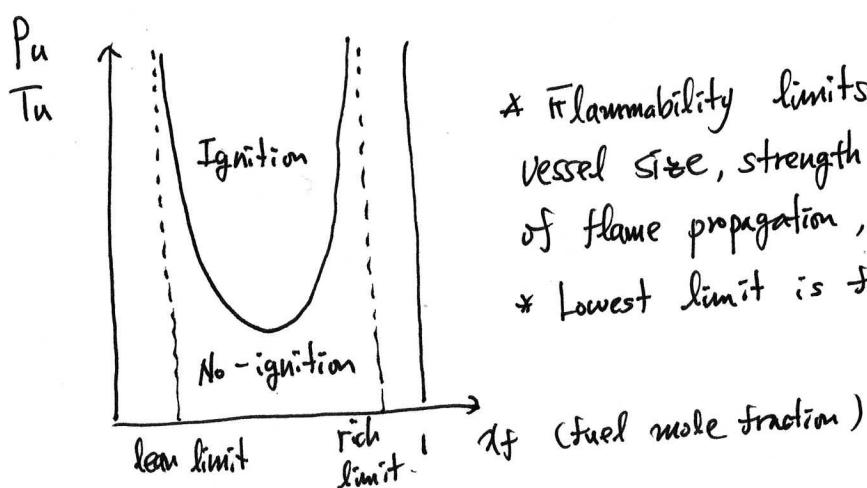
⇒ Flammable mixture is ignitable.

This depends on ignition source, mixture T/P, O₂/diluent concentration, specific geometric configuration.

- Extinction or quenching occurs when there is sufficient energy removal via heat transfer, expansion work, removal of radical species from combustion zone.

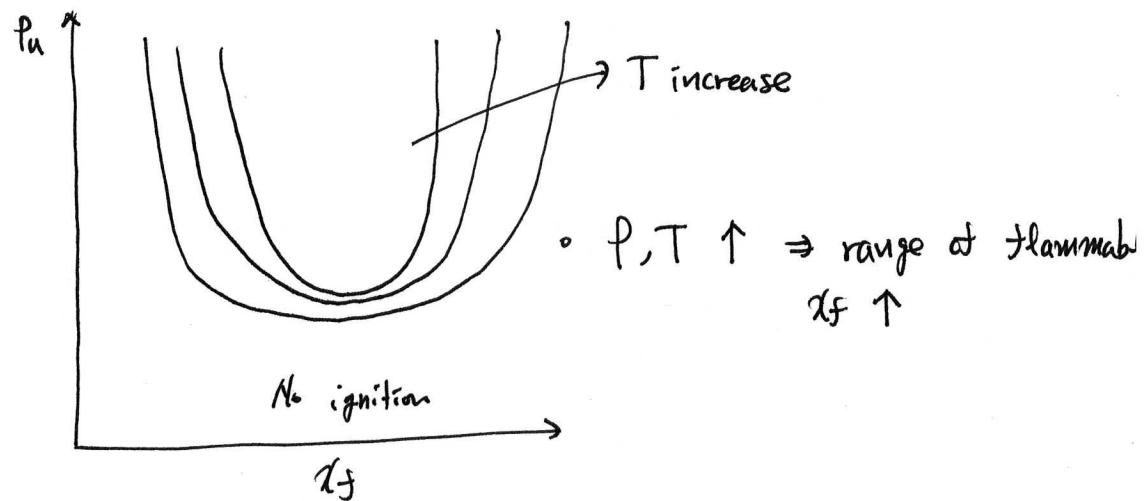
⇒ reaction is not self-sustaining.

Cold boundaries, large stretch can extinguish flames.



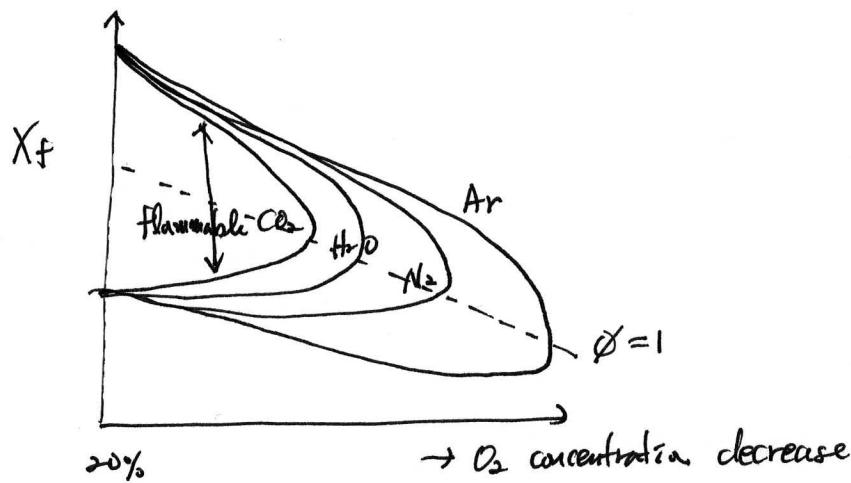
- * Flammability limits are dependent on vessel size, strength of ignition source, direction of flame propagation, P/T, and diluent gas.
- * Lowest limit is found for upward propagation

* P/T effects on flammability limits.



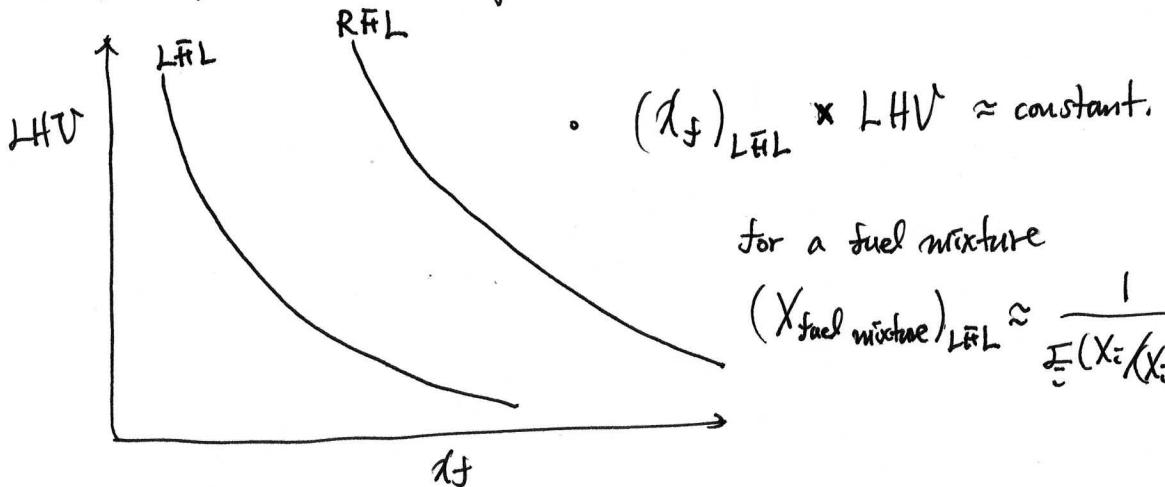
• $P, T \uparrow \Rightarrow \text{range of flammability } \chi_f \uparrow$

* Influence of diluent.



* Flammable χ_f range decreases at the diluent concentration increases

* Influence of Heating value

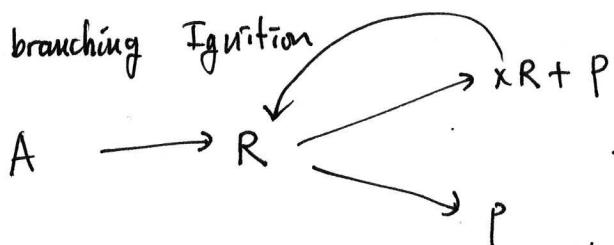


$$(X_{\text{fuel mixture}})_{LFL} \approx \frac{1}{\sum_i (X_i / (X_i)_{LFL})}$$

- At LFL, air (O_2, N_2) is the dominant gas species.
 $\therefore \langle C_p \rangle \approx \text{constant}$ with different HC fuels.
- $(X_{\text{fuel}})_{\text{LFL}} \cdot \text{LHV} \approx \text{constant} \Rightarrow \text{same heat energy from rxns.}$
- $\Rightarrow \text{Burned gas temperature at LFL} \approx \text{constant.}$
 $= 1525 \pm 35 \text{ K for HC fuels.}$
- recall that $C_{p_{O_2}} \approx C_{p_{N_2}}$
 $\therefore T_b$ of fuel-air and fuel- O_2 mixture at LFL \approx constant.
- e.g., C_3H_8 -air LFL $T_b = 1530 \text{ K}$
 C_3H_8 - O_2 LFL $T_b = 1525 \text{ K}$
- Also, LFL in terms of X_{fuel} is same in fuel-air and fuel- O_2 mixtures. (however ϕ_{LFL} is different.)

* Ignition mechanism.

- Chain branching Ignition

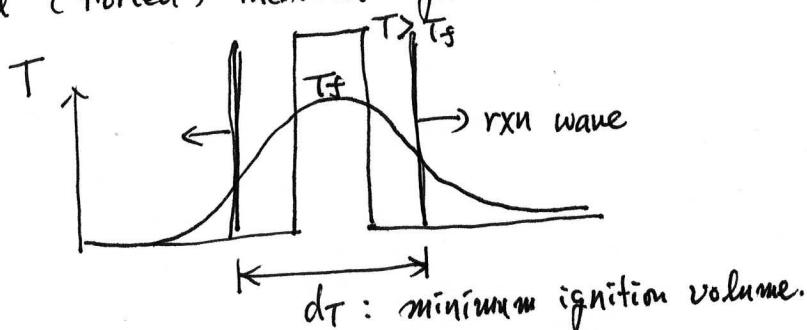


$$\text{ign}[A] \approx \frac{\text{constant}}{x-1} \cdot \exp\left(\frac{E_b}{RT}\right)$$

- Thermal ignition

- Thermal homogeneous ignition : T/C gradient = 0

- local (forced) thermal ignition : non-zero T/C gradient



$$d_T \approx 2\delta_f \Rightarrow \left[\frac{\lambda(T_b - T_c)}{\langle RR''_{\text{fuel}} \rangle \Delta H_c} \right]^{1/2}$$

$$\propto P^{-\frac{a+b}{2}} \cdot \exp\left(\frac{E_b}{2RT_b}\right)$$

$$\textcircled{1} \quad \bar{\epsilon}_{\min} = V_{\min} \rho_u \langle C_p \rangle (T_b - T_u) = \left(\frac{\pi d_T^3}{6} \right) \cdot \rho_u \langle C_p \rangle (T_b - T_u)$$

↑
sphere volume

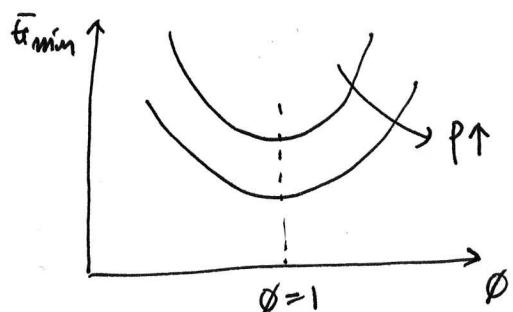
$$d_T \propto \delta_f \propto \frac{\alpha}{S_u}, \quad \alpha \propto \frac{\lambda}{\rho_u \langle C_p \rangle}$$

$$\bar{\epsilon}_{\min} \propto d_T^2 \cdot \delta_f \cdot \rho_u \cdot \langle C_p \rangle (T_b - T_u)$$

$$\therefore \bar{\epsilon}_{\min} \propto \frac{d_T^2}{S_u} \propto \frac{\alpha^2}{S_u^3}$$

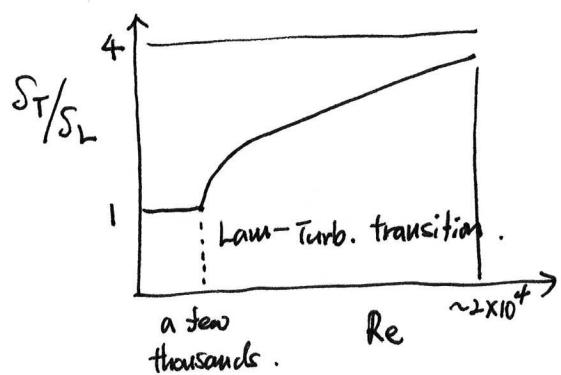
$$d_T \propto P^{-\frac{a+b}{2}}, \quad S_u \propto P^{\frac{a+b-2}{2}}$$

$$\therefore \bar{\epsilon}_{\min} \propto P^{1 - \frac{3}{2}(a+b)}$$



② Turbulent premixed flame.

$$S_T \text{ (turbulent flame speed)} \equiv \frac{\dot{Q}}{A_f}$$

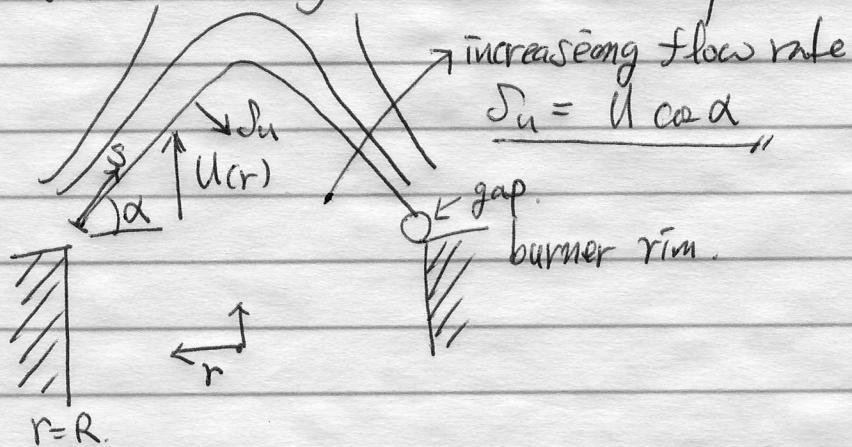


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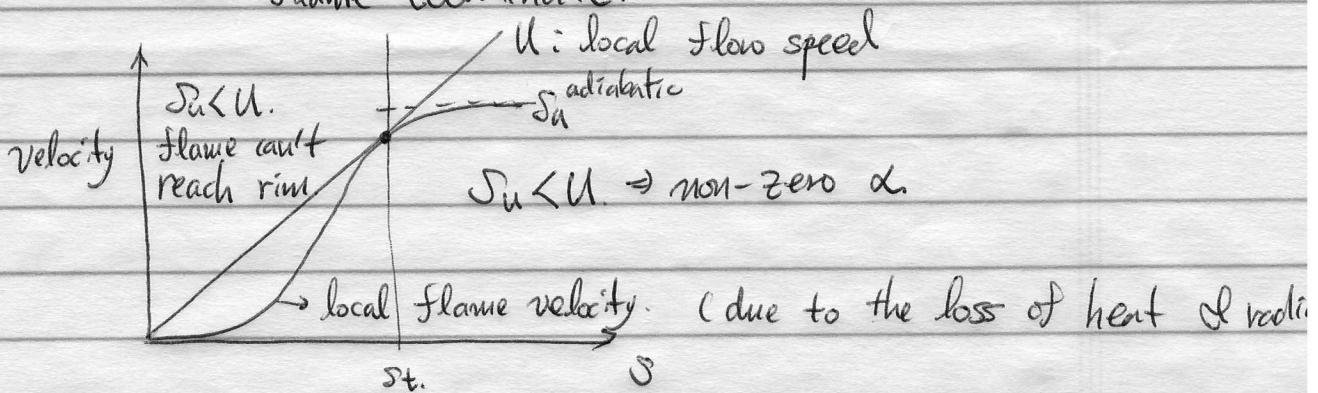
◎ Stabilization of Laminar Premixed Flames.

* flow velocity in combustion systems (e.g., burners)
is not uniform.

\Rightarrow local flow velocity = local flame speed.



s : flame coordinate.



* flashback : flame enters the burner due to reduced flow velocity.

\rightarrow Defined by critical velocity gradient, g_f at burner wall and laminar flame speed S_u .

d_p : flame standoff distance from the burner wall.

S_f : laminar flame thickness ($\propto \frac{\alpha}{S_u}$)

$$g = -\frac{dU(r)}{dr} \Big|_{r=R}, \quad U(r) = N(R^2 - r^2), \quad \text{Poisson profile.}$$

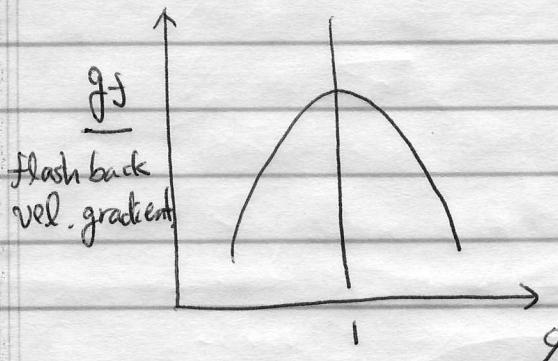
$$= 2MR$$

Volume flow rate, \dot{Q}

$$\dot{Q} = 2\pi \int_0^R u(r) \cdot r dr = \frac{\pi}{2} n R^4 = \bar{U} (\pi R^2)$$

$$\therefore g = \omega n R = \frac{4}{\pi R^3} \cdot \left(\underbrace{\frac{\pi}{2} n R^4}_{=\dot{Q}} \right) = \frac{4\bar{U}}{R} = \frac{8\bar{U}}{d}$$

$$g_f \sim \frac{S_u}{dp} \sim \frac{S_u}{\delta_f} \sim \frac{S_u^2}{\alpha}$$



$$g_f \propto P^{(a+b)-1}$$

$$\therefore S_u \propto P^{\frac{a+b-2}{2}}, \alpha \propto \frac{T^n}{P}$$

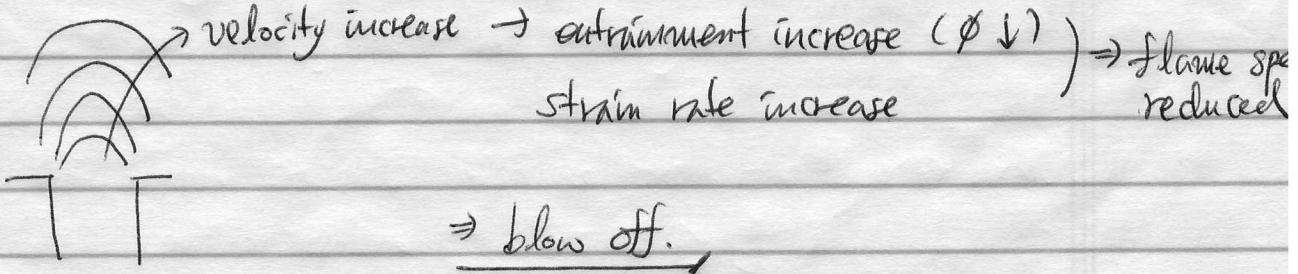
* for most fuels $a+b > 1$

\Rightarrow flashback is more likely to occur at elevated pressures.

$g \leq g_f \Rightarrow$ flashback occurs.

$$P \uparrow \Rightarrow g_f \uparrow$$

② \uparrow blow off.



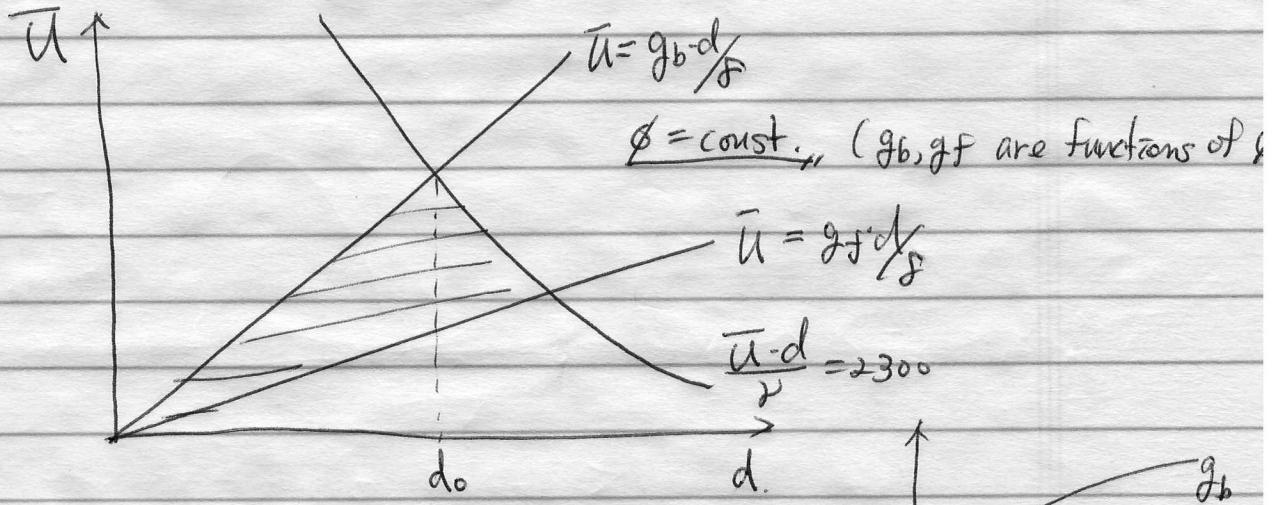
* lifted flame : fuel rich flames stabilized at some distance above the burner.

< burner operation range >

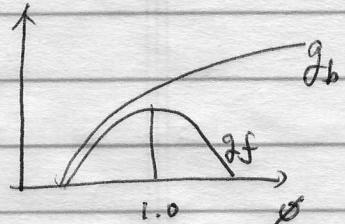
$$g_f < g < g_b$$

flashback limit. \uparrow blow out limit

e for cylindrical tubes $Re_{crit} = \frac{\bar{U}d}{\nu} \approx 2300$ for laminar flow

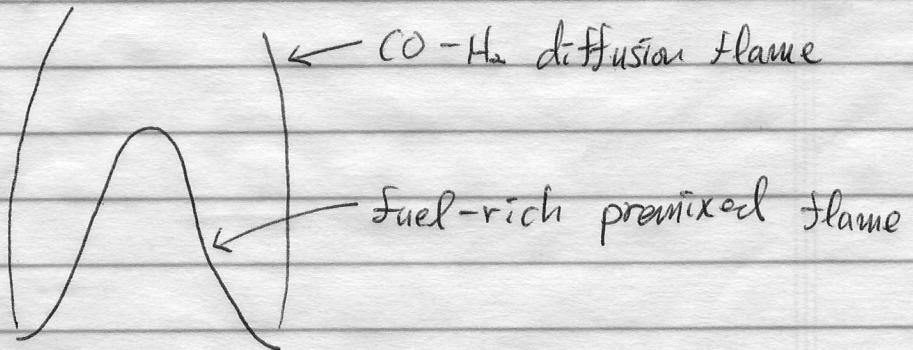


$$* g_b/g_f = \text{turn down} = \text{const.}$$



d_0 gives maximum firing rate ($\equiv \inf \Delta H_c$)

ex)

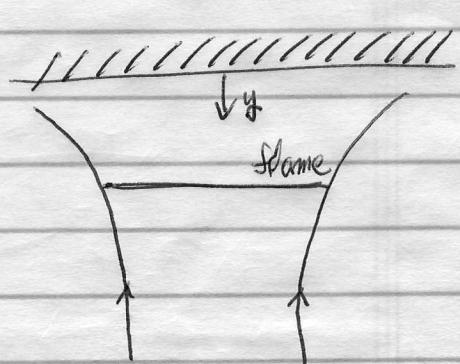
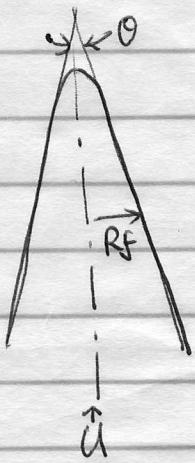


$$K \text{ (flame stretch rate)} = \frac{1}{A_f} \frac{dA_f}{dt}$$

i) flow non-uniformities, ii) flame curvature

\Rightarrow Stretch alters flame speed.

Axis-symmetric Bunsen flame. Stagnation flame



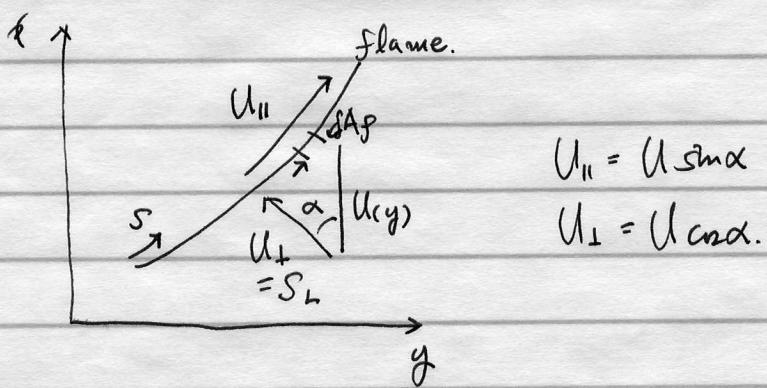
$$U(0, y) = -ay$$

$$K = -U \sin \theta / 2R_f < 0$$

compressive stretch

$$K = a > 0$$

extensive stretch

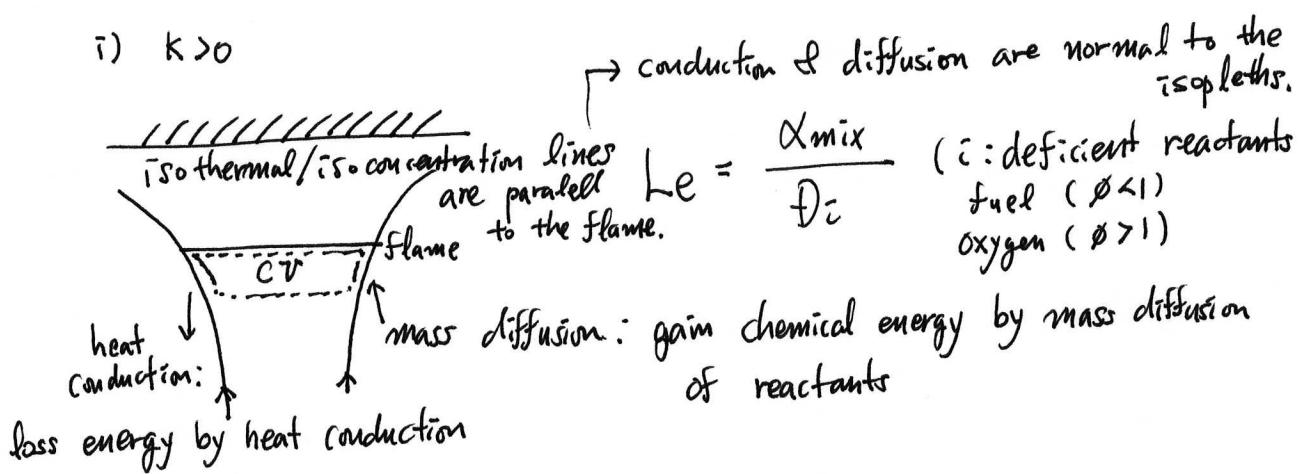


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$K > 0$: extensive strain

$K < 0$: compressive strain

i) $K > 0$



- When $Le = 1$, energy loss by conduction = energy gain by diffusion

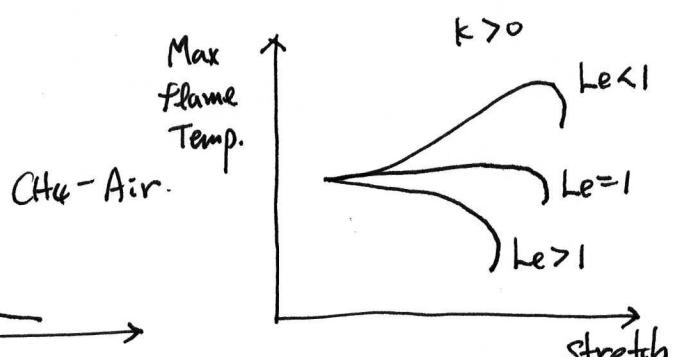
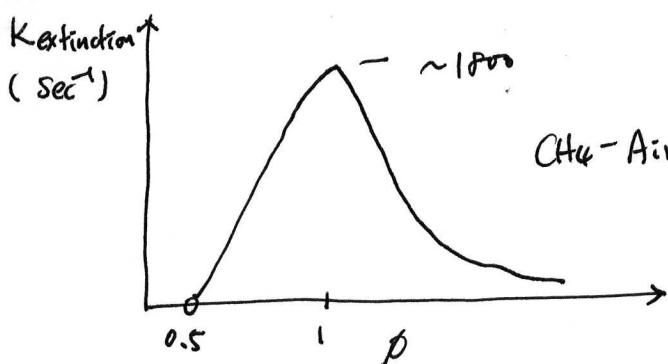
$$\Rightarrow T_b = T_b^* \text{ (adiabatic value)}, S_u = S_u^* \text{ (stretch free value)}$$

\Rightarrow No effect of stretch on these flame properties.

- when $Le > 1$, then $\alpha_{mix} > D_i$

energy loss > energy gain

$$\Rightarrow T_b < T_b^*, S_u < S_u^* (\because T_b \downarrow \Rightarrow S_u \downarrow)$$

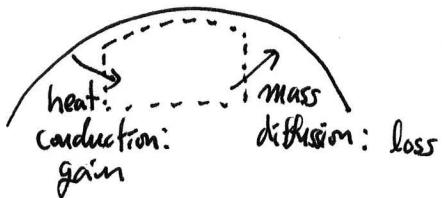


- when $Le < 1$, then energy loss < energy gain

$$T_b > T_b^*, S_u > S_u^*$$

ii) $K < 0$

at the tip of the flame



- When $Le > 1$, then $\alpha_{mix} > \phi_i$

\Rightarrow energy gain > energy loss.

$$\Rightarrow T_b > T_b^{\circ}, S_u > S_u^{\circ}$$

- When $Le < 1$, energy gain < energy loss.

$$\Rightarrow T_b < T_b^{\circ}, S_u < S_u^{\circ}$$

* At sufficiently high stretch rates, flame extinction will occur. for any value of Le , even in the absence of heat loss, due mainly to decreasing residence time in the flame zone.

- ② for $\phi < 1$, deficient reactant is the fuel.

$$D_i = D_{fuel \text{ in air}} = f(\hat{M}_{fuel})$$

- when $\hat{M}_{fuel} < \hat{M}_{air}$, $D_{fuel \text{ in air}} > \alpha_{air}$

$$\Rightarrow Le < 1$$

- when $\hat{M}_{fuel} > \hat{M}_{air}$, $D_{fuel \text{ in air}} < \alpha_{air}$

$$\Rightarrow Le > 1$$

$\Rightarrow Le$ depends on the fuel and stoichiometry.

ex) Lean C₃H₈ - Air mixture, $\hat{M}_{C_3H_8} > \hat{M}_{air}$, $\phi < 1$

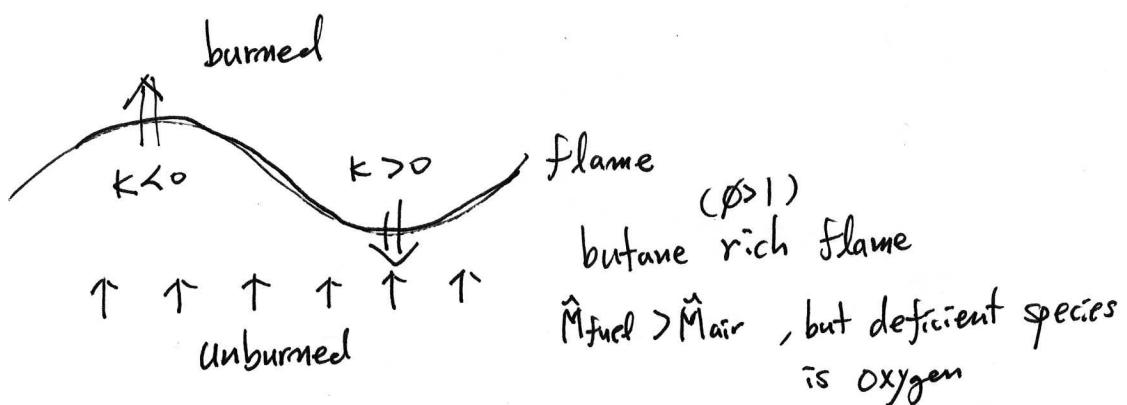
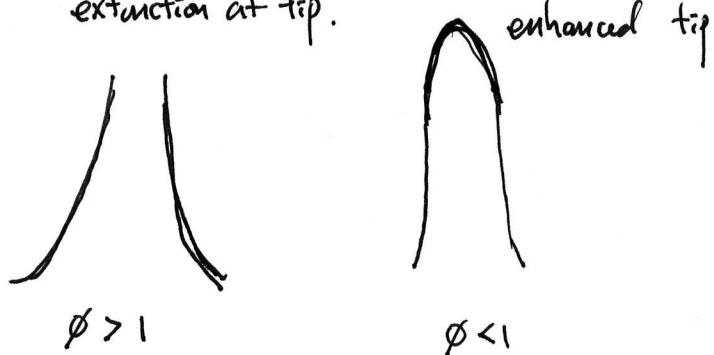
$$\therefore Le > 1$$

at burner tip $K < 0$, $T_b > T_b^{\circ} \Rightarrow$ intensified burning

Rich (C_3H_8 -Air mixture, $\text{Le} < 1$)

at burner tip ($K < 0$), $T_b < T_b^\circ$ (reduced burning)

extinction at tip.



$\therefore \text{Le} < 1$.

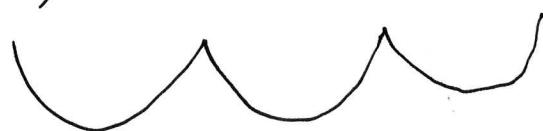
for $K < 0$, $S_u < S_{u^\circ}$ \rightarrow flame will be pushed back to burned gas.

$K > 0$, $S_u > S_{u^\circ}$

\rightarrow flame will propagate toward unburned g

\Rightarrow growth of perturbation.

\Rightarrow steady state flame structure:



cellular flame.

$$* \text{ Karlovitz number } (Ka) = \frac{K}{S_u / S_{ph}} = \frac{K < \alpha >}{S_u^\circ / S_{ph}^\circ}$$

S_{ph}° preheat zone thickness
 S_u° flame speed) for stretch-free flame.

$$\frac{\delta_{ph}^o}{\delta_u^o} = \text{flame zone residence time}$$

$$\therefore K_a = K \times \text{flame zone residence time.}$$

* Markstein #. (Ma)

$$= \frac{(\delta_u - \delta_u^o)/k}{\delta_f}$$

\uparrow flame thickness.

$$\frac{\delta_u}{\delta_u^o} = 1 - Ma \cdot K_a$$