**Course Name: Theory of Fire Propagation (Fire Dynamics)**

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**Week – 04**

**Lecture – 05**

**Module 3 – Review of Premixed and Diffusion Flames**

Laminar flame speed:

If $\omega$ represents the reaction rate based on fractional conversion of the reactant, $\tau$ is the overall reaction time, then the reaction zone thickness, $\delta$, is given by, $\delta = S_L \times \tau \approx S_L/\omega$. Therefore,

$$S_L = \frac{\lambda}{\rho c_p}\frac{\left(T_f - T_i\right)}{\delta(T_i - T_o)} = \frac{\lambda}{\rho c_p}\frac{\omega\left(T_f - T_i\right)}{S_L(T_i - T_o)}$$

$$S_L = \left(\frac{\lambda}{\rho c_p}\frac{\left(T_f - T_i\right)}{(T_i - T_o)}\omega\right)^{0.5}$$

Laminar flame speed is proportional to square root of the product of thermal diffusivity, $\alpha = \lambda/(\rho c_p)$ and reaction rate, $\omega$. That is, $\mathbf{S_L \approx (\alpha\omega)^{0.5}}$. This dependency is shown even by comprehensive theories. Since $\boldsymbol{\omega}$ is exponentially dependent on temperature, $S_L$ has similar dependence.

Laminar flame speed and thickness:

For an $n^{th}$ order reaction, the reaction rate depends on pressure, p, as $p^{n-1}$. Therefore, dependence on $S_L$ on p is expressed as,

$$S_L \approx \left(\frac{1}{\rho} p^{n-1}\right)^{1/2} \approx (p^{n-2})^{1/2}$$

$S_L$ is almost independent of p for n = 2.

Experiments show that $S_L$ presents a decreasing trend with increasing pressure up to 10 atm.

Flame thickness is estimated as: $\delta = \frac{2\alpha}{S_L}$

Limiting oxygen concentration:

Adding inert (non-combustible) gas to a flammable reactant mixture can lead to no flame propagation. This is expressed as Limiting Oxygen Concentration (LOC).

Inert gas absorbs some quantity of heat transferred during the flame propagation causing flame extinction. For example, LFL of butane is = 1.9% by volume.

Considering its stoichiometric reaction with oxygen:

$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O$, LOC can be defined as,

$$LOC = \left[\frac{\text{moles fuel}}{\text{total moles}}\right]_{LFL} \left[\frac{\text{moles O}_2}{\text{moles fuel}}\right]_{stoichiometric}$$

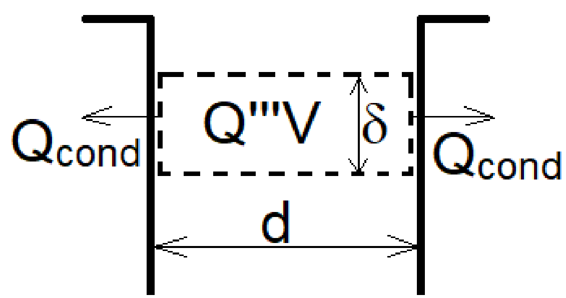
$$= 1.9\left(\frac{6.5}{1}\right) = 12.35 \text{ vol \% } O_2$$

Premixed flame quenching:

Consider a premixed flame traveling through a space between two plane vertical walls. For the flame to propagate, the heat released should balance the heat lost through the walls by conduction.

$Q'''V = Q_{cond,\ total}$.

Heat released is evaluated using net reaction rate ($-\dot{\omega}_F'''$) and heat of combustion ($\Delta h_C$). Heat loss is evaluated using the temperature gradient of the gas at the wall (dT/dx) and thermal conductivity ($\lambda$).




$$Q''' = -\dot{\omega}_F'''\Delta h_C$$

$$Q_{cond} = -\lambda A \left(\frac{dT}{dx}\right)_w$$

Quenching distance:

Temperature gradient at the wall is evaluated as, $(T_f - T_w)/(d/2)$. Understanding that dT/dx will be much grater than this, d/2 is replaced by d/b, where b is expected to be greater than 2. Area of conduction is 2δL, where L is the length in the direction perpendicular to the paper and factor 2 is for the presence of two walls. Using these the heat balance is written as,

$$-\dot{\omega}_F{}''' \Delta h_C (L\delta d) = \lambda(2\delta L)\frac{(T_f - T_w)}{d/b} \;\Rightarrow d^2 = \frac{2\lambda b}{-\dot{\omega}_F{}''' \Delta h_C}(T_f - T_w)$$

Assuming $T_W$ as the unburnt reactant temperature, $T_u$, applying the relation between reaction rate & $S_L$ and $\Delta h_c = (1+s)c_p(T_f - T_u)$,

$$d = \frac{2\alpha(b)^{0.5}}{S_L} = (b)^{0.5}\delta$$

Quenching distance for various fuels:

| Fuel ($\phi$=1) | d (mm) | $S_L$ (cm/s) |
|---|---|---|
| Methane | 2.5 | 40 |
| Ethane | 2.3 | 43 |
| Propane | 2.0 | 44 |
| Acetylene | 2.3 | 136 |
| Ethylene | 1.3 | 67 |
| Hydrogen | 0.64 | 210 |

Maximum gap in flame arrester for most hydrocarbon fuels is approximately half of the quenching distance. For example, the quenching distance for gasoline is around 2 mm, and gap in flame arrester screen is kept as 1 mm. Maximum Experimental Safe Gap (MESG) are tabulated for various fuels in NFPA 497.