Module 5: Premixed Flame

Lecture 23: Structure of 1D Premixed Flame

The Lecture Contains:

- Structure of 1D Premixed Flame
- Laminar Flame Theory
- Flame Thickness
- Burning Velocity Measurement Methods

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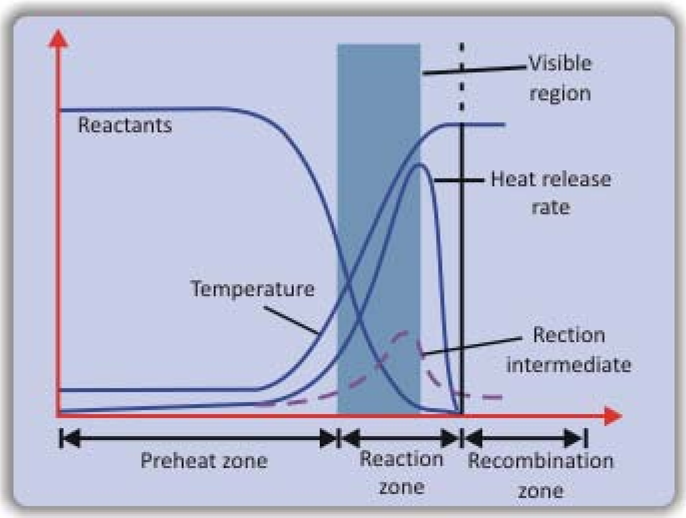
Structure of 1D Premixed Flame

Preheat zone: Negligibly small heat release

- Certain chemical reactions take place in this zone

Reaction zone:

- most of the chemical energy is released in the form of heat
- Decomposition of fuel takes place, leading to intermediate radical formation
- Reaction zone is very thin as compared to the preheat zone.
- Temperature gradient and concentration gradient are high.



(Figure 23.1)

Recombination zone:

- CO_2 and H_2O are formed;
- No heat release in this zone

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Laminar Flame Theory

Assumptions:

- 1D, steady, inviscid flow.
- Flame is quite thin.
- Ignition temperature is very close to flame temperature.
- No heat loss including radiation; ⇒ Adiabatic flame.
- Pressure difference across the flame is negligibly small.
- Binary diffusion, Fourier and Fick's law are valid.
- Unity Lewis number.
- Constant transport properties $\left(k_g, C_p, \mu, D \sim \text{constant}\right)$

Mass conservation: $\frac{d}{dx}(\rho V_x) = 0 \Rightarrow \dot{m}'' = (\rho V_x) = const$ … (1)

Species conservation:

Fuel: $\rho V_x \frac{dY_F}{dx} = \rho D \frac{d^2 Y_F}{dx^2} + \dot{m}_F'''$ … (2)

Oxidizer: $\rho V_x \frac{dY_{Ox}}{dx} = \rho D \frac{d^2 Y_{Ox}}{dx^2} + \dot{m}_{Ox}'''$ … (3)

Product: $\rho V_x \frac{dY_P}{dx} = \rho D \frac{d^2 Y_P}{dx^2} + \dot{m}_P'''$ … (4)

Energy equation:

$\rho V_x C_p \frac{dT}{dx} = k_g \frac{d^2 T}{dx^2} - \sum \hat{h}_{f,i}^0 \dot{m}_i'''$ … (5)

Global reaction mechanism:

$F + \upsilon Ox \rightarrow (\upsilon + 1) P$ … (6)

Laminar Flame Theory (Contd.)

Heat release due to chemical reaction:

$$\sum \hat{h}^0_{f,i}\dot{m}'''_i = \left[\hat{h}^0_{f,F}\dot{m}'''_F + v\hat{h}^0_{f,Ox}\dot{m}'''_F - (v+1)\hat{h}^0_{f,P}\dot{m}'''_F\right] = \dot{m}'''_F\Delta\hat{H}_c \qquad \dots (7)$$

Now energy equation becomes

$$\dot{m}''C_p\frac{dT}{dx} = k_g\frac{d^2T}{dx^2} - \dot{m}'''_F\Delta\hat{H}_c \qquad \dots (8)$$

Boundary conditions (For preheat zone)

$$x = -\infty; T = T_u; \frac{dT}{dx} = 0$$

$$x = +\infty; T = T_F; \frac{dT}{dx} = 0$$

Recasted energy equation for preheat zone,

$$\dot{m}''C_p\frac{dT}{dx} = k_g\frac{d^2T}{dx^2} \qquad \dots (9)$$

Heat transfer due to conduction is balanced by convective heat transfer.

In the reaction zone,

$$x = -\infty; T = T_u; \frac{dT}{dx} = 0$$

$$x = -x_{ig}; T = T_{ig}$$

$$\left.\frac{dT}{dx}\right|_{ig} = \frac{\dot{m}''C_p}{k_g}\left(T_{ig} - T_u\right) \qquad \dots (10)$$

$$k_g\frac{d^2T}{dx^2} = \dot{m}'''_F\Delta H_c \qquad \dots (11)$$

Rewriting, E.g. (11).

$$dT\frac{d}{dx}\left(\frac{dT}{dx}\right) = \frac{\Delta H_c}{k_g}\dot{m}'''_F\,dT \qquad \dots (12)$$

$$\left(\frac{dT}{dx}\right)_{ig} = \left[\frac{2\hat{H}_c}{k_g}\int_{T_{ig}}^{T_F}\dot{m}'''_F\,dT\right]^{0.5} \qquad \dots (13)$$

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Laminar Flame Theory (Contd.)

Combining equations (10) and (13),

$$\frac{\dot{m}'' C_\rho}{k_g}\left(T_{ig} - T_u\right) = \left[\frac{2\Delta \widehat{H}_c}{k_g}\int_{T_{ig}}^{T_F} \dot{m}_F''' \, dT\right]^{0.5} \quad \text{… (14)}$$

$$\Rightarrow \dot{m}'' = \frac{k_g}{C_\rho}\frac{1}{\left(T_{ig} - T_u\right)} = \left[\frac{2\Delta \widehat{H}_c}{k_g}\int_{T_{ig}}^{T_F} \dot{m}_F''' \, dT\right]^{0.5} \quad \text{… (15)}$$

Also,

$$\dot{m}'' = \rho_u S_L \quad \text{… (16)}$$

Combining equations (15) and (16),

$$S_L = \frac{k_g}{\rho_u C_p}\frac{4}{3(T_F - T_u)}\left[\frac{2\Delta H_c}{k_g}\int_{T_{ig}}^{T_F} \dot{m}_F'' dT\right]^{0.5} \quad \text{… (17)}$$

Mean fuel burning rate per unit volume,

$$\bar{\dot{m}}_F'' = \frac{1}{(T_F - T_u)}\left[\int_{T_u}^{T_F} \dot{m}_F''' \, dT\right] \quad \text{… (18)}$$

Mean fuel burning rate can also be expressed as,

$$\bar{\dot{m}}_F'' = MW_F A_f C_F^{n_1} C_{Ox}^{n_2} e^{-E/R_u T} \quad \text{… (19)}$$

Expression for burning velocity becomes,

$$S_L = \left[\frac{32\alpha}{9\rho_u}(v+1)\overline{\dot{m}_F'''}\right]^{0.5}$$

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Flame Thickness

Flame Thickness (d_L): Ratio of maximum temperature difference to the temperature difference at the inflection point

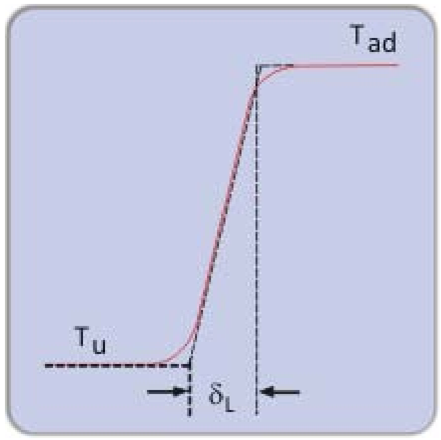
$$\delta_L \equiv \frac{(T_F - T_u)}{(dT/dx)_{ig}}$$

Ignition temperature can be approximated as

$$T_{ig} = 0.75\, T_F + 0.25 T_u$$

The temperature gradient at the flame surface is

$$\left.\frac{dT}{dx}\right|_{ig} = \frac{3}{4}\frac{\dot{m}'' C_p}{k_g}(T_F - T_u)$$



(Figure 23.2)

Flame thickness:

$$\delta_L \equiv \frac{4}{3}\frac{k_g}{C_p}\frac{1}{\dot{m}''}$$

$$\boxed{\delta_L = \frac{4}{3}\frac{\alpha}{S_L}}$$

Where, $\alpha = k_g/\rho C_p$

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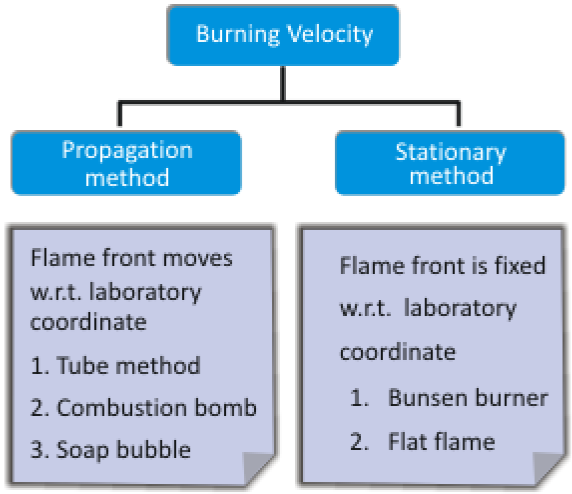
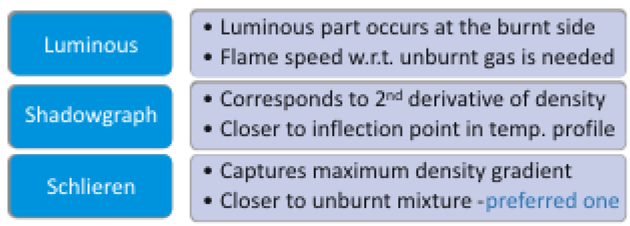
Burning Velocity Measurement Methods



(Figure 23.3)

Flame front visualization

- Luminous photography
- Shadowgraph photography
- Schlieren Photography



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