Course Name: Theory of Fire Propagation (Fire Dynamics)

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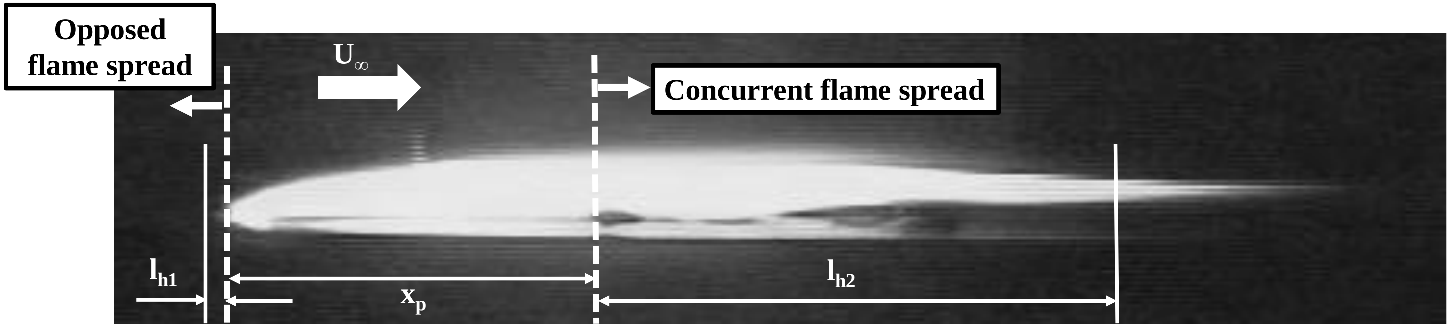
Week – 08

Lecture – 02

Module 5 – Burning of Solid Fuels

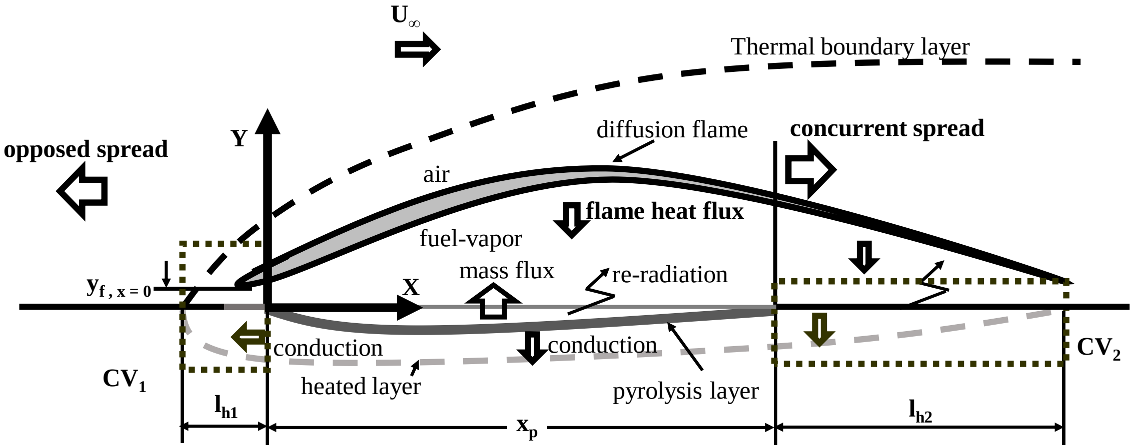
Flame spread:

Flame spread is the phenomenon of a moving flame in close proximity to the source of the fuel vapor or gas originating from the condensed phase (solid or liquid). Fuel gas or vapor originates because of pyrolysis or vaporization of the fuel because of heat transfer from the flame itself. Figure shows photograph of a flame moving on 2.5 mm thick PMMA slab with an air flow velocity of 0.8 m/s. Region of the fuel surface that is pyrolyzing is the pyrolysis length x_p as shown. Portion being heated by the flame is shown as l_h, called the heated length.



Flame spread – heat and mass transfer:

Heat and mass transfers involved during flame spread process is shown schematically, following Fernandez-Pello (1995). Heat flux from the flame to surface is mainly from conduction at the leading edge, where flame stands at a distance of $\mathbf{y_{f,\, x=0}}$. Flame slowly propagates against the direction of the flow.



Flame spread rate:

There is a similarity between the flame spread and ignition process. After a fuel is ignited, flame must heat up the unignited fuel ahead of it to pyrolysis (or ignition) temperature. Spreading of a flame can be viewed as a sequence of ignitions of a 'heated length' caused by a flame that acts as both a heat source and a pilot. Relatively simple expression is used for quantifying the rate at which a flame spreads on a solid surface:

$$\text{Flame spread rate} = \frac{\text{flame heated length } (l_{h_1} \text{ or } \mathrm{l}_{h_2})}{\text{time to ignite } (t_{\mathrm{ig}})}$$

Flame heated length depends on the nature of the flow field. For opposed flow spread, the heated length, l_{h1} is shorter and for concurrent flame spread, the heated length, l_{h2} is longer.

Flame spread rate velocity:

For the flame to spread, unburnt fuel should be heated from surface temperature (T_s) to ignition temperature (T_{ig}). T_{ig} is also the pyrolysis temperature (T_p). The heat for this is transferred from the flame. Heat balance is written as:

$$\dot{q} = \rho V_f A c\left(T_{ig} - T_s\right)$$

Here, $\rho,\ V_f,\ A$ and c are density of the fuel, flame spread velocity, surface area of the exposed fuel and specific heat of the fuel, respectively. Here, product $\rho V_f A$ represents the mass flow rate (kg/s) at which the unburnt fuel, which has a specific heat of c, is heated from T_s to T_{ig}. This amount of heat should come from flame to the fuel surface, as shown as $\dot{q}$ in kW. Thus, V_f in m/s is:

$$V_f = \frac{\dot{q}}{\rho A c\left(T_{ig} - T_s\right)}$$

Flame spread rate – thermally thin case:

Flame spread rate can be written in terms of heat flux ($\dot{q}''$) incident on a fuel surface of width, w, and the heated length, l_h.

$$V_f = \frac{\dot{q}'' \times l_h \times w}{\rho A c\left(T_{ig} - T_s\right)}$$

Surface area of fuel being heated is w × δ, where δ is the depth to which pyrolysis has occurred. For thermally thin case, δ is almost equal to the physical thickness of the fuel ($\delta = t_p$). Thus,

$$\boldsymbol{V_f} = \frac{\dot{q}" \times l_h \times w}{\rho(w \times \delta)c\left(T_{ig} - T_s\right)} = \frac{\dot{q}" \times l_h}{\rho c \delta\left(T_{ig} - T_s\right)} = \frac{\boldsymbol{\dot{q}" \times l_h}}{\boldsymbol{\rho c t_p\left(T_{ig} - T_s\right)}}$$

It may be seen that this expression is the ratio of heated length (l_h) to the ignition time, where the ignition time for thermally thin solid is used. Heat flux is net heat flux incident on the surface.

The heat flux ($\dot{q}"$) incident on a fuel surface is mainly due to conduction, especially for opposed flame spread.

$$\dot{q}" = k_g \frac{T_f - T_{ig}}{y_{f,\,x=0}}$$

Here, $\mathbf{y_{f,\,x=0}}$ is the flame stand-off distance at the leading edge, x = 0, k_g is thermal conductivity of gas mixture and T_f is the flame temperaure. It was shown by de Ris (1969) that $\boldsymbol{l_h} = \mathbf{(2)^{0.5}} \times \mathbf{y_{f,\,x=0}}$. Using these,

$$\boldsymbol{V_f} = \frac{\boldsymbol{\sqrt{2}k_g(T_f - T_{ig})}}{\boldsymbol{\rho c t_p\left(T_{ig} - T_s\right)}}$$

This expression holds good for opposed flame spread under forced convection.

Flame spread rate – thermally thick case:

Flame spread rate in m/s can be written as:

$$\text{Flame spread rate} = \frac{\text{flame heated length } (l_h)}{\text{time to ignite } (t_{\text{ig}})}$$

For thermally thick case, time for ignition is:

$$t_{ig} = \frac{\left(\frac{\pi}{4}\right) k\rho c\left(T_{ig} - T_s\right)^2}{\left(\dot{q}_i^{"}\right)^2}$$

From these, the flame spread rate in m/s is written as:

$$\boldsymbol{V_f = \frac{l_h}{t_{ig}} = \left(\frac{4}{\pi}\right)\frac{l_h\left(\dot{q}_i^{"}\right)^2}{k\rho c\left(T_{ig} - T_s\right)^2}}$$

For opposed flame spread under force convection, the flow velocity (U_∞) will also influence heated length and flame stand-off distance: $l_h \approx \alpha_g/U_\infty \approx y_{f,\,x=0}$. Here, α_g is thermal diffusivity of the immediate gas-phase = $k_g/(\rho_g c_{pg})$. Using these and conduction heat flux, an expression for opposed flame spread under force convection for thick solid is written as:

$$\boldsymbol{V_f \approx \frac{k_g\rho_g c_{pg} U_\infty\left(T_f - T_{ig}\right)^2}{k_s\rho_s c_{ps}\left(T_{ig} - T_s\right)^2}}$$

Here, suffix g is used to indicate gas-phase properties and suffix s is to indicate solid properties.

For fire spread under natural convection, The flow velocity (m/s) due to buoyancy (U_b) is calculated as:

$$U_b = \left(\frac{g\,\nu_g \Delta h_C Y_{O,\infty}}{c_{pg} T_\infty}\right)^{1/3}$$

Here, g is acceleration due to gravity (m/s^2), ν_g is kinematic viscosity (m^2/s), Δh_C is heat of combustion (J/kg), $Y_{O,\infty}$ is oxygen mass fraction, c_{pg} is the specific heat of gas mixture and T_∞ is the ambient temperature (K). For concurrent flame spread, it is quite difficult is get straight forward expressions for flame spread velocity. Some expressions for concurrent flame spread are reported in Pello (1995).