Course Name: Theory of Fire Propagation (Fire Dynamics)

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Week – 08

Lecture – 03

Module 5 – Burning of Solid Fuels

Flame spread rate – thermally thick case:

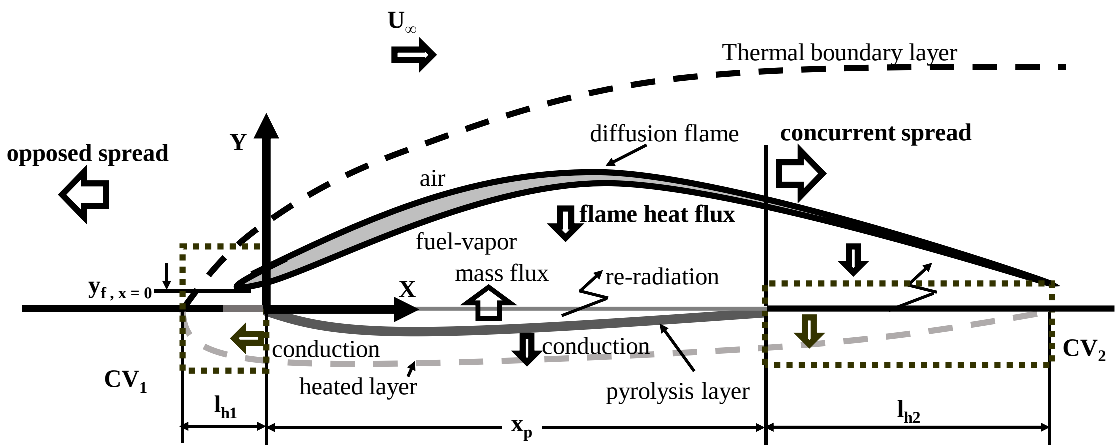
For fire spread under natural convection, The flow velocity (m/s) due to buoyancy (U_b) is calculated as:

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

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).

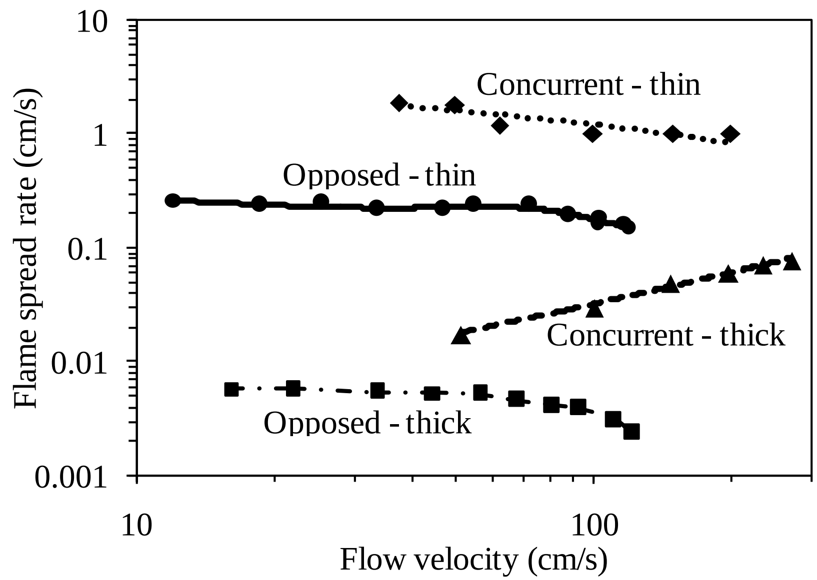
Flame spread rate – concurrent flame spread:

Apart from conduction heat transfer from the flame to the solid, radiation from the flame to the solid and re-radiation from the solid surface to the ambient also occur. Pyrolysis length, x_p, is much longer. Thus V_f is much larger. V_f can be expressed as dx_p/dt. Within pyrolysis zone, flame stand-off distance is small at the leading edge and it increases as $x^{0.5}$ and $x^{0.25}$ in forced and natural convection.



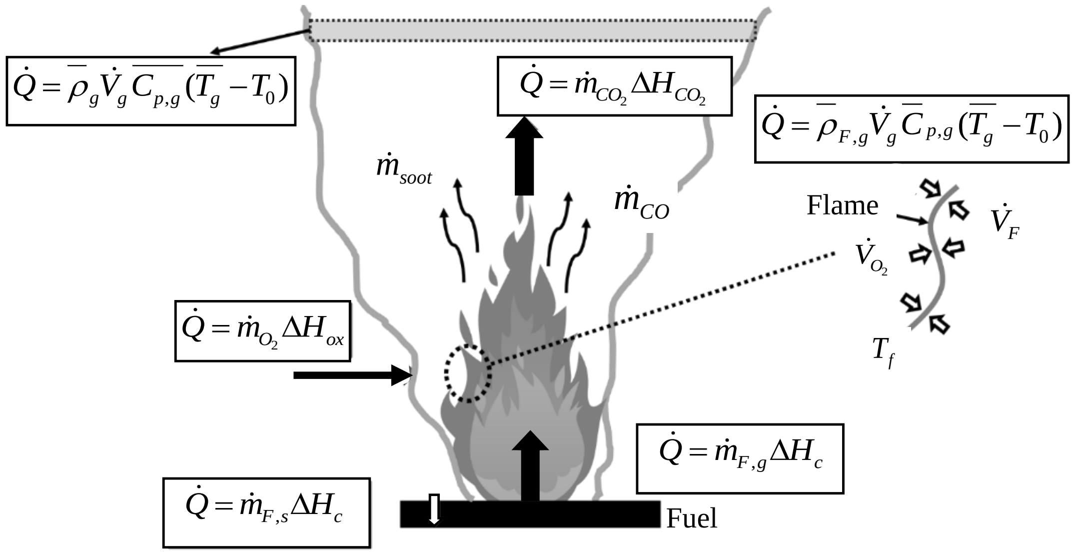
Flame spread rate – in forced convection:

Figure shows the variation of flame spread rate with flow velocity for opposed and concurrent flame spread (Pello,1995). (Thick material: PMMA, Thin material: Paper)



Mass burning rate:

Heat release rate or the burning rate ($\dot{Q}$) forms the single most important parameter in defining a fire hazard. Six expressions to calculate $\dot{Q}$ is shown during STEADY burning of a turbulent fire.



Mass burning and heat release rates:

$$\dot{Q} = \dot{m}_{Fs} \Delta h_c$$

$$\dot{Q} = \dot{m}_{Fg} \Delta h_c$$

$$\dot{Q} = \dot{m}_{O_2} \Delta h_{O_2}$$

$$\dot{Q} = \dot{m}_{CO_2} \Delta h_{CO_2}$$

$$\dot{Q} = \bar{\rho}_{F,g} \dot{V}_F \bar{c}_{pg} \left(\bar{T}_f - T_0\right)$$

$$\dot{Q} = \dot{m}_g \bar{c}_{pg}\left(\bar{T}_g - T_0\right) = \bar{\rho}_g \dot{V}_g \bar{c}_{pg}\left(\bar{T}_g - T_0\right)$$

Radiation is neglected in these expressions.

$$\dot{Q} = \text{heat release rate (W)}$$

$$\dot{m}_{Fg} = \dot{m}_{Fs} = \text{mass burning rate (kg/s)}$$

$$\Delta h_c = \text{heat of combustion (J/kg)}$$

$$\dot{m}_{O_2} = \text{Oxygen consumption rate (kg/s)}$$

$$\dot{m}_{CO_2} = \text{CO}_2 \text{ production rate } \left(\frac{\text{kg}}{\text{s}}\right)$$

$$\Delta h_{O_2} = 13.1 \text{ kJ/g}, \quad \Delta h_{CO_2} = 13.3 \text{ kJ/g}$$

$$\bar{\rho}_{F,g} = \text{average density of fuel kg/m}^3$$

$$\bar{c}_{pg} = \text{average speific heat of gas J/kgK}$$

$$\bar{T}_f = \text{average flame temperature (K)}$$

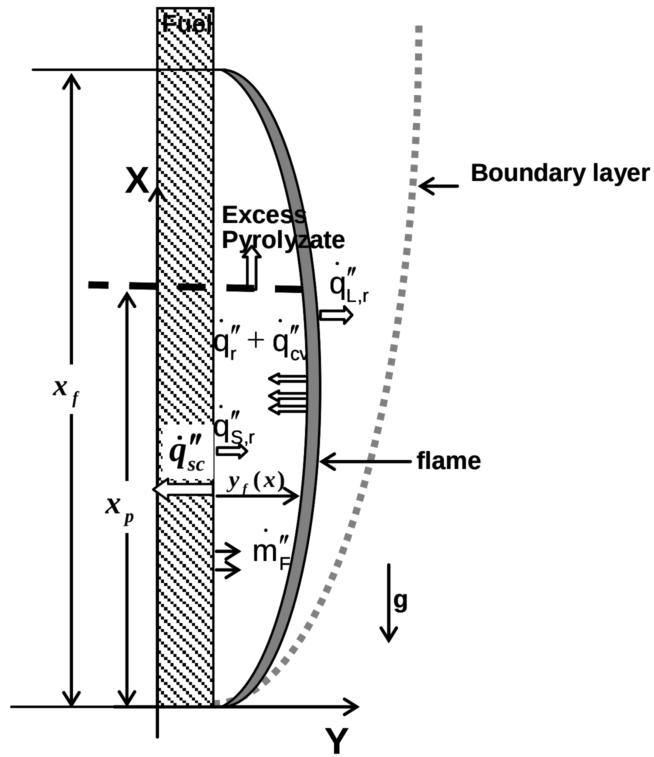
$$\bar{T}_g = \text{average gas temperature (K)}$$

$$T_0 = \text{ambient temperature (K)}$$

$$\dot{V}_F, \dot{V}_g = \text{volumetric flow rates m}^3/\text{s}$$

$$\bar{\rho}_g = \text{average density of gas kg/m}^3$$

Mass burning rate – theory:



Consider burning of a vertical solid slab under natural convection as shown in figure. Heat feedback from flame is sufficient to cause pyrolysis. Pyrolyzate evolve at a specific velocity known as blowing velocity or Stefan mass transfer velocity and mixes with oxygen from air to sustain a diffusion flame.

Burning rate per unit area is the product of gas-phase density and gas velocity normal to the fuel surface.

$\dot{m}'' = \rho_g \times v_g$ (kg/m^2-s)

For steady burning, the heat balance at the solid surface is given by,

$\dot{q}'' = \dot{m}'' \times L$ (W/m^2)

Here, L is the heat (J) required to release pyrolyzate from the solid.

$L = \Delta h_P + c_{ps} \times (T_P - T_0)$

Δh_P is heat of pyrolysis and T_P is pyrolysis/ignition temperature.

Net heat flux ($\dot{q}''$) to the surface depends on the nature of the flow field and boundary conditions (free stream temperature, ambient oxygen concentration etc.). It also depends on $\dot{m}''$, an effect called as the blocking effect. If the net heat flux to the surface increases, then mass flux or mass loss rate per unit area will also increase, causing the boundary layer to thicken and reducing the gradients. A larger burning rate will push the flame farther from the surface thereby making the flame standoff distance $y_f(x)$ bigger. Flame will be closer to the surface, if the environment contains more oxygen or if the fuel is impure. The burning rate therefore does not increase linearly with heat flux and to develop a general solution requires generalization of the heat flux to the fuel.

It can be assumed that the heat flux to the surface is a product of a global heat transfer coefficient (h) considering radiation (h_T) and temperature difference between the flame (T_f) and the surface (T_s) the mass loss rate per unit area can be represented as:

$$\dot{m}" = \frac{\dot{q}"}{L} = \frac{h(T_f - T_s)}{L} = B\frac{h}{c_{p,g}}$$

Here, B number based on heat transfer is used:

$$B = \frac{c_{p,g}(T_f - T_s)}{L}$$

Heat transfer coefficient is expressed in terms of Nusselt number.

$$Nu = \frac{hx}{k_g}$$

In the Nusselt number's expression, k_g is thermal conductivity of the gas-phase and x is characteristic length. Using these, mass burning rate is written as:

$$\dot{m}" = B\frac{k_g}{xc_{p,g}}Nu$$

Evaluation of Nusselt number depends on the convective conditions – forced or natural or mixed convection and the regime; laminar or turbulent. Nu is a function of Reynolds number ($Re = Ux/\nu$) and Prandtl number ($Pr = \mu \times c_p/k_g$) for forced convection. For natural convection, it is a function of Grashoff number ($Gr = g\beta\Delta T x^3/\nu^2$) and Prandtl number. Here, $\beta = 1/T_{avg}$. Several empirical expressions are available for finding $\dot{m}"$.