Course Name: Theory of Fire Propagation (Fire Dynamics)

Professor's Name: Dr. V. Raghavan

Department Name: Mechanical Engineering

Institute: Indian Institute of Technology Madras, Chennai – 600036

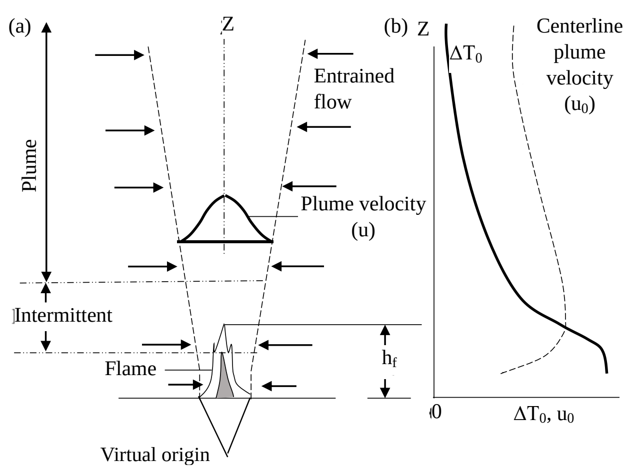
Week – 09

Lecture – 01

Module 6 – Analysis of Fire Plumes

Fire plume zones:

Fire plume has three zones (Heskestad, 1995 & Quintiere, 2017)



Heat release occurs in the flame zone near the fuel surface. This zone extends to an average flame height. Above this zone, an intermittent zone prevails. Here, the flame is seen intermittently. This zone encompasses the maximum flame length, which is almost twice the minimum flame height. Significant fluctuations are observed in this zone. Above this zone, only hot product gases exist, and it is called the plume zone. Flame height is determined by plotting a variable called intermittency, I, which is the ratio of the time for which a flame is present in a given location over the total time of observation. In the flame zone, the value of I is unity. In the intermittent zone, the value of I reduces sharply, and it is zero in the plume zone. The mean flame length is the axial location, where I = 0.5.

Fire plume - energy and temperature:

Net energy content in the gases increases along the height from the fuel surface due to heat release from the flame and becomes almost a constant around the tip of the flame (at the average flame height). The energy content of plume gases is the heat released due to combustion minus heat lost to the environment. Heat loss is estimated as a fraction of the heat release rate. The average plume temperature increases with height from the fuel surface and reaches the maximum value. It remains almost constant in the flame zone. Then, it decreases in the intermittent and the plume zones.

Fire plume velocity:

Froude number is expressed as $Fr = U^2/(gD)$, where U is the characteristic velocity, taken as the average plume velocity, D is the characteristic length, taken as the diameter of the plume source, and g is the acceleration due to gravity. An estimate of the buoyant flow velocity (U) at an elevation of z from the fuel surface is obtained by comparing the buoyancy (relative density) term $(\rho - \rho_\infty)gz$ to the gain in the kinetic energy $0.5\rho U^2$. Here, the subscript ∞ denotes the ambient condition. For open plumes, the pressure variation along the plume is quite negligible. Writing density as the inverse of temperature,

$$U \approx [2(T - T_\infty)gz/T_\infty]^{0.5}$$

where T is the average radial temperature at height z. U is proportional to $[g \times z]^{0.5}$.

Fire plume over condensed fuels:

In fires over condensed fuels, vaporized or gas fuel coming out of the fuel surface has a velocity of the order of a few cm/s, significantly smaller than the plume velocity. Entrainment of air is caused by much higher plume velocity. In gas jet diffusion flame, the fuel jet velocity dictates the entrainment rate. The average plume temperature remains nearly constant in the flame zone. Then it decreases with height. As the plume temperature decreases, the average velocity of the plume also decreases. Thus, the rate of air entrainment decreases with plume height. Air entrained up to the flame height is used for burning the fuel.

Fire plume – air entrainment:

Since in the flame zone, the average flame temperature remains constant, the rate of mass of air entrained is approximately estimated in terms of pool/plume circumference, height of the flame (h_f) and average entraining air velocity (U_e) as,

$$\dot{m}_a \approx \rho_\infty \times \pi \times D \times h_f \times U_e.$$

Since the entrainment rate is dependent on the plume velocity (U), it is noted from the estimation of U that the maximum plume velocity is proportional to $[g \times z]^{0.5}$. In the flame zone, the plume velocity, and as a result, the entrainment velocity (U_e) is proportional to $[g \times h_f]^{0.5}$. Diffusion flames form when fuel and oxidizer mix in stoichiometric proportion. If s is the stoichiometric air-to-fuel ratio, then $s = \dot{m}_a/\dot{m}_f$. Here, $\dot{m}_f$ is the mass burning rate of the fuel.

Fire plume – heat release, flame height:

Using the estimations of $\dot{m}_a$ and U_e:

$$s \approx \frac{\rho_\infty \times \pi \times D \times h_f \times U_e}{\dot{m}_f} \approx \frac{\rho_\infty \times \pi \times D \times h_f \times \sqrt{g h_f}}{\dot{m}_f}$$

From this, average flame height is estimated as:

$$h_f/D \approx [(\dot{m}_f \times s)/(\pi\rho_\infty D^2[gD]^{0.5})]^{2/3}$$

Total heat release rate is $\dot{Q} = \dot{m}_f \times \Delta H_c$, using this:

$$\frac{h_f}{D} \approx \left(\frac{s c_{p\infty} T_\infty}{\pi \Delta H_c}\right)^{\frac{2}{3}} \left(\frac{\dot{Q}}{\rho_\infty c_{p\infty} T_\infty \sqrt{gD} D^2}\right)^{\frac{2}{3}} \approx C(Q^*)^{2/3}$$

Here, Q^* is a non-dimensional quantity called Zukoski number. Denominator defining Q^* represents thermal energy transported by the plume, where D^2 represents area and $(gD)^{0.5}$, the velocity.

Q^*, the Zukoski number, indicates momentum dominated jet if its value is greater than 10^4, as indicated by McCaffrey. Q^* also represents the ratio of combustion energy to nominal plume energy. Q^* is also used to represent a ratio of a length scale as:

$$(\boldsymbol{Q}^*)^{2/5} = \left(\frac{\dot{\boldsymbol{Q}}}{\boldsymbol{\rho}_\infty \boldsymbol{c}_{\boldsymbol{p}\infty} \boldsymbol{T}_\infty \sqrt{\boldsymbol{g}\boldsymbol{D}}\boldsymbol{D}^2}\right)^{\frac{2}{5}} = \left(\frac{\dot{\boldsymbol{Q}}}{\boldsymbol{\rho}_\infty \boldsymbol{c}_{\boldsymbol{p}\infty} \boldsymbol{T}_\infty \sqrt{\boldsymbol{g}}}\right)^{\frac{2}{5}} \Big/ \boldsymbol{D}$$

Observing the power of **2/5** for $\dot{\boldsymbol{Q}}$ in this equation, Hesteskad reported correlation using $\dot{\boldsymbol{Q}}$ in kW for flame height (in m):

$$\boldsymbol{h}_{\boldsymbol{f}} = \mathbf{0.23}\left(\dot{\boldsymbol{Q}}\right)^{\frac{2}{5}} - \mathbf{1.02}\boldsymbol{D}$$