Course Name: Theory of Fire Propagation (Fire Dynamics)

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Week – 09

Lecture – 04

Module 6 – Analysis of Fire Plumes

Fire plume – correlations from literature:

ΔT (K)	u_0 (m/s)	z_0 (m)	Reference
$13.74\left[\frac{\dot{Q}_c^{2/5}}{z}\right]^{5/3}$	$0.59\left[\frac{\dot{Q}_c}{z}\right]^{1/3}$	No virtual origin used	Zukoski et al. (1981)
$25\left[\frac{\dot{Q}_c^{2/5}}{z-z_0}\right]^{5/3}$	$1\left[\frac{\dot{Q}_c}{z-z_0}\right]^{1/3}$	$0.083\dot{Q}^{2/5}-1.02D$	Heskestad (1995)
$22.3\left[\frac{\dot{Q}_c^{2/5}}{z}\right]^{5/3}$	$1.1\left[\frac{\dot{Q}}{z}\right]^{1/3}$	No virtual origin used	McCaffrey (1979)

$4.58\left[\frac{\dot{Q}_c^{2/5}}{z^* - z_0}\right]^{5/3}$	$1.29\left[\frac{\dot{Q}_c}{z^* - z_0}\right]^{1/3}$	$0.095\dot{Q}^{2/5} - z_{00}$	Kung & Stavrianidis (1982)

z, z* (m) – distance from top of fuel surface, $\mathbf{z_{00}}$ – average height = 1.6 m (2 tier), 2.4 m (3 tier and 4 tier) - Kung & Stavrianidis (1982)

Fire plume – air entrainment rate:

For idealized fire plumes, the air entrainment into the plume was assumed to be equal to α × u. Air entrainment quite high in plume region and is expressed as,

$$\dot{m}_{ent} = E\rho_\infty \pi b_u^2 u_0$$

Here, E is non-dimensional constant, b_u is plume radius, radial location where centreline velocity reduces to half of its value at a given height. Value of b_u is evaluated using the expression of b_T by setting $T_0/T_\infty = 1$. Using this, and the expression of u_0, air entrainment rate is expressed as:

$$\dot{m}_{ent} = E\left(\frac{g\rho_\infty^2 \dot{Q}_c}{c_p T_\infty}\right)^{\frac{1}{3}} (z - z_0)^{\frac{5}{3}}$$

Yih (1952) reported E = 0.153. Later, Centegen et al. (1982), assuming $\dot{Q}_c$ = 70% of $\dot{Q}$, reported E = 0.24.

Fire plume – air entrainment rate correlation:

Heskestad (1986) added one more term to the mass entrainment expression, for strong plumes, as follows:

$$\dot{m}_{ent} = E\left(\frac{g\rho_\infty^2 \dot{Q}_c}{c_p T_\infty}\right)^{\frac{1}{3}} (z - z_0)^{\frac{5}{3}} \left[1 + \frac{G\dot{Q}_c^{2/3}}{\left(g^{0.5} c_p \rho_\infty T_\infty\right)^{2/3} (z - z_0)^{5/3}}\right]$$

Values of E = 0.196 and G = 2.9 are able to estimate the mass entrainment rates at and above the mean flame height closer to experimental data. Under atmospheric conditions, using the above values of E and G, correlations for mass entrainment rate above the mean flame length is given by,

$$\dot{m}_{ent} = 0.071\, \dot{Q}_c^{1/3} (z - z_0)^{5/3} \left(1 + 0.027 \dot{Q}_c^{2/3} (z - z_0)^{-5/3}\right)$$

Fire plume – air entrainment at & in flame zone:

At the mean flame length, the correlation is expressed by considering ΔT = 500 K, given as,

$$\dot{m}_{ent} = 0.0056\, \dot{Q}_c$$

For fire diameters of 0.3 m or greater, the mass entrainment rate for $z \leq h_f$, is written as,

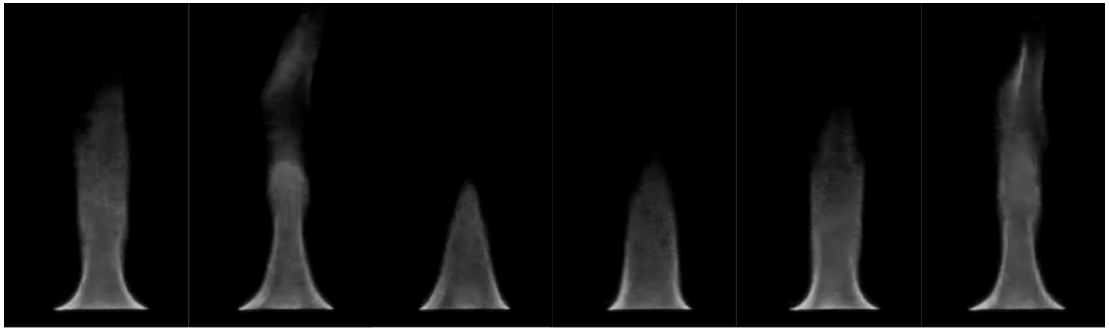
$$\dot{m}_{ent} = 0.0059\, \dot{Q}_c \left(z/h_f\right)$$

In all these correlations, $\dot{Q}_c$ is in kW, length dimensions are in m and mass entrainment rate is in kg/s. In general, fires with much lower h_f/D ratios have not been studied and these equations must be used with caution for such cases.

Fire plume – flame pulsation:

Flame pulsations result from of air entrainment, and these are quantified by several experiments. Cetegen and Ahmad (1993) researched on fire diameters in the range of 0.03 m to 20 m and arrived at the correlation for flame pulsation frequency, f (Hz), in terms of fire diameter (m), given as:

$$\mathbf{f = 1.5/D^{0.5}}$$



14.26 cm 18.55 cm 8.04 cm 9.28 cm 12.13 cm 16.68 cm

Direct photographs of instantaneous methanol pool flames; D = 6 cm

Plume interaction with ceiling:

Several researchers have investigated the effects the interaction of the plume with ceiling. Plume rises vertically, impinges on the ceiling and bends in perpendicular direction. Movement of the plume after impinging with the ceiling is called ceiling jet. Characteristics of ceiling jet; magnitudes of its temperature and velocity, are quite important for the performance of fire safety devices, such as smoke detectors, heat detectors and sprinklers, which are usually embedded just below the ceiling. Interaction between the plume and adjacent walls or corners are relatively insignificant when compared to the interaction of the plume with the ceiling.

Ceiling jet flow:

A schematic of the steady ceiling jet flow is shown in the figure.