Course Name: Theory of Fire Propagation (Fire Dynamics)

Professor's Name: Dr. V. Raghavan

Department Name: Mechanical Engineering

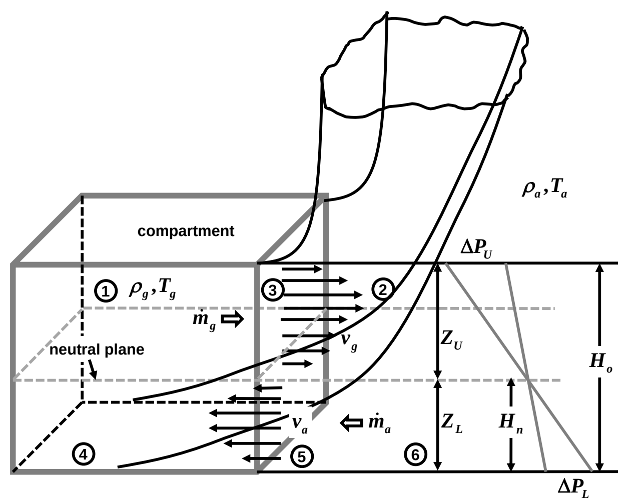
Institute: Indian Institute of Technology Madras, Chennai – 600036

Week – 10

Lecture – 04

Module 7 – Enclosure Fires

In and out flow of gases from enclosure:



Flow of gases in & out of an enclosure during fully developed stage

H_0 = Opening height.

T_g = temperature of gases.

ρ_g = density of the hot gases.

$\dot{m}_g$ = mass flow rate of hot gases out of enclosure.

v_g = velocity of hot gases flowing out of enclosure.

H_n = Neutral plane height, where $\Delta p = 0$.

Suffix a: Quantities related to air flowing into the enclosure.

In fully developed stage, hot gases rise up and smoke flows out from top portion of the compartment and the cold air flow in through its lower part. Flow is triggered due to pressure differences (due to temperature differences) existing across the opening. At some height above the floor, the pressure difference is zero - this height is the neutral plane height denoted by **H_n**. Hot gases flow out above the neutral plane and air flows in below the neutral plane. To obtain mass flow out of the compartment, consider three points above the neutral plane - point 1 inside the enclosure, point 2 outside the enclosure and point 3 at the exit plane of the enclosure. Applying Bernoulli equation across 1 and 2:

$$p_1 + \frac{\rho_g v_{g1}^2}{2} + Z_U \rho_g g = p_2 + \frac{\rho_a v_{a2}^2}{2} + Z_U \rho_a g$$

Velocities at points 1 & 2 (well inside the enclosure and well outside it, respectively) will tend to zero. Using this, the Bernoulli equation is written as:

$$p_1 - p_2 = \Delta p_U = Z_U g(\rho_a - \rho_g)$$

This is the maximum pressure difference in upper part of the vent. Applying Bernoulli equation between points 1 & 3:

$$p_1 + \frac{\rho_g v_{g1}^2}{2} + Z_U \rho_g g = p_3 + \frac{\rho_g v_{g3}^2}{2} + Z_U \rho_g g$$

Note that ρ_g is used at point 3, as gas goes out. Since $v_{g1} \approx 0$:

$$p_1 - p_3 = \frac{\rho_g v_{g3}^2}{2} \Rightarrow v_{g3} = \sqrt{\frac{2(p_1 - p_3)}{\rho_g}} = \sqrt{\frac{2Z_U g(\rho_a - \rho_g)}{\rho_g}}$$

Here, $p_1 - p_3 \approx p_1 - p_2 = \Delta p_U$ and v_{g3} is maximum velocity.

To obtain mass flow into the compartment, consider three points below the neutral plane - point 4 inside the enclosure, point 6 outside the enclosure and point 5 at the exit plane of the enclosure. Applying Bernoulli equation across 6 and 4:

$$p_6 + \frac{\rho_a v_{a6}^2}{2} + Z_L \rho_a g = p_4 + \frac{\rho_g v_{g4}^2}{2} + Z_L \rho_g g$$

Velocities at points 4 & 6 tend to zero. Also, Z_L is negative, with reference to neutral plane located at H_n. Using this,

$$p_4 - p_6 = \Delta p_L = Z_L g(\rho_a - \rho_g)$$

This is the maximum negative pressure difference in the lower part of the vent. Applying Bernoulli equation across points 6 & 5:

$$p_6 + \frac{\rho_a v_{a6}^2}{2} + Z_L \rho_a g = p_5 + \frac{\rho_a v_{a5}^2}{2} + Z_L \rho_a g$$

Note that ρ_a is used at point 5, as air comes in. Since $v_{a6} \approx 0$:

$$p_6 - p_5 = \frac{\rho_a v_{a5}^2}{2} \Rightarrow v_{a5} = \sqrt{\frac{2(p_6 - p_5)}{\rho_a}} = \sqrt{\frac{2|Z_L| g(\rho_a - \rho_g)}{\rho_a}}$$

Here, $p_6 - p_5 \approx p_6 - p_4 = |\Delta p_L|$ and v_{a5} is the maximum incoming velocity.

Velocities as a function of height (z) above and below the neutral plane can be written as,

$$v_g(z) = \sqrt{\frac{2zg(\rho_a - \rho_g)}{\rho_g}}$$

$$v_a(z) = \sqrt{\frac{2|z|g(\rho_a - \rho_g)}{\rho_a}}$$

These can be integrated over the height to get net velocity in the upper & lower regions during a fully developed fire, where the pressures have reached a steady state.

Mass flow rate of outgoing gases:

Mass flow of gases out of the enclosure occurs above H_n.

$$\dot{m}_{out} = C_d \int_0^{z_U} \rho_g v_g(z) dA = C_d \int_0^{z_U} \rho_g v_g(z) W dz$$

Here, W is the width of the opening and all properties in the enclosure are assumed as constant (well-mixed scenario). Also, z is defined as zero at the neutral plane. Outflow occurs till $z = Z_U$.

$$\dot{m}_{out} = C_d W \rho_g \int_0^{z_U} \sqrt{\frac{2zg(\rho_a - \rho_g)}{\rho_g}} dz = C_d W \rho_g \sqrt{\frac{2g(\rho_a - \rho_g)}{\rho_g}} \int_0^{z_U} \sqrt{z} dz$$

$$\Rightarrow \dot{m}_{out} = C_d W \rho_g \sqrt{\frac{2g(\rho_a - \rho_g)}{\rho_g}} \left(\frac{2}{3} Z_U^{\frac{3}{2}}\right) \qquad (A)$$

This is the steady mass flow rate of outflow for well-mixed case.

Mass flow rate of incoming air:

$$\dot{m}_{in} = C_d \int_0^{Z_L} \rho_a v_a(z) dA = C_d \int_0^{Z_L} \rho_a v_a(z) W dz$$

Mass flow rate of atmospheric air in to the enclosure below H_n.

W is the width of the opening and z is defined as zero at the neutral plane. Inflow occurs till from z = 0 to z = Z_L.

$$\dot{m}_{in} = C_d W \rho_a \int_0^{Z_L} \sqrt{\frac{2|z|g(\rho_a - \rho_g)}{\rho_a}} dz = C_d W \rho_a \sqrt{\frac{2g(\rho_a - \rho_g)}{\rho_a}} \int_0^{Z_L} |z| dz$$

$$\Rightarrow \dot{m}_{in} = C_d W \rho_a \sqrt{\frac{2g(\rho_a - \rho_g)}{\rho_a}} \left(\frac{2}{3} Z_L^{\frac{3}{2}}\right) \qquad (B)$$

This is the steady mass flow rate of air coming in from opening below H_n.

Location of neutral plane:

The height of the opening is $H_0 = Z_U + Z_L$. Under steady conditions, in a steady fire in an enclosure, $\dot{m}_{in} = \dot{m}_{out}$. That is,

$$C_d W \rho_a \sqrt{\frac{2g(\rho_a - \rho_g)}{\rho_a}} \left(\frac{2}{3} Z_L^{\frac{3}{2}}\right) = C_d W \rho_g \sqrt{\frac{2g(\rho_a - \rho_g)}{\rho_g}} \left(\frac{2}{3} Z_U^{\frac{3}{2}}\right)$$

This can be simplified as,

$$\frac{\rho_a}{\sqrt{\rho_a}} \left(Z_L^{\frac{3}{2}}\right) = \frac{\rho_g}{\sqrt{\rho_a}} \left(Z_U^{\frac{3}{2}}\right) \left(\frac{Z_U}{Z_L}\right)^{\frac{3}{2}} = \sqrt{\frac{\rho_a}{\rho_g}} \Rightarrow \frac{Z_U}{Z_L} = \left(\frac{\rho_a}{\rho_g}\right)^{\frac{1}{3}}$$

Using, $H_0 = Z_U + Z_L$, an expression for Z_L can be obtained:

$$\frac{H_0 - Z_L}{Z_L} = \left(\frac{\rho_a}{\rho_g}\right)^{\frac{1}{3}} \Longrightarrow Z_L = \frac{H_0}{1 + (\rho_a/\rho_g)^{\frac{1}{3}}}$$