Course Name: Theory of Fire Propagation (Fire Dynamics)

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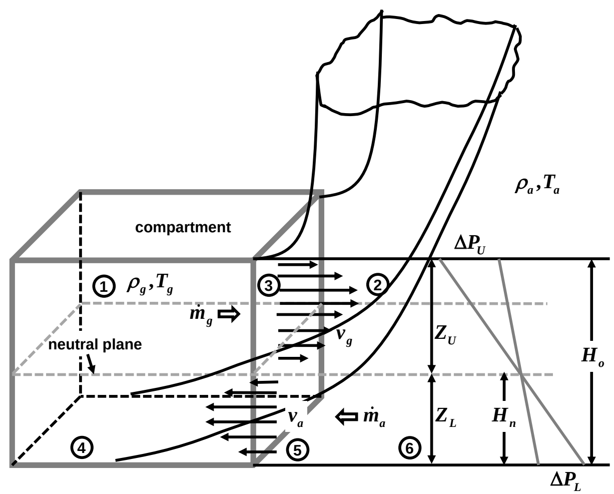
Week – 11

Lecture – 01

Module 7 – Enclosure Fires

In and out flow of gases from enclosure:



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

$\mathbf{H_0}$ = Opening height.

$\mathbf{T_g}$ = temperature of gases.

$\boldsymbol{\rho_g}$ = density of the hot gases.

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

$\mathbf{v_g}$ = velocity of hot gases flowing out of enclosure.

$\mathbf{H_n}$ = 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 $\mathbf{H_n}$. 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,

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

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

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

Simplified expression for air flow rate:

Since the expression to evaluate Z_L is known, the mass flow rate of air under steady conditions, in a steady fire, can be written as,

$$\dot{m}_{in} = \frac{2}{3} C_d W \rho_a \sqrt{\frac{2g(\rho_a - \rho_g)}{\rho_a}} \left(\frac{H_0}{1 + (\rho_a/\rho_g)^{\frac{1}{3}}}\right)^{\frac{3}{2}}$$

This can be simplified as,

$$\dot{m}_{in} = \frac{2}{3} C_d A_0 \sqrt{H_0} \sqrt{2g} \rho_a \sqrt{\frac{(\rho_a - \rho_g)\rho_a}{\left(1 + (\rho_a/\rho_g)^{\frac{1}{3}}\right)^3}}$$

Here, A_0 = W × H_0 is the area of the vent. Parameter in square-root is called density factor. The mass flow rate of the out going gases will be equal to the mass flow rate of incoming air.

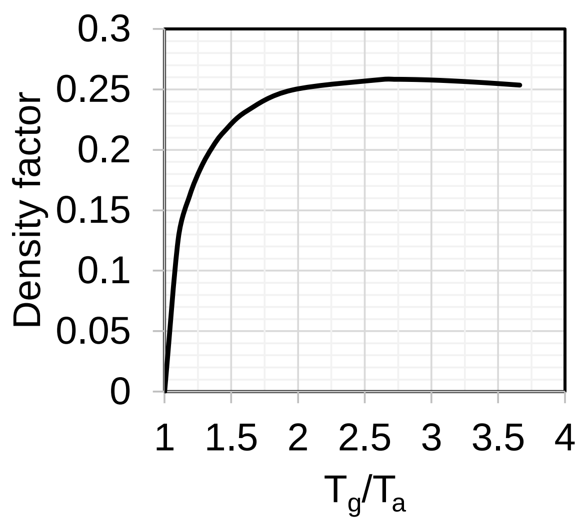
Density factor:

Quantity in square-root in the expression of air mass flow rate is density factor (DF) and is written as a function of temperature as,

$$DF = \sqrt{\frac{(\rho_a - \rho_g)\rho_a}{\left(1 + (\rho_a/\rho_g)^{\frac{1}{3}}\right)^3}} = \left(\frac{353}{T_a}\right) \sqrt{\frac{(T_g - T_a)}{\left(1 + (T_g/T_a)^{\frac{1}{3}}\right)^3}}$$

This is derived using ideal gas law:

p = ρRT. Here, p is the atmospheric pressure = 101325 N/m^2, R is the specific gas constant for air = R_u/M = 8314/28.9 = 287.7 J/kg-K, T in K and ρ = 101325/(287.7×T) ≈ 353/T.



At $T_g/T_a = 2.72$, DF reaches its maximum value and remains almost a constant.

Air flow rate in regime I fully developed fire:

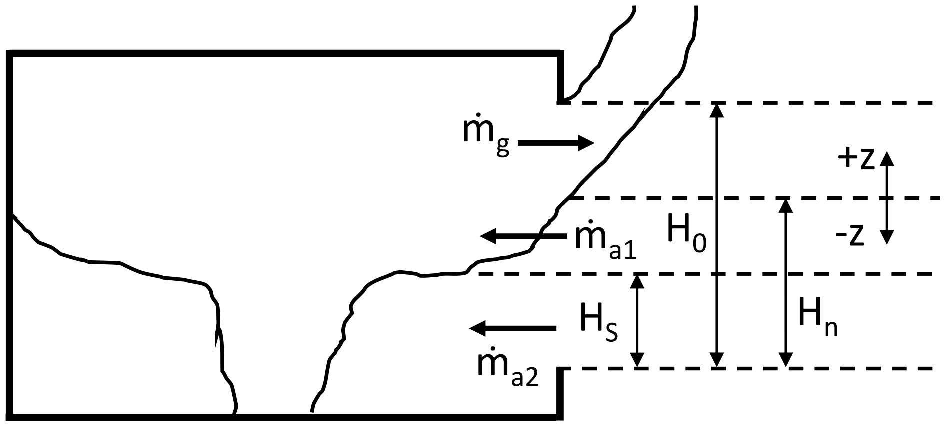
For fully developed compartment fires, the value of density factor can be taken as 0.214. Further, using $C_d = 0.7$, $\rho_\infty = 1.2$ kg/m^3, mass flow rate of air can be expressed as,

$$\dot{m}_{in} = 0.5\, A_0 \sqrt{H_0}$$

The equation shows that the mass flow rate of air into a compartment during the fully developed Regime I fire is only a function of the vent height and vent area. This equation gives an estimate of the mass flow rate for fires with gas temperature being at least two times the ambient temperature (in Kelvin). Also, it is assumed that the gases inside the enclosure are well-mixed and its temperature is uniform within the enclosure volume. This equation is quite useful in analysing post-flashover fires.

Gas and air flow for developing stage:

When the fire is developing, depending on the fire strength and vent opening height, H_0, stratified smoke layer forms, as shown.



Smoke layer has descended to a particular height from the ceiling, H_S. measured from the bottom of the vent. Below this, air from atmosphere enters. Above this level, a neutral plane is formed at a height of H_n, measured from bottom of the vent. Above H_n, hot gas leaves and below H_n, air comes in.

Mass flow rates of gas & air in developing stage:

Proceeding like before, Rockett (1976) has derived expressions for mass of the gases going out of the enclosure above the neutral plane as:

$$\dot{m}_g = \frac{2}{3} C_d A_o \sqrt{H_0} \sqrt{2g} \rho_a \left[\frac{T_a}{T_g} \left(1 - \frac{T_a}{T_g} \right) \right]^{1/2} \left[\frac{1 - H_n}{H_0} \right]^{3/2}$$

Here, integration of velocity is performed between H_n and H_0. For air mass flow rates, two integrations are performed – one between H_S and H_n, and second, between 0 and H_S. Total mass flow rate of air, $\dot{m}_a = \dot{m}_{a1} + \dot{m}_{a2}$, is expressed as,

$$\dot{m}_a = \frac{2}{3} C_d A_o \sqrt{H_0} \sqrt{2g} \rho_a \left[1 - \frac{T_a}{T_g} \right]^{1/2} \left(\frac{H_n}{H_0} - \frac{H_s}{H_0} \right)^{1/2} \left(\frac{H_n}{H_0} + \frac{H_s}{2H_0} \right)$$

Heights H_n and H_S are to be determined. A two-zone model is required for this. A numerical approach is used for this.

Correlation by McCaffrey, Quintiere & Harkleroad:

McCaffrey, Quintiere and Harkleroad (1981) further explored the ventilation factor, and developed the famous MQH correlation.

Using energy balance, convective heat release rate is written as,

$$\dot{Q}_c = (\dot{m}_a + \dot{m}_f) c_p (T_g - T_a) + h_k A_T (T_g - T_a)$$

Here, A_T is the total internal surface area of the enclosure (walls, ceiling, floor), neglecting openings and h_k is a global heat transfer coefficient, which has been a subject of several experimental studies in compartment fire literature. Assuming h_k to be a constant and neglecting $\dot{m}_f$, since $\dot{m}_a >> \dot{m}_f$, $T_g - T_a = \Delta T$, is,

$$\frac{(T_g - T_a)}{T_a} = \frac{\Delta T}{T_a} = \frac{\dot{Q}_c}{(\dot{m}_a c_p + h_k A_T) T_a} = \frac{\dfrac{\dot{Q}_c}{\dot{m}_a c_p T_a}}{\left(1 + \dfrac{h_k A_T}{\dot{m}_a c_p}\right)}$$

MQH correlation:

Mass flow rate of air is proportional to $\rho_a A_0 (g H_0)^{0.5}$. Using this, the ratio of $\Delta T / T_a$ can be expressed as a function of two non-dimensional numbers.

$$\frac{\Delta T}{T_a} = f\left(\frac{\dot{Q}_c}{\rho_a A_0 \sqrt{g H_0} c_p T_a}, \frac{h_k A_T}{\rho_a A_0 \sqrt{g H_0} c_p}\right) = C X_1^N X_2^M$$

Here, C an empirical constant and exponents, N and M, are determined by experimental data, and X_1 and X_2 are non-dimensional numbers. More than 100 experimental fires (from eight series of tests involving gas burners, wood cribs, plastic cribs and liquid fuel fires) with size of the enclosures from conventional room fires to 1/8 size with varying construction material and with a wide range of thermal properties, were analysed by McCaffrey et al. (1981) to obtain the required correlation.

Specifically, the first non-dimensional number (X_1) is Zukoski number (ratio of fire power to enthalpy flow rate). MQH correlation is written as,

$$\frac{\Delta T}{T_a} = 1.63\left(\frac{\dot{Q}_c}{\rho_a A_0 \sqrt{g H_0} c_p T_a}\right)^{2/3}\left(\frac{h_k A_T}{\rho_a A_0 \sqrt{g H_0} c_p}\right)^{-1/3} \qquad (C)$$

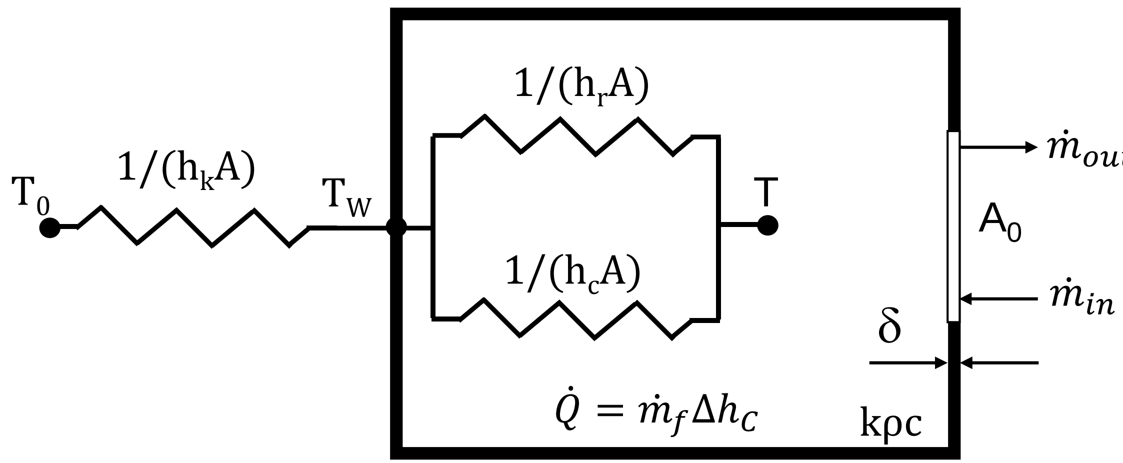
Using g =9.81 m/s^2, ρ_a =1.2 kg/m^3, T_a =293 K, c_p =1.05 kJ/kg-K, the expression is written as,

$$\frac{\Delta T}{T_a} = 6.85\left(\frac{\left(\dot{Q}_c\right)^2}{h_k A_T A_0 \sqrt{H_0}}\right)^{1/3} \qquad (D)$$

Here, T is in K, $\dot{Q}_c$ is in kW, h_k is in kW/m^2-K, A in m^2 and all length dimensions are in m. Further, correlation is valid only when upper gas layer temperature does not exceed 600ºC.

Determination of heat transfer coefficient:

In MQH correlation, determination of h_k is non-trivial. It depends on the duration of the fire and the thermal characteristics of the compartment boundary. Consider the figure below. Resistances for heat transfer, temperatures and mass flows through the opening are indicated. Wall thickness is δ and its thermal inertia is kρc.



In case where $T_w \approx T$, the heat flux is expressed (by solving transient heat conduction) as,

$$\dot{q}" = \frac{1}{\sqrt{\pi}}\sqrt{\frac{k\rho c}{t}}(T - T_a)$$

Here, characteristic burn time, $t < t_P$ ($= \delta^2/4\alpha$), the thermal penetration time, where α is thermal diffusivity ($k/\rho c$). Here, h_k is,

$$h_k = \sqrt{\frac{k\rho c}{\pi t}} \approx \sqrt{\frac{k\rho c}{t}}$$

For $t > t_P$, stationary conduction through wall occurs. For this,

$$\dot{q}" = (k/\delta)(T - T_a)$$

Here, $h_k = k/\delta$. For different wall materials, appropriate weighted areas and properties are to be used to sum up the value of h_k.

Flashover:

MQH correlation is also used to predict if a fire in an enclosure can cause flashover. A temperature rise of 500ºC in the upper layer gas is taken as a conservative criterion at the onset of flashover. Rewriting MQH correlation (equation C) to evaluate $\dot{Q}_c$:

$$\dot{Q}_c = \left(\sqrt{g}c_p\rho_a T_a^2 \frac{1}{1.63^3}\left(\frac{\Delta T}{T_a}\right)^3 h_k A_T A_0 \sqrt{H_0}\right)^{0.5}$$

Substituting g =9.81 m/s^2, ρ_a =1.2 kg/m^3, T_a =294 K, c_p =1.05 kJ/kg-K and ΔT = 500 K, the expression is written as,

$$\dot{Q}_c = \dot{Q}_{FO} = 620\left(h_k A_T A_0 \sqrt{H_0}\right)^{0.5}$$

$\dot{Q}_{FO}$ (kW) is the rate of heat release needed to produce flashover. Here, h_k is in kW/m^2-K, A in m^2 and H_0 is in m.

Fire severity – average smoke temperature:

Recall equation (D), where an empirical constant value of 6.85 has been used in the expression to determine $\Delta T/ T_a$. This value has been determined from experiments with fire sources located at the centre of the enclosure. In general, the equation is,

$$\frac{\Delta T}{T_a} = C_T \left(\frac{\left(\dot{Q}_c\right)^2}{h_k A_T A_0 \sqrt{H_0}} \right)^{1/3}$$

For corner fire, C_T = 12.4 and 16.5 for room linings. Here, $\dot{Q}_c$ is in kW, h_k is in kW/m^2-K, A in m^2 and H_0 is in m. The value of h_k can be either k/δ or $(k\rho c/t)^{0.5}$, as discussed earlier, based on whether $t > t_p$ or $t < t_p$. The quantity $A_0\sqrt{H_0}$ is called ventilation factor.