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 – 05

Lecture – 02

Module 3 – Review of Premixed and Diffusion Flames

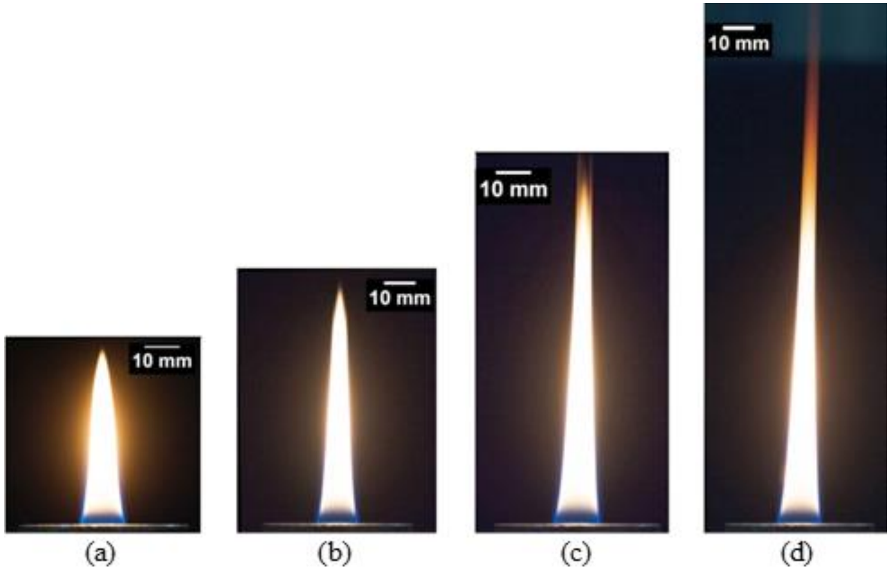
Diffusion flame – colours and length:

Consider a jet of gaseous fuel such as Liquefied Petroleum Gas (LPG), which is a higher order hydrocarbon fuel, injected from a port. A jet diffusion flame forms. In the laminar regime, as the flow rate of the fuel increases, the flame length also increases. Premixed flames display bright blue and non-luminous blue colours, the diffusion flames, display a range of colours including bright yellow or orange colour.

These are non-luminous near the burner rim, where fresh air from ambient mixes with the emerging fuel jet. Further upwards for burner exit, soot inception and its growth take place. The bright emission arises basically from soot radiation. Laminar jet diffusion flames are quite steady, even though tip oscillations are observed above a certain fuel flow rate. Based on the fuel and oxidizer supply, soot incepted may not be oxidized and soot particles may leave the flame tip as smoke.

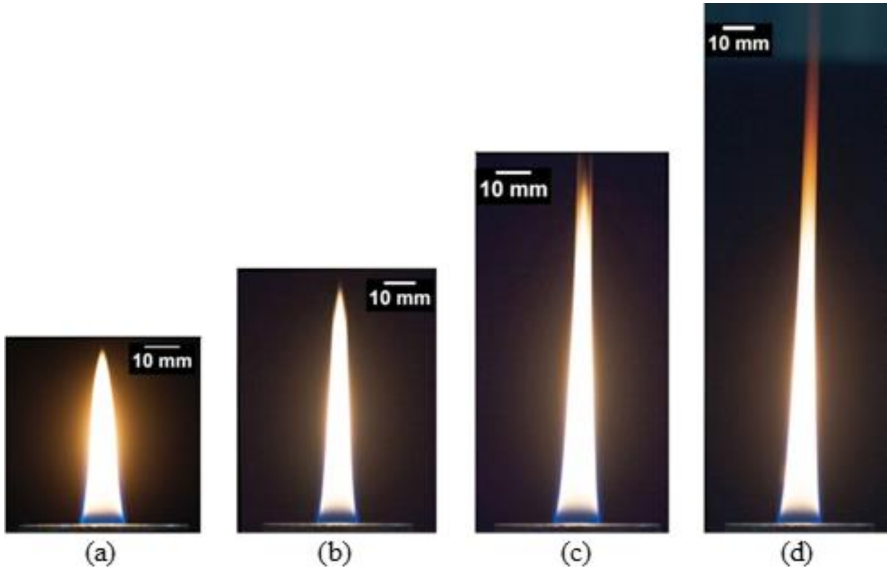
Soot formation and smoke point:

At low flow rates, soot incepted and formed would also get oxidized and there is no soot particles exiting out of the flame. At a given flow rate, the flame tip opens and soot particles leave. Flow rate at which visible smoke is exhibited from the flame tip is called smoke point. If soot is not oxidized within the flame, the tip opens up and smoke comes out.



Smoke points of various fuels:

Smoke point of saturated hydrocarbons such as propane and n-heptane is 7.87 mg/s and 5.13 mg/s, respectively. For unsaturated species such as propylene and acetylene, it reduces notably to 1.12 mg/s and 0.51 mg/s, respectively. For aromatics with cyclic structure, such as toluene, it is as low as 0.27 mg/s.

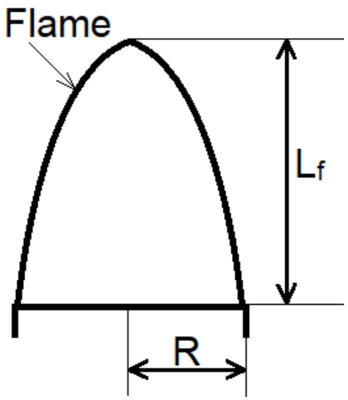


Diffusion flame length:

A diffusion flame is characterized by its visible length. A simple scaling analysis is done to understand the factors on which the length of a diffusion flame depends upon. When the reaction rates are much higher than the rates of diffusion and convection processes, the resultant reaction zone has almost zero thickness. For a jet diffusion flame, molecular diffusion is predominant along the radial direction and convection occurs along the axial direction.In the laminar regime, due to molecular diffusion, if the fuel molecules travel a distance y in the radial direction, then in terms of molecular diffusivity, D, y may be expressed using Einstein diffusion equation (average square displacement), as, $y^2 \sim 2Dt$.

Diffusion flame length – scaling analysis:

Since the distance travelled by the fuel molecule in the radial direction is of the order of the burner radius, R, here, y ~ R. Thus, $R^2 \sim 2Dt$, or $t \sim R^2/2D$. If v_e is the fuel jet velocity at the nozzle exit, the time taken for the fuel molecule to reach the flame height, L_f, is given by $t \sim L_f / v_e$.



This time should be same as that required for a fuel molecule to diffuse in the radial direction. That is, $R^2/2D \sim L_f / v_e$. Or,

$L_f \sim v_e R^2/2D$.

In terms of volume flow rate of fuel, $Q_F = \pi R^2 v_e$, flame height is:

$L_f \sim Q_F/2\pi D$.

In laminar regime, the flame height depends on Q_F, which is obtained by different combinations of R and v_e.

Diffusion flame regimes:

Flame Froude number (Fr) is defined as the ratio of initial jet momentum to the buoyant force experienced by the flame. Initial jet momentum is a function of jet exit velocity and the buoyant force is a function of the flame height itself. The acceleration due to buoyant force is: $\mathbf{a \sim 0.6g(T_f - T_\infty)/T_\infty}$.

Here g is acceleration due to gravity (9.81 m/s^2), T_f and T_∞ are flame and ambient temperatures, respectively.

Then, $\mathbf{Fr \approx (v_e)^2/(aL_f)}$.

If **Fr >> 1**, then the flame is momentum controlled, since the jet momentum is higher than the buoyant force experienced by the flame.

If **Fr ≈ 1**, both jet momentum as well as buoyant force control the flame.

When **Fr << 1**, then the flame is buoyancy controlled.

Laminar diffusion flame height correlations:

Roper proposed several correlations for flame height. Based on the experimental results for circular ports, the flame height in the laminar regime, whether it is in momentum or buoyancy-controlled regime, may be expressed as,

$$L_f = 1330\,\frac{Q_F(T_\infty/T_F)}{ln(1+1/S)}$$

Here, S is the **molar** stoichiometric oxidizer to fuel ratio, T_∞ is the oxidizer stream temperature, T_F is the fuel stream temperature and Q_F is the volumetric flow rate of the fuel.

For a hydrocarbon fuel, C_xH_y, the molar stoichiometric air to fuel ratio, S, is expressed in terms of x, y and mole fraction of O_2, as,

$$S = \frac{x + y/4}{X_{O_2}}$$