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 – 03

Module 3 – Review of Premixed and Diffusion Flames

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,

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

Laminar diffusion flame height correlations:

Laminar jet diffusion flame heights depend on type of fuel, diluents added to fuel stream, amount of air added to fuel stream, called the primary air, and so on. Flame length increases as H/C ratio of fuel decreases. As mole fraction of oxygen increases, flame length decreases. Even a small reduction in mole fraction of oxygen results in notable increase in flame length. For methane jet in a pure oxygen environment, flame length is around one-fourth of its value in air environment. When the fuel stream is diluted with inert gas such as nitrogen, the S is expressed using the mole fraction of the diluent, X_{dil}, as,

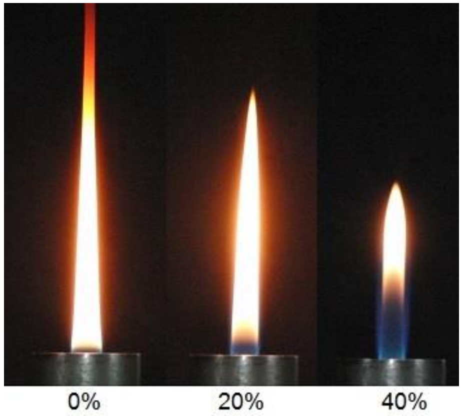
$$S = \frac{x + y/4}{[1/(1 - X_{dil})]X_{O_2}}$$

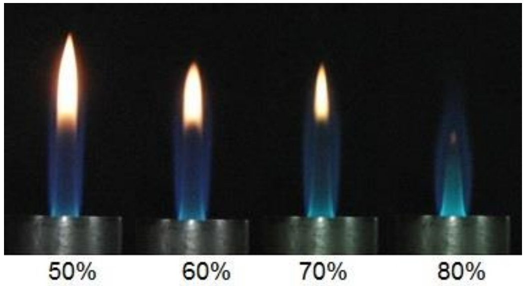
As X_{dil} increases, the flame length decreases.

Laminar diffusion flame height correlations:

When primary air is added to the fuel, the flame length decreases significantly. If X_{pri} is the fraction of the stoichiometric air supplied as the primary air, S_{fuel} is the value of S when fuel alone is supplied to the burner, then the modified value of S is given as,

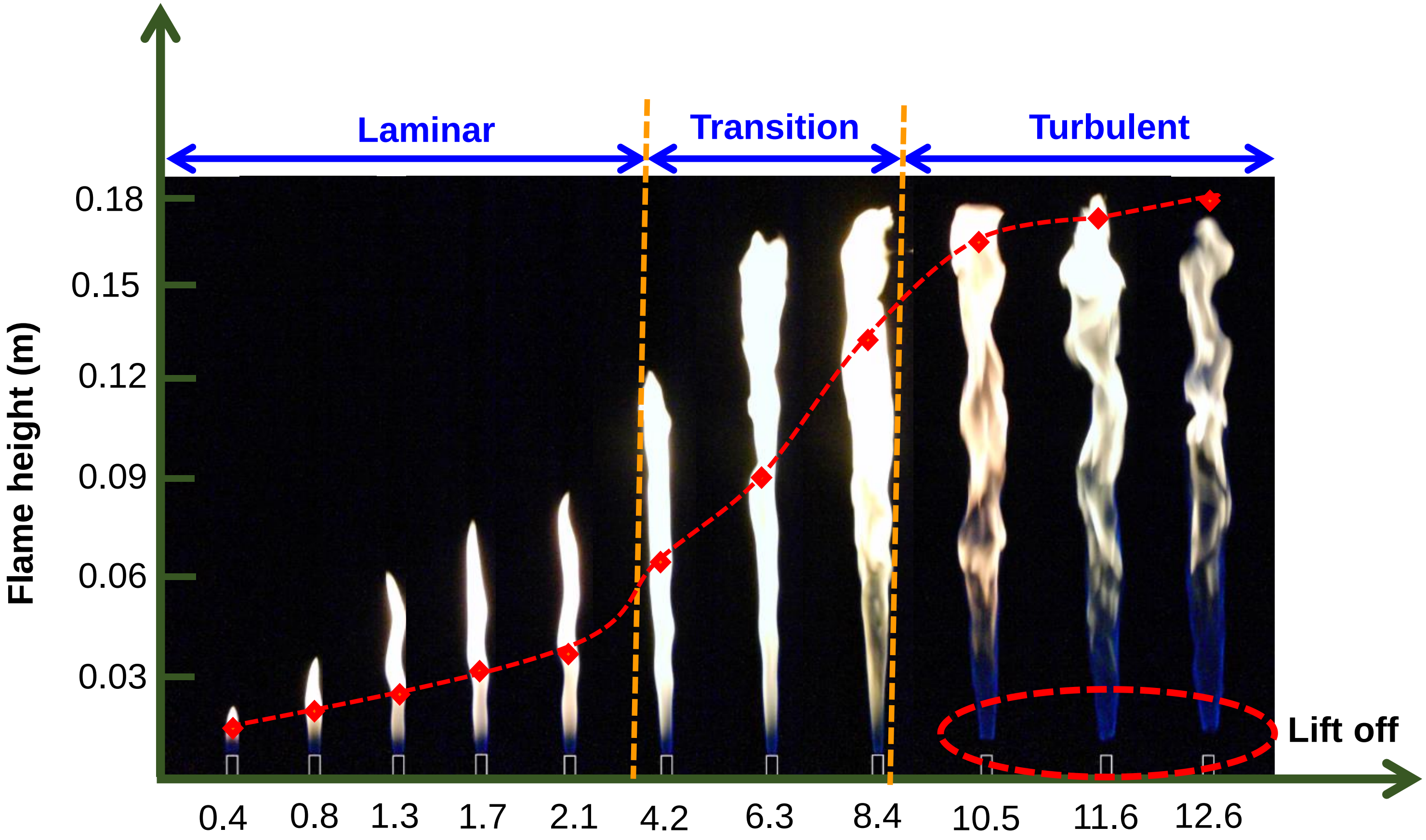
$$S = \frac{1 - X_{pri}}{X_{pri} + \left(1/S_{fuel}\right)}$$





To control sooty flames, some amount of primary air may be added along with the fuel. Mixture is not flammable when primary air < ~40%.

Jet Flames:



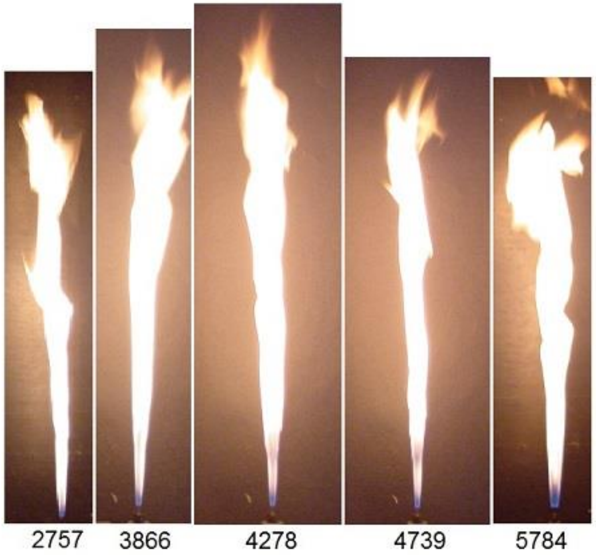
Roper, F. G., *"The prediction of laminar jet diffusion flame sizes: Part 1. Theoretical model."* Combustion and Flame, 29: 219-226 (1977)

Theoretical value;

$$L_{f,thy} = \frac{Q_F \left(\frac{T_\infty}{T_F}\right)\left(\frac{T_\infty}{T_f}\right)^{0.67}}{4\pi\, D_\infty\, ln(1+\frac{1}{S})}$$

Turbulent jet diffusion flames:

Turbulent jet diffusion flame is obtained when the fuel flow rate is increased beyond a critical value. Tip oscillations are observed in laminar diffusion flames, at this flow rate. At higher fuel flow rates, these tip oscillations are seen to propagate upstream, creating fluctuations over entire flame. A smooth laminar flame surface gradually transitions to a highly oscillatory turbulent flame, as shown in the instantaneous flame photographs.



Turbulent jet diffusion flames:

Oscillations are due to contribution of turbulent eddies of different scales to the mixing process. Also, the molecular level mixing process in a laminar flame is highly enhanced due to the turbulent eddies. Therefore, once the jet flow becomes fully turbulent, the turbulent flame length remains almost a constant. It may be noted, in the photos shown, that the flame lengths are almost the same for a wide range of Reynolds numbers. Further increase in the fuel flow rate results in an increase in the noise level of the flame. At another critical fuel flow rate, the flame lifts-off from the burner and sustains at a certain height from the burner exit. When the fuel flow rate is further increased, the lift-off height gradually increases and the flame eventually blows-off.

Turbulent jet diffusion flame height:

For turbulent flows, the molecular diffusivity, D, is replaced by turbulent mass diffusivity, which is expected to be of same order as that of turbulent eddy viscosity, ν_t. Further, the eddy viscosity may be expressed as the product of turbulent mixing length, ℓ_m and turbulent intensity, v'_{rms}. Using these, the turbulent jet diffusion flame height is written as,

$$L_{f,t} \approx \frac{vR^2}{\nu_t} \approx \frac{vR^2}{l_m v'_{rms}}$$

Turbulent mixing length is of the order of jet radius (integral scale) and maximum fluctuating component is of the order of jet velocity itself. Thus,

$$L_{f,t} \approx \frac{vR^2}{l_m v'_{rms}} \approx \frac{vR^2}{Rv} \approx \mathrm{R}$$