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

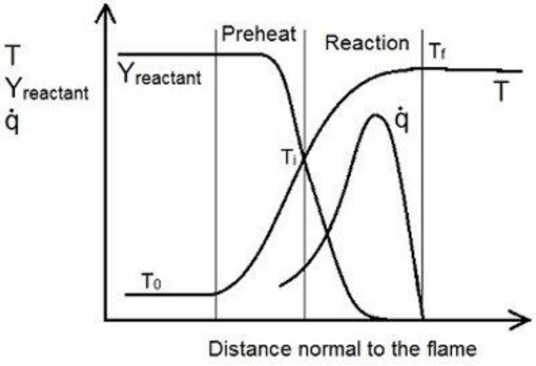
Week – 04

Lecture – 04

Module 3 – Review of Premixed and Diffusion Flames

Structure of premixed flame:

Premixed reactant approaches the flame in the direction normal to it. Due to heat transfer from flame, its temperature increases from initial value of T_0 to ignition temperature, T_i.



This zone is called the preheat zone. Reaction zone exists next to it. Reaction zone has a very small thickness; order of a milli-meter. Towards the end of the reaction zone, a bright or luminous zone is present. Here, the temperature is maximum (flame temperature, T_f).

Preheat and reaction zones:

Radicals such as H, O, OH and so on, are also transported from the reaction to the preheat zone. Reactants heated to the ignition temperature, react with these radicals through the chain initiation reactions, and enable the onset of chain propagation and chain branching reactions in the reaction zone. For lean to stoichiometric mixtures, this causes a reduction in the mass fraction of the reactants and a further rise in the temperature in the reaction zone. When the reaction proceeds and the reactants are consumed, by chain termination reactions, the heat release rate rapidly increases and attains a maximum value. As the major reactant species are consumed at this point, the heat release rate decreases to zero rapidly.

Formation of diffusion flame:

Recombination of the species occurs downstream of the reaction zone. Depending on the initial composition of the reactant mixture, a plume of burned gas or a diffusion (non-premixed) flame is present in this zone. Intermediate species are formed towards the end of preheat zone and are consumed before the end of the reaction zone. In the case of rich mixtures, the fuel transported out of the reaction zone burns in a diffusion flame mode.

Flammability limits:

In an isolated system, when the fuel and oxidizer are mixed in proper proportions and ignited using a localized high temperature source, sustained reaction may take place. Such a reactant mixture, in which a flame can be initiated is called a flammable mixture. In other words, any reactant mixture, which can burn without additional oxidizer or fuel, is called a flammable mixture.

A reactant mixture, based on the type of fuel or oxidizer used, will be flammable only in certain proportions and under certain conditions of temperature and pressure. The heat released during combustion will also vary based on the composition of the mixture. Limits of flammability are determined by using standard test procedures.

Flammability limits of various fuels:

Fuel	Volumetric % of fuel		% fuel in stoichiometric fuel
	Lower	Upper	
Methane	5.0	15.0	9.47
Propane	2.37	9.5	4.02
Butane	1.86	8.41	3.12
Heptane	1.0	6.0	1.87
Ethylene	2.75	28.6	6.52
Acetylene	2.5	80.0	7.72
Benzene	1.4	6.75	2.7
Hydrogen	4.0	74.2	29.5
Carbon monoxide	12.5	74.2	29.5
Methanol	6.72	36.5	12.2
Ethanol	3.28	18.95	6.52

Correlations for flammability limits:

Flammability limits are of practical interest in safety considerations because mixtures outside of these limits can be handled without concern for ignition. For most practical applications, though, the flammability limits are correlated using the heat of combustion as shown by Suzuki and Koide:

$$LFL = \frac{-3.42}{\mathit{\Delta} H_c} + 0.569\mathit{\Delta} H_c + 0.0538\mathit{\Delta} {H_c}^2 + 1.80$$

$$UFL = 6.30\mathit{\Delta} H_c + 0.567\mathit{\Delta} {H_c}^2 + 23.5$$

Heat of combustion is in kJ/mol and LFL and UFL are in vol% of fuel in air.

Premixed flame theories:

Following are used to analyse laminar premixed flames:

(1) thermal theory,

(2) diffusion theory and

(3) comprehensive theory.

Thermal theory assumes that the mixture is heated by conduction to a temperature at which the rate of reaction is sufficiently rapid and self-sustaining. Heat transfer from the flame alone is assumed to be sufficient. In diffusion theory, diffusion of active species such as atoms and radicals, from the reaction zone or the burned gas, into the unreacted mixture, is assumed to initiate the reaction as well as sustain it. In reality, both diffusion of heat and diffusion of active radicals into the preheat zone contribute to flame propagation. Such a detailed analysis is employed in the comprehensive theory.

Thermal theory:

Mallard and Le Chatelier postulated a two-zone model. In zone 1, the reactant mixture is preheated to a certain temperature, called the ignition temperature, and in zone 2, all the reactions are completed.Interface between these zones reaches ignition temperature (T_i). In zone 2, temperature reaches the flame temperature (T_f). Zone 1 is similar to the preheat zone; the slope of the temperature profile in this zone is assumed to be linear. Thickness of the zone 2 (reaction zone) be δ.

Energy balance in terms mass flow rate of reactants, its initial temperature, specific heat, thermal conductivity and flame thickness and its area is:

$$\dot{m}c_p(T_i - T_o) = \lambda \frac{\left(T_f - T_i\right)}{\delta} A$$

$$\dot{m} = \rho A u = \rho A S_L$$

$$S_L = \frac{\lambda}{\rho c_p} \frac{\left(T_f - T_i\right)}{\delta(T_i - T_o)}$$