Course Name: Theory of Fire Propagation (Fire Dynamics)

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Week – 05

Lecture – 04

Module 3 – Review of Premixed and Diffusion Flames

Height of a fire:

Fire is a turbulent diffusion flame fuelled by gas, liquid or solid materials. Its height can be determined using the heat release rate or burning rate or mass loss rate of the fuel. Similarly, when the height of the fire is measured, its heat release rate can be estimated. A few empirical correlations are listed below.

Thomas et al. (1961):

$$L_f = 42D\left[\frac{\dot{m}''}{\rho_a\sqrt{gD}}\right]^{0.61}$$

Heskestad (1983):

$$L_f = 0.23[\dot{Q}]^{\frac{2}{5}} - 1.02D$$

For wall fires:

$$L_f = 0.174\left[c\dot{Q}\right]^{0.4}$$

L_f = flame or fire length (m)

D = Fire diameter (m)

$\dot{m}''$ = mass burning rate flux (kg/m^{2}s)

$\dot{Q}$ = Heat release rate (kW)

c is an empirical constant

ρ_a is the density of air (kg/m^3)

Thermophysical properties:

Density, ρ, dynamic viscosity, μ, thermal conductivity, λ, specific enthalpy, h, specific heat at constant pressure, c_p and mass diffusivity, D, are the important physical and thermal properties used in calculations. These properties strongly depend on temperature. Density is calculated using the ideal gas equation of state using the mixture molecular weight. Dynamic viscosity, thermal conductivity, specific enthalpy and specific heat at constant pressure for each species in the mixture are calculated as a function of temperature. Subsequently, the corresponding mixture property is calculated based on the mass fractions of the constituents of the species. Mass diffusivity of each species for its diffusive transport into the mixture is calculated as a function of temperature and pressure.

Important non-dimensional numbers:

Diffusion coefficients: Mass diffusivity, D, kinematic viscosity, $\nu = \mu/\rho$, thermal diffusivity, $\alpha = \lambda/(\rho c_p)$, are important transport properties having unit of m^2/s.

Nondimensional numbers are formulated with these properties:

Lewis number (Le) is the ratio of rate of energy to mass transport, α/D

Prandtl number (Pr) is the ratio of rate of momentum to energy transport, ν/α

Schmidt number (Sc) is the ratio of rate of momentum to mass transport, ν/D

Two assumptions are commonly made to simplify the analysis:

(1) Le = 1; Pr = 1 and Sc = 1, implying $\nu = \alpha = D$. Here, D is equal for all the species.

(2) Specific heat, c_p, is same for all species.

Controlling factors in combustion or fires:

Three categories controlling the combustion phenomena:

Primarily controlled by chemical kinetics; examples: ignition, explosion, extinction and quenching of flames. Controlled by physical mixing processes like diffusion, flow and turbulence; examples: pool fires, open fires, flames from gaseous fuel jet, liquid fuel spill (film), spray or droplets, combustion of a carbon particle and burning of a candle. Controlled by both kinetics and physical mixing; examples: compartment fires, flames from Bunsen burner, gasoline engine and partially premixed flames.

Time scales and Damköhler number:

Characteristic chemical time (t_C) is the time taken for the reactant to reach 1/e of the initial concentration, at a given temperature. Another characteristic time is the residence time (t_R) of the reactants.

For diffusion dominated transport (low flow velocity), residence time or physical time of the species is represented by L^2/D, where L is the characteristic length and D is the mass diffusion coefficient.

In a convection dominated transport, physical time or flow residence time is defined as the ratio of characteristic dimension (L) to the flow velocity (U) = L/U.

An important non-dimensional number, Damköhler number (Da), is defined as the ratio of the chemical time to the physical or residence time.

Effects of Damköhler number:

If $t_C \gg t_R$, the combustion phenomena is kinetically controlled.

When reactants are thoroughly mixed, the gradients in species and temperature are zero. Here, the rate of the depletion of the reactant mixture is dictated by the chemical kinetics.

Damköhler number, **$Da = t_c/t_R \gg 1$** (is large).

If $t_C \ll t_R$, the combustion phenomena is transport controlled.

Here, reactants are mixed only at the flame zone and gradients in species are significant. Rate of the depletion of reactants is dictated by the relatively slower transport rate of reactants into the flame zone, and chemical kinetics is much faster.

Damköhler number, **Da =** $\mathbf{t_c/t_R \ll 1}$ (is small).

If $\mathbf{t_C \approx t_R}$, the combustion phenomena is controlled by both.