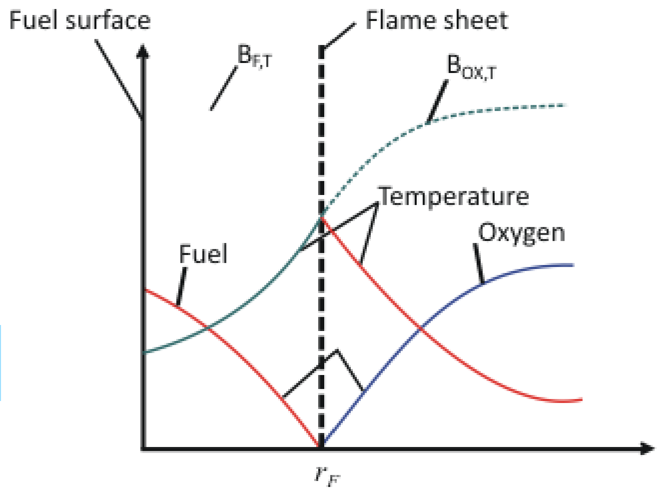
Module 6: Diffusion Flame

Lecture 32: The Temperature Profile

The Lecture Contains:

The Temperature Profile

- No oxygen exists in the inner flame region.
- No fuel exists in the outer region of flame.
- Using the transfer function for fuel and oxidizer,



(Figure 32.1)

Temperature profile for the inner region,

$$\frac{\dot{m}_F'' r_s^2}{\rho\alpha}\frac{1}{r} = ln\left[\frac{C_P(T_\infty - T_s) + \Delta\widehat{H}_C f Y_{Ox,\infty} + Q_V}{C_P(T - T_s) + Q_V}\right]$$

Rearranging the above equation,

$$C_P(T - T_s) = \left[C_P(T_\infty - T_s) + \Delta\widehat{H}_C f Y_{Ox,\infty} + Q_V\right] \times exp[-(\dot{m}_F'' r_s^2)/\rho\alpha r] + \Delta\widehat{H}_C - Q_V$$

Temperature profile for the outer region,

$$C_P(T - T_s) = \left[C_P(T_\infty - T_s) - \Delta\widehat{H}_C + Q_V\right] \times exp[-(\dot{m}_F'' r_s^2)/\rho\alpha r] + \Delta\widehat{H}_C - Q_V$$

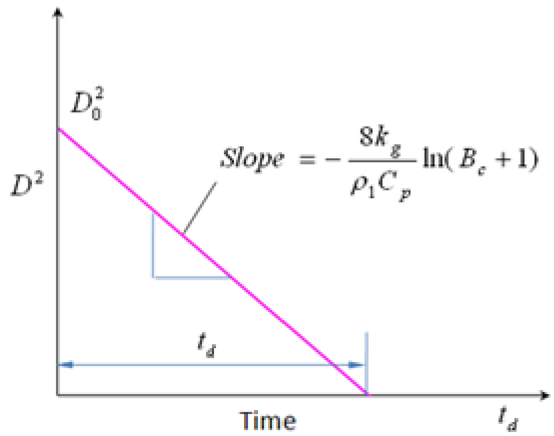
Droplet Burning Time

Importance of droplet burning time:

Essential for desining combustion chamber
For complete combustion, residence time > life time of largest droplet in spray.

Factors dictating residence time of droplet:

- Air stream velocity
- Droplet velocity
- Fuel injection angle
- Combustor geometry



(Figure 32.2)

Continuity equation at the surface of the droplet:

$$-\frac{dm_D}{dt} = -\dot{m}_F \qquad \text{-------(1)}$$

Droplet mass is evaluated as follows,

$$m_D = \rho_1 V = \rho_1 \pi D^3/6 \qquad \text{-------(2)}$$

Where, D is the droplet diameter at any instant

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Droplet Burning Time (Contd.)

Recall,

$$\dot{m}_F'' = \frac{\rho\alpha}{r_s} ln(B_c+1)$$ -------(3)

Using (1) & (2) in (3),

$$D\frac{dD}{dt} = \frac{-4k_g}{\rho_l C_P} ln(B_c+1)$$ -------(4)

Expressing droplet diameter in terms of D^2,

$$\frac{dD^2}{dt} = \frac{-8k_g}{\rho_l C_P} ln(B_c+1)$$ -------(5)

Burning constant for typical hydrocarbons

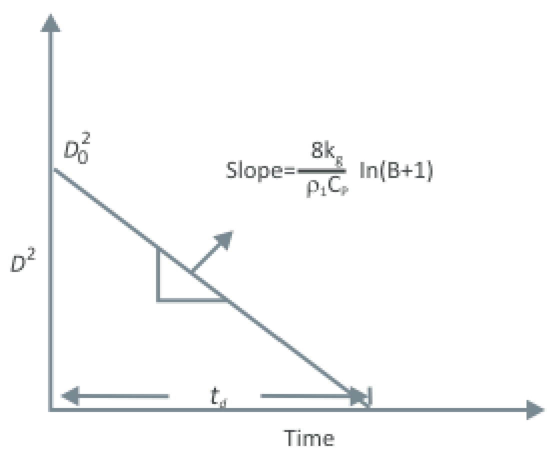
Fuel	k 10^{-7} m^2/s (Calculated)	k 10^{-7} m^2/s (Measured)
Ethyl alcohol	9.3	8.1
N-Heptane	14.2	9.7
ISO-Octane	14.4	9.5
Kerosene	9.7	9.6
Benzene	11.2	9.7
Toluene	11.1	6.6

In this expression, D^2 varies linearly with time (See figure 32.3). Slope of the plot is the burning rate constant, K

$$K = \frac{8k_g}{\rho_l C_p} ln(B_c+1)$$ -------(6)

Integrating (5) with time,

$D^2(t) = D_0^2 - Kt$ is D^2 law



(Figure 32.3)

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Droplet Combustion in Convective Environment

In practical devices, both free and forced convection will prevail,

Flow past the fuel droplet for Re > 20

- Front portion of the droplet – Boundary layer.
- Rear portion – Wake region

In practical devices, forced convection is more predominant

Boundary condition at the droplet surface,

$$\bar{h}_c \Delta T = \rho_s V_s \Delta \hat{H}_V = \frac{\dot{m}_F}{4\pi r_s^2}\Delta \hat{H}_V = \frac{\rho \alpha}{T_s} ln(1+B_c)\Delta \hat{H}_V \qquad \text{-------(1)}$$

Where,

$$\Delta T \approx \frac{f_{stoi} Y_{Ox,\infty}\, \Delta \hat{H}_C}{C_p} + (T_\infty + T_s) \qquad \text{-------(2)}$$

$\bar{h}_c$ - Convective heat transfer coefficient

Combining the above two expressions,

$$\bar{h}_c \left(\frac{f_{stoi} Y_{Ox,\infty} \Delta \hat{H}_C + C_p (T_\infty + T_s)}{C_p} \right) = \frac{\rho \alpha}{T_s} ln(1+B_c)\Delta \hat{H}_V = \frac{k_g}{C_p T_s} ln(1+B_c)\Delta \hat{H}_V \qquad \text{-------(3)}$$

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Droplet Combustion in Convective Environment

Rearranging the above equation,

$$\frac{\bar{h}_c r_s}{k_g} = \frac{ln(1+B_c)}{f_{stoi} Y_{Ox,\infty} \Delta\hat{H}_C + C_P(T_\infty + T_s)/\Delta\hat{H}_V} \qquad \text{-------(4)}$$

$$N_{u_{r_s}} = \frac{ln(1+B_c)}{B_c} \qquad \text{-------(5)}$$

For high Reynolds number,

$$N_{u_{r_s}} = \frac{ln(1+B_c)}{B_c}\left[1 + 0.39\, Pr^{0.33} Re_{r_s}^{0.5}\right] \qquad \text{-------(6)}$$

For unit Prandtl number, *Re* >> *Pr*,

$$N_{u_{r_s}} = 0.39 Re_{r_s}^{0.5} \frac{ln(1+B_c)}{B_c} \qquad \text{-------(7)}$$

Droplet Combustion in Convective Environment

$$\frac{\bar{h}_c r_s}{k_g} = \frac{\rho_s V_s r_s}{\mu} \frac{\Delta \hat{H}_V}{\left[f_{stoi} Y_{Ox,\infty} \Delta \hat{H}_C + C_P (T_\infty + T_s)\right]} \frac{C_P \mu}{k_g} = \frac{\rho_s V_s r_s}{\mu} \frac{Pr}{B_c} \qquad \text{-------(8)}$$

Then Eq. (7) becomes,

$$\frac{\rho_s V_s r_s}{\mu} = 0.39 Re_{r_s}^{0.5} ln(1 + B_c)$$

- The above expression would not provide accurate prediction
- Wake region behind the droplet is not considered here.
- For predicting the experimental data, the above expression is modified as,

$$\frac{\rho_s V_s r_s}{\mu} = 0.39 Re_{r_s}^{0.5} \frac{ln(1 + B_c)}{B_c^{0.15}} \qquad \text{-------(9)}$$

Under convective condition, laminar droplet burning rate follows $D^{3/2}$

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