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 – 06

Lecture – 02

Module 4 – Burning of Liquid Fuels

Steady evaporation – Spalding numbers:

Mass evaporation rate from mass transfer and energy transfer should be the same, That is,

$$\dot{m}'' = \frac{\rho D_{AB}}{L} ln(1 + B_Y) = \frac{k_g}{c_p L} \ln\left(1 + B_q\right)$$

Here, $\mathbf{B_q}$ and $\mathbf{B_Y}$ are written as,

$$B_q = \frac{c_p(T_\infty - T_s)}{h_{fg}}, B_Y = \frac{(Y_{A,i} - Y_{A,\infty})}{(1 - Y_{A,i})}, (1 + B_Y) = (1 + B_T)^{Le}$$

Here, $\mathbf{Le = \lambda/(\rho D_{AB} c_p)}$. Based on ambient temperature (T_∞), liquid fuel surface attains an equilibrium temperature (T_s), close to the saturation temperature; thermodynamic equilibrium prevails. Partial pressure or mole fraction of fuel vapor at the interface is calculated using equations such as Clausius-Clapeyron equation.

Equilibrium under steady evaporation:

Mass fraction of the fuel at the interface may be evaluated from:

$$\boldsymbol{Y_{A,i} = 1 - \frac{1 - Y_{A,\infty}}{\left(1 + \frac{c_p(T_\infty - T_s)}{h_{fg}}\right)^{Le}}} \qquad (\boldsymbol{C})$$

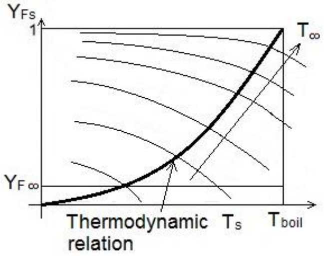
It is clear that when T_∞ tends to infinity or h_{fg} tends to zero, $Y_{A,i}$ tends to unity. Since $Y_{A,i}$ is a function of T_s, it is evaluated by solving equation (C) along with a thermodynamic relation such as Clausius - Clapeyron equation, which is written using h_{fg}, specific gas constant of the fuel and its boiling point, T_{boil}.

$$\boldsymbol{X_{A,i} = \frac{p_{sat}}{p} = \exp\left(-\frac{h_{fg}}{R}\left[\frac{1}{T} - \frac{1}{T_{boil}}\right]\right)} \qquad (\boldsymbol{D})$$

Interface quantities:

The equilibrium temperature, T_s, for various values of the ambient temperature, may be determined using the below procedure:

First a value of T_s is assumed. Using the thermodynamic relation {equation (D)}, the saturation pressure at T_s is evaluated. The mole- and mass-fractions of the fuel at the droplet surface are calculated. The values of B_q and B_Y are calculated. Substitute these values in Equation (C) and determine if the equation is satisfied. If Equation (C) is not satisfied, the value of T_s is adjusted and steps 2 to 5 are repeated until Equation (C) is satisfied.



The equilibrium temperature, T_s, for various values of the ambient temperature is shown in the figure. Thick black line is equation (D). Equilibrium surface temperatures are the intersections of curves of a thermodynamic relation and those obtained by solving Equation (C) at different ambient temperatures.

Piloted ignition of liquid fuel pool:

An external heat source provides the necessary heat for the liquid surface to reach its flash point from its initial temperature. Fuels with flash point lower than the ambient temperature, such as gasoline, n-heptane and methanol, will have enough vapours adjacent to their surface to mix with the ambient air, without the need of an additional heat source as above for sensible heating. The reactant mixture formed over the liquid surface, when it is at its flash point, is ignited by an ignition source and a momentary premixed flame is formed. After this flash formation, it takes a while to form the reactant mixture again and to cause a premixed flame to show up with the help of the ignition source.

Piloted ignition criteria:

For the occurrence of ignition, sufficient volume of reactant mixture (fuel vapor + air) should form over the liquid surface and it should be flammable (exists within the flammable limits defined for the fuel). When a heat source with sufficient energy (called minimum ignition energy) is introduced to this mixture, ignition takes place. That is, for piloted (using an external heat source) ignition to occur, the requirements are the presence of minimum volume of a flammable mixture and an ignition source with sufficient energy. Ignition location also plays an important role. Ignition cannot occur too close to fuel surface. Similarly, it cannot be too far. Standard test procedure is used to determine the ignition delay, the igniter is kept at a particular location above the fuel surface.

Piloted ignition – factors affecting:

Fuel surface at its fire point has enough vapours to sustain a diffusion flame over its surface. As a result of this flame, certain quantity of heat is released. If the quantity of heat released is more than the heat losses to the ambient, then the combustion becomes sustainable. Ignition source may now be removed. It is difficult to ignite a liquid fuel with a high fire point (crude oil) using a pilot flame. A low flash point liquid is used in required quantity during ignition. A wick (made of low thermal conductivity material) may be placed over the liquid surface to facilitate ignition.

Auto ignition:

When fuel vapor and air mixture is exposed to a temperature called auto-ignition temperature, the mixture is ignited without the need of an external ignition source. A common example for this is the flame formation on the surface of over-heated cooking oil kept on a frying pot that is being heated underneath. In practice, the liquid fuel or flammable solvent coming into contact with a hot surface of a machinery component, evaporates and produces vapor at a higher temperature that mixes with air. Temperature of the mixture sometimes exceeds the auto-ignition temperature and, depending upon the temperature of the hot surface, the mixture self-ignites. Auto-ignition temperatures are determined by a standard test using the Setchkin apparatus under idealized conditions.