Course Name: Theory of Fire Propagation (Fire Dynamics)

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Week – 07

Lecture – 05

Module 5 – Burning of Solid Fuels

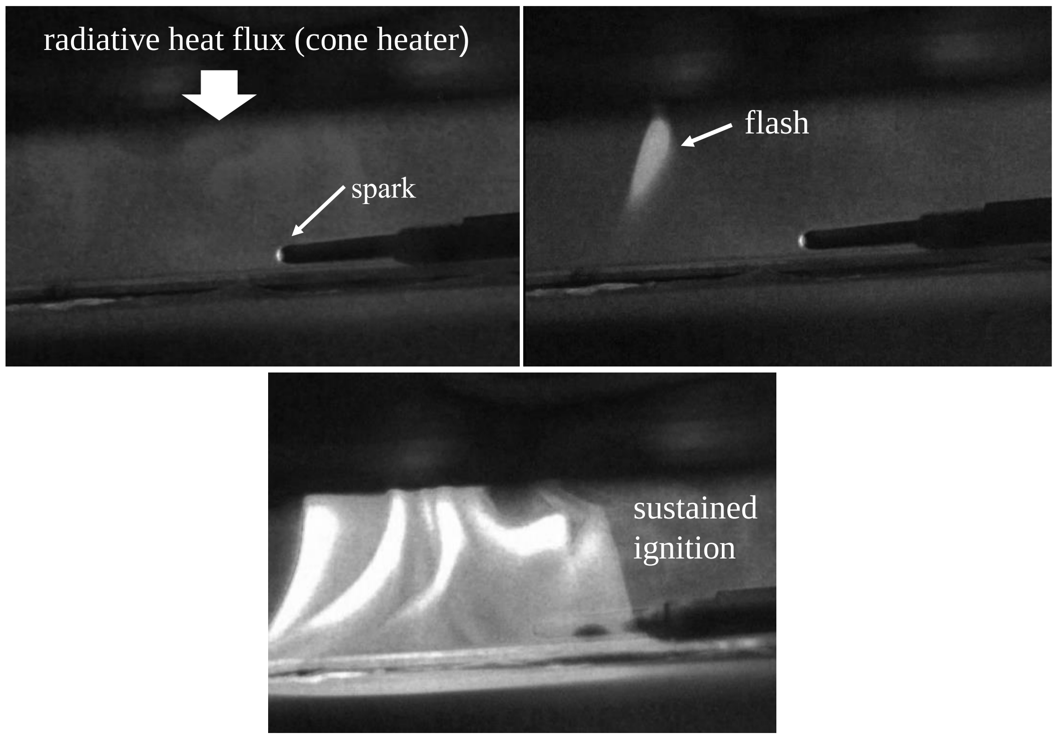
Types of ignition:

Solids are classified as charring and non-charring types. Wood is an example of charring type solid. Polyethylene is an example for non-charring type. Wood is a heterogeneous solid having moisture, volatiles (trapped gases), solid carbon and inert mineral (ash). Upon heating moisture and volatiles are released at appropriate temperatures of ≈ 100°C and ≈ 350°C – 400°C, respectively. Volatiles mix with ambient air and if this mixture is within flammability limits, it may be ignited using a pilot flame (piloted ignition) or if its temperature is more than Auto Ignition Temperature (AIT), auto ignition occurs. Fixed carbon, when heated to a temperature of ≈ 900°C, oxygen from ambient reaching its surface reacts. This surface reaction is called glowing ignition, as carbon displays radiant red colour.

Non-charring solids, which are mostly polymers, do not produce the carbon (char) upon devolatilization. Polymer has a softening temperature and melting temperature, apart from the pyrolysis temperature. When the solid is heated to pyrolysis temperature, gas leaves the material. Polymers like polyethylene and PMMA melt and vapours form.The gas and vapours leaving the solid upon heating need not be the pure monomer component and can be multi-component in nature. The gas mixture leaving the solid must achieve the Lower Flammability Limit (LFL) of that mixture to be ignited in piloted ignition or must be in at a flammable concentration and at AIT to cause autoignition.

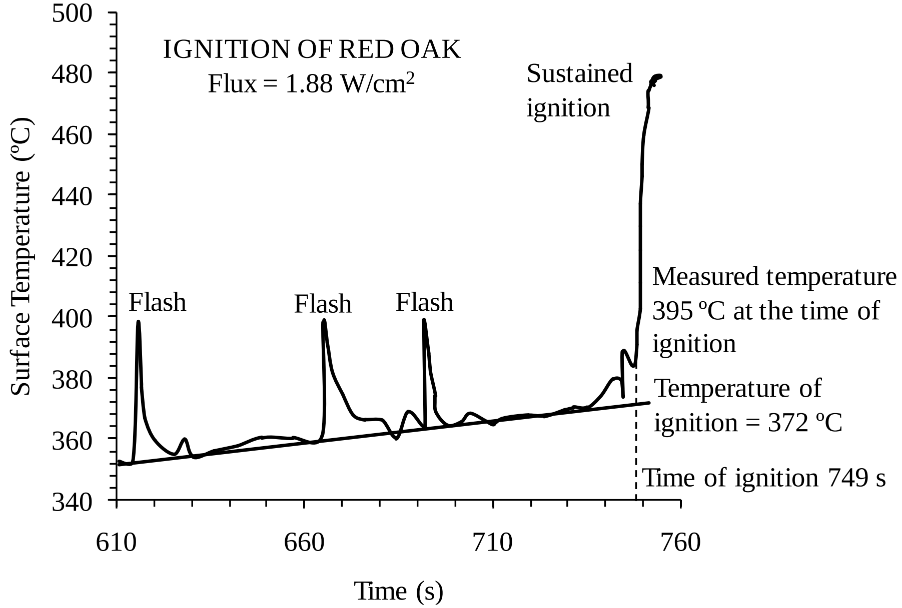
Piloted ignition of a solid fuel:

Photographs show piloted ignition of a solid fuel sample imposed with a radiative heat flux from above.



Piloted ignition – surface temperature profile:

Surface temperature vs. time for a red oak sample exposed to radiative heat flux of 1.88 W/cm^2. [Atreya and Wichman (1989)].



Red oak sample flashes 3 times until the temperature of its surface reaches a critical value, leading to sustained flaming. Ignition occurs when the temperature of the surface is around 485ºC, and critical mass flux is generated.

Thermally thin or thermally thick solid:

Surface temperature of a solid material is an important parameter for ignition. It should reach pyrolysis or ignition temperature. This varies as a function of incident heat flux, material properties as well as its physical thickness (t_p). Solid fuel is classified as thermally thin using the criterion:

$$\boldsymbol{t_p \leq \frac{2k\left(T_{ig} - T_{\infty}\right)}{\dot{q}_i''}}$$

Here, k is thermal conductivity, T_{ig} is ignition temperature, T_∞ is the ambient temperature and $\dot{q}_i''$ is the incident heat flux. For example, if $\dot{q}_i''$ is 10 kW/m^2, k is 0.15 W/m-K and ($T_{ig} - T_\infty$) is about 300°C, then t_p should be less than ≈ 9 mm for the solid to be thermally thin. For 50 kW/m^2, this criteria becomes ≈1.8 mm.

Ignition of thermally thick solid:

Ignition time for thermally thick solid depends on heat conduction within the solid. Governing equation for solving this problem is written as:

$$\boldsymbol{\rho_s c_s \frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial x^2}}$$

Here, ρ_s, c_s and k_s are density, specific heat and thermal conductivity of the solid, respectively. This equation requires one initial condition and two boundary conditions. Initial condition specifies initial temperature of the solid. Specified heat flux, zero heat flux, specified temperature and convective condition, are possible boundary conditions. Heat loss is usually specified as a fraction of incident heat flux. Overall heat transfer coefficient (convection + radiation) is also specified.

Ignition of thermally thick solid – some cases:

Constant Surface Heat Flux on one side of semi-infinite solid

$$-k_s \frac{\partial T}{\partial x}\bigg|_{x=0} = \dot{q}_s''$$

Constant Convective Heating on one side of semi-infinite solid

$$-k_s \frac{\partial T}{\partial x}\bigg|_{x=0} = h(T_\infty - T_{x=0})$$

Constant Surface Heat Flux and Convective Cooling on one side of semi-infinite solid. In all these, initial condition is: $T(x, 0) = T_i$.

$$-k_s \frac{\partial T}{\partial x}\bigg|_{x=0} = h_T(T_\infty - T_{x=0}) + \dot{q}_s''$$

$$h_T = h + \frac{\varepsilon\sigma\,(T(0,t)^4 - T_\infty^4)}{T(0,t) - T_\infty}$$

For these cases, analytical solution is available.