Fundamentals of Combustion for Propulsion
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Lecture - 31
Summary - non-premixed flames

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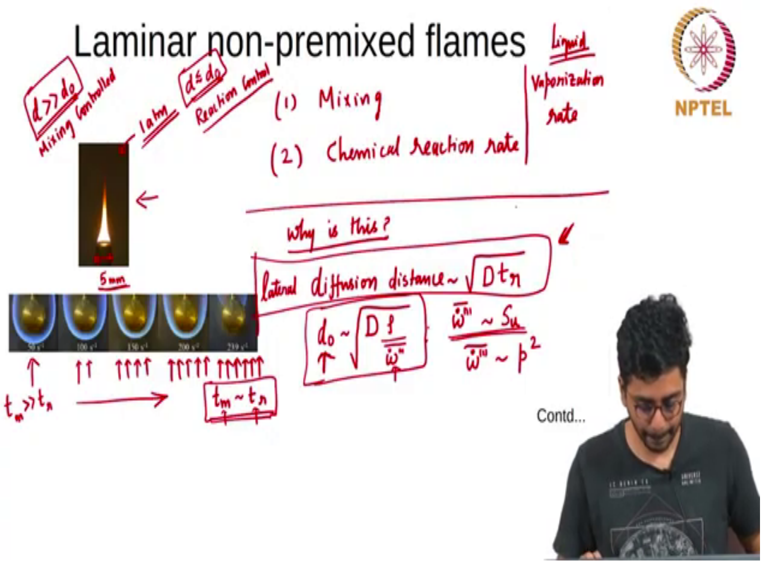

Laminar non-premixed flames

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Let us move onto laminar non premixed flames. Unlike premixed flames where we could clearly show that the quantity that matters the most is the laminar flame speed. And it can be in a very simple way directly related to the average reaction rate. Unlike that in non premixed flames the consumption rate of the fuel is a complex function of many processes. Including the rate of mixing, chemical reaction rate and when the fuel is not in gaseous form and it is in lets say in liquid form. The vaporization rate can also control the fuel consumption rate or liquid fuels.

In fact, you we could say that in propulsion systems using liquid fuels. Where the fuel is introduced as a fine spray into the combustion chamber invariably its the vaporization time of the droplets that controls the fuel consumption rate. Every other process including mixing, ignition and the rate of chemical reaction the timescale associates associated with these processes are usually much much smaller than the timescale of vaporization.

And therefore, most propulsion systems in fact, all propulsion systems using liquid fuels are designed for designed by keeping in mind that it is the vaporization time that is the rate limiting ok. that is the statement that can be made that is generally true ok

But of course, there are situations where this is not I mean if we if you are not thinking about liquid propulsion systems if you look at composite solid propellants. And other example that we discussed in detail in the course we saw that whether the burn rate of particular a p particle size is controlled by chemical reaction rate or by mixing is a function of pressure and a p particle size why is this?

We use the simple example of an ethylene jet diffusion flame to explain this idea. In the picture that is shown here the diameter of the ethylene jet if i remember right? Is about 5 millimeters and the ethylene jet is issuing in two ambient which is at 1 atmosphere and contains air. So, the ambient pressure is 1 atmosphere ok.

So, the key thing to decide what controls the consumption rate of the fuel in a non-premixed situation is the diffusion distance or the lateral diffusion distance. What is the lateral diffusion distance? It is nothing, but if you consider the ethylene jet issuing out of this tube it is the distance that ethylene can diffuse out and air can diffuse in and ethylene and air can start mixing ok. The distance that ethylene can move out before it starts reacting ok. So, it is the reaction rate controlled diffusion distance. So, that is nothing, but square root of the diffusion coefficient multiplied by the reaction time ok.

And let me denote this lateral diffusion distance as d 0 is proportional to D the reaction time is density divided by the average reaction rate this is the reaction time. This is equal to D rho divided by D rho divided by the reaction rate goes as a exponential let me not go into those details probably it is not. We saw that omega dot triple dash bar is related to the flame speed let me just say that ok.

So, the message that I want to give is that, the more reactive a fuel oxidizer mixture is the smaller is the diffusion distance of course, d the diffusion coefficient also has a role for example, if you take hydrogen air mixture hydrogen has very low diffusivity, but we should also keep in mind that hydrogen air mixture is lot more reactive than methane air mixture. And as it turns out the net effect the inc the d 0 tends to go up because the diffusion coefficient is going up.

It will go down because the reaction rates are higher. The net effect seems to be that the d 0 actually is lower for hydrogen air mixtures compared to methane air mixtures simply because the effect of reaction rate over and length overwhelms the effect of the increase in the diffusion coefficient ok. So, larger the diffusion distance rather larger the reactivity smaller is the diffusion distance.

And this simple measure or this simple length scale can be used to decide whether the fuel consumption rate in a non premixed situation is controlled by mixing or by reaction rate? The criteria is very simple if the for example, in this particular case where we are looking at an ethylene diffusion flame. If the diameter of the jet is much much greater than diffusion distance then we do not have to worry about lateral diffusion. The phenomena is simply controlled by mixing rate alone. On the other hand if d is comparable or less than d 0 then we have reaction control we have reaction control.

And with this simple expression now we can actually figure out under what conditions or under a given condition if a particular premixed non premixed situation is diffusion controlled or mixing controlled. Typically at atmospheric pressures and a fuel jet diameters of the order of a few millimeters the non premixed flame is controlled only by mixing only by diffusion. For it to become a reaction controlled flame what we need to do we need to increase the diffusion distance has to increase compared it has to become comparable to the diameter of the fuel jet.

And for that to happen the average reaction rate has to decrease substantially we know that omega dot triple dash is goes as p squared and therefore, if we decrease the pressure the reaction rate will decrease. And at a particular pressure d 0 will become comparable to d. And the non-premixed flame will become reaction controlled. This is one way that a non premixed mixing controlled flame can be converted into a non premixed reaction controlled flame.

Another strategy is to simply keep decreasing the diameter of the fuel jet till it becomes comparable to d 0. And that is what is that is what typically happens in a composite solid propellant because we have ammonium perchlorate particles which have a size ranging from as small as a 0.5 micron to as large as 500 micron. And therefore, it is possible that even under non premixed situation smaller particles will tend to behave like premixed particles or controlled by premixed reaction rates ok.

So, the key idea is the idea of lateral diffusion which is measured as the reaction rate limited diffusion distance and the relative magnitudes of the length scale of the system and the diffusion distance determines whether a non premixed flame is diffusion controlled or reaction controlled.

Here I have shown this is also an an other example that we discussed in class this is methane fuel is issuing out of the cylinder and air is flowing pass the cylinder from the bottom. When the air flow rates are low we have this nice blue envelope flame which is mixing controlled. And as the airflow rate is slowly increased the airflow rate is increased there comes a point at which as the airflow rate is increased the time for mixing. Here t mixing is much much greater than t reaction as you keep increasing the airflow rate there comes a point where t mixing becomes comparable to t reaction ok.

And we end up supplying reactants to the reaction zone at a rate that is larger than the rate at which consumption can happen because of the this the flame extinguishes. This is called flame extinction. And the nice envelope flame which was at the stagnation point of this cylinder has extinguished and it has moved to the beak. So, this is an other situation where its possible to make the mixing time comparable to reaction time. And the flame structure depends becomes dependant on the reaction rate ok.

So, to quickly summarize key idea is lateral diffusion it can either be the key idea is lateral diffusion which is a strong function of pressure. And if the typical length scale if the relevant length scale is much greater than d 0. The dynamics is mixing controlled if d becomes comparable or smaller than d 0. Than the reaction rate starts playing the role ok. That is as far as laminar non premixed flames are concerned.

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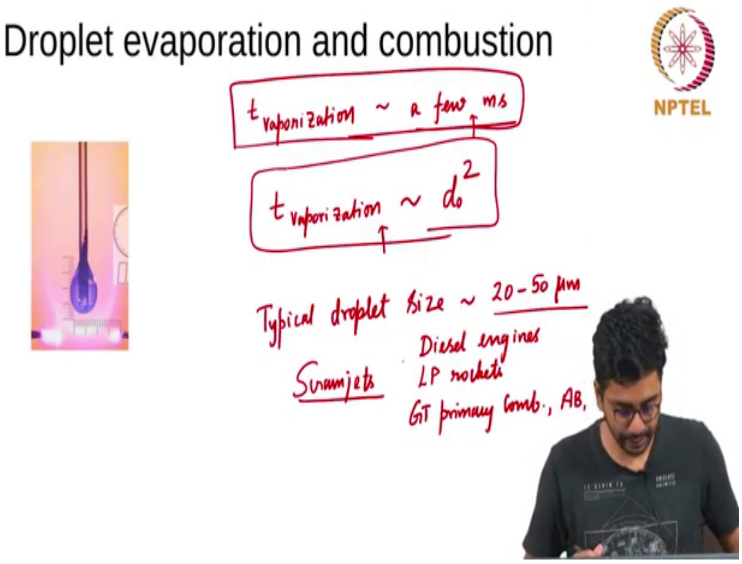

Droplet evaporation and combustion

$\boxed{t_{\text{vaporization}} \sim \text{a few ms}}$

$\boxed{t_{\text{vaporization}} \sim d_0^2}$

Typical droplet size ~ 20 - 50 μm

Scramjets

Diesel engines
LP rockets
GT primary Comb., AB,

I will also quickly tell you what happens when there is a condensed phase fuel or a liquid droplet in this case. Here its not even the mixing time that is rate controlling it is the vaporization time which is for droplets of typical size of 20 to 50 microns it is used in propulsion systems. The vaporization time is usually a few milliseconds ok. A few milliseconds and therefore, every other timescale including mixing and reaction rate are lower or smaller than the vaporization timescale and therefore, it is only the vaporization timescale that is rate limiting.

Key ideas are time for vaporization is proportional to the diameter of the droplet squared ok. Using this simple idea with the fact that the time available for vaporization is only a few milliseconds you can arrive at the conclusion that, the droplet sizes are the mean droplet sizes that are allowed are allowable in propulsion systems cannot be much bigger than 50 microns.

So, typical droplet sizes will be about 20 to 50 micron it cannot be much more than this simply because the time available for the vaporization will be lower leading to incomplete combustion if the droplet sizes are larger ok. This applies to diesel, liquid propellant rockets, gas turbine primary combustors, afterburners and also scram jets. For all these propulsion systems using liquid fuels it is usually the droplet size that is rate limited ok.

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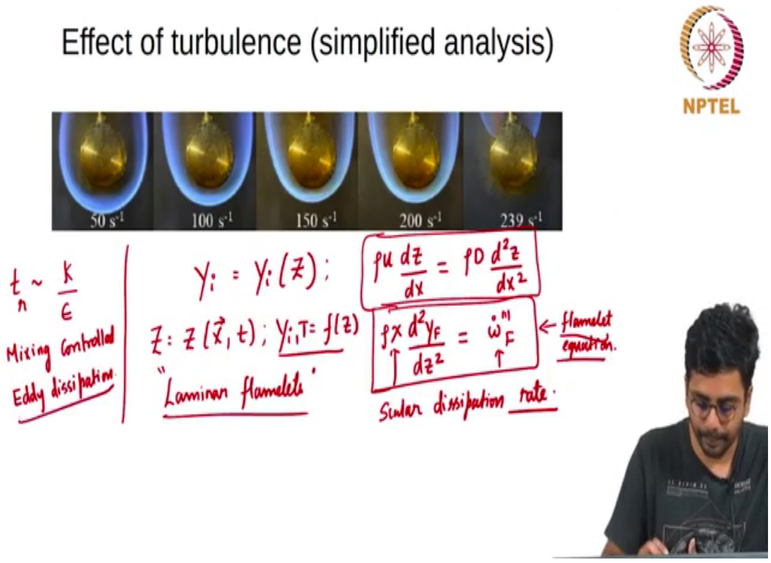

Effect of turbulence (simplified analysis)

$t_n \sim \frac{k}{\epsilon}$

Mixing Controlled

Eddy dissipation.

$Y_i = Y_i(Z);$

$Z : Z(\vec{x}, t); \; Y_i, T = f(Z)$

"Laminar flamelets"

$$\boxed{\rho u \frac{dZ}{dx} = \rho D \frac{d^2 Z}{dx^2}}$$

$$\boxed{\rho \chi \frac{d^2 Y_F}{dZ^2} = \dot{\omega}'''_F}$$

← Flamelet equation.

Scalar dissipation rate.

A quick overview of the effect of turbulence on non premixed flames, here we saw that when the dynamics is mostly mixing controlled. The local state of the reactant the local state of the reactant is only a function of conserved scalar called the mixture fraction ok. And the mixture fraction itself is in the simple one dimensional example. The mixture fraction itself is governed by a convection diffusion balance without a source term and that is why it is a conserved scalar. And the reaction rate can be related to the rate of dissipation or the scalar dissipation rate ok.

So, rho chi d squared by F by d z squared is equal to omega dot triple dash F ok, chi is the scalar dissipation rate. Why is this concept useful? Simply because when the dynamics is mixing controlled the flame is thin and therefore, the internal structure of the flame is not affected by turbulence it is only like in the premixed situation the flame is only the flame brush is only affected by the, the flame brush which can be considered to consist of a large number or a unsample of laminar flamelets is affected by turbulence, but the internal structure of the flame itself is not affected by turbulence.

So, the internal structure of the flame is a solution to this equation. And for the turbulence flow part we can get Z as a function of time and X, Z as a function of time and X ok. And we already know Y i and T as a function of Z ok. And using appropriate statistical methods we can describe a turbulent non premixed flame as an unsample of laminar flamelets ok, laminar flamelets ok. And this is in a very simple form is the effect of turbulence on non premixed flames ok. So, this is called the flamelet equation

In fact, further simplification is also possible if the reaction chemical reaction rate can be assumed to be infinitely fast. Then the reaction or then the flame is completely controlled only by the mixing rate. And the mixing rate can be calculated from the turbulence quantities ok. And the reaction rate can be taken to be equal to the timescale of mixing because of turbulence. And these models these mixing control models are very useful in getting a first cut picture of what is happening in a combustion chamber in a non premixed turbulent situation.

Common commonly used models include the eddy dissipation model ok. Which is equivalent to assuming that omega dot triple dash f is a direct delta function ok.