Fundamentals of Combustion for Propulsion
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Lecture – 27
Effect of turbulence on flames

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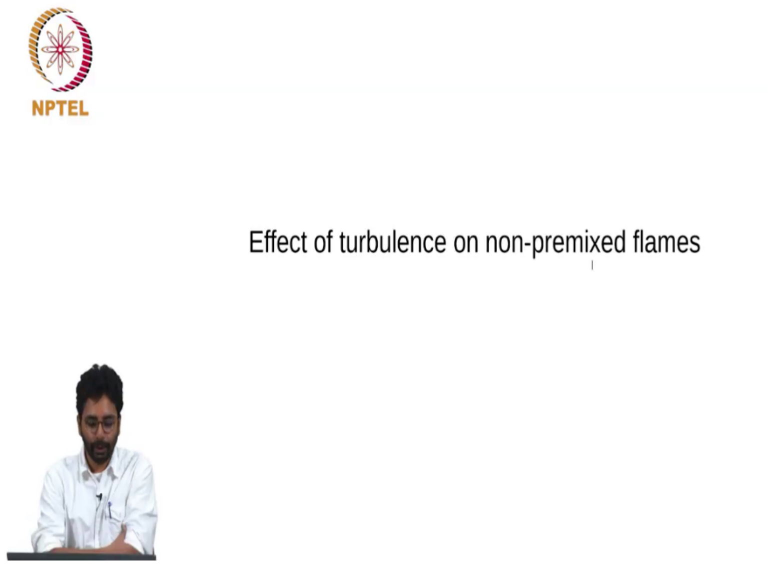

Effect of turbulence on non-premixed flames

Let us continue. We discuss the structure of the laminar non-premixed flame and the idea of mixed fraction and the idea of scalar dissipation rate that follows from mixed fraction. Now, let us extend this idea to turbulence now turbulent non-premixed flames.

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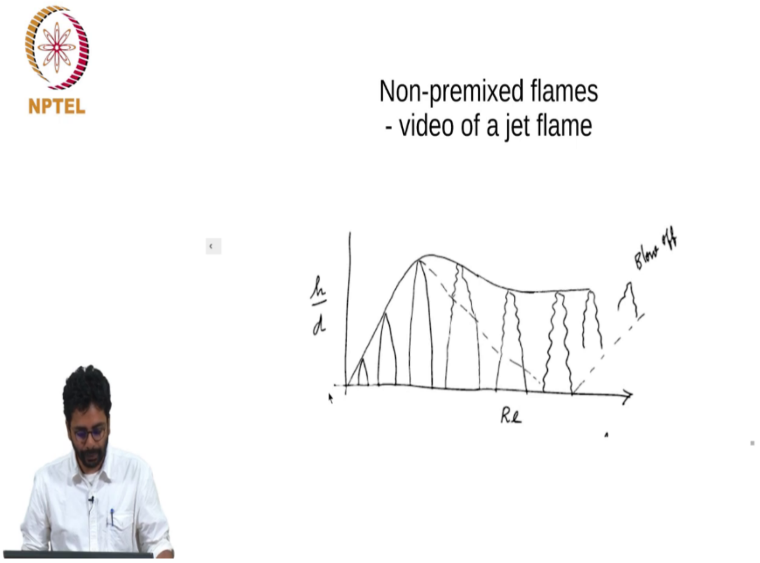

Non-premixed flames
- video of a jet flame

And, this we have already discussed the for in the relationship between the non-dimensional height of a non-premixed flame as a function of a Reynolds number. We saw yesterday that simple scaling analysis indicates that the h by d will linearly increase with Reynolds number till the flame becomes turbulent, and then the flame height goes down a little bit and then settles down at a constant height ok.

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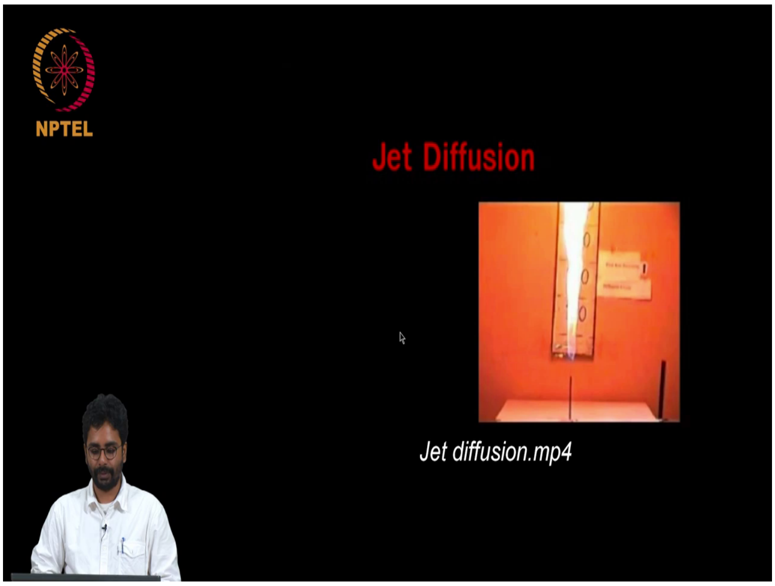

Jet Diffusion

Jet diffusion.mp4

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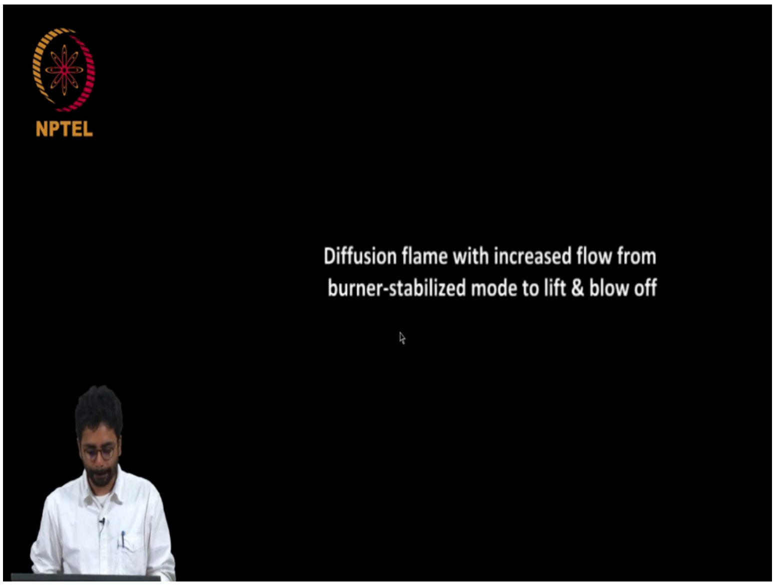

Diffusion flame with increased flow from burner-stabilized mode to lift & blow off

I will show you now a video of this phenomena where you can observe the linear increase in height with increase in Reynolds number.

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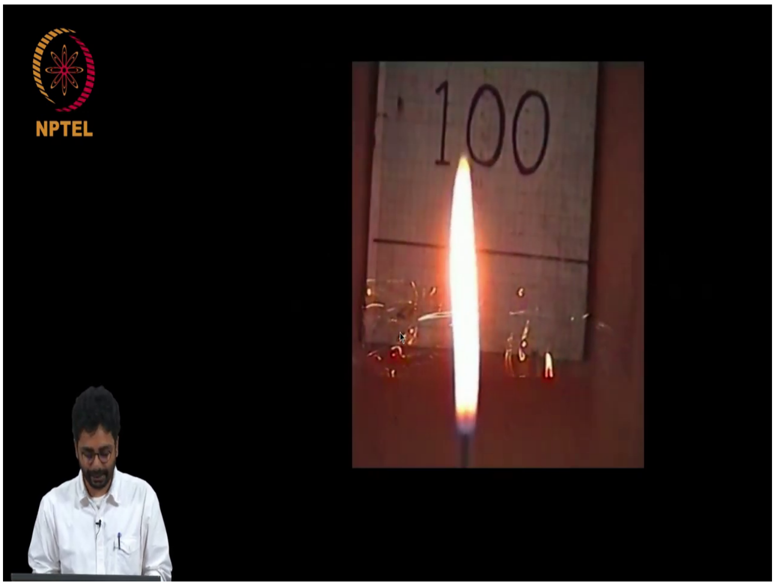

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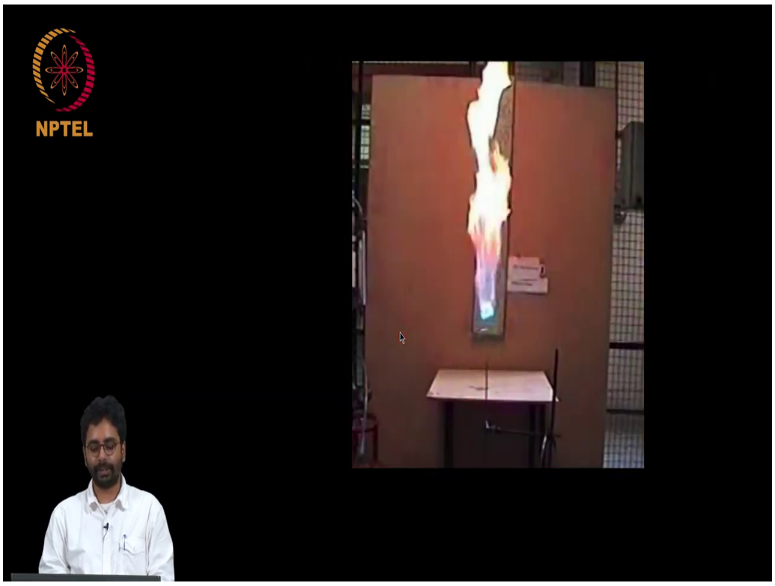

Now, you see that the tip is becoming unstable, the you know the flame has lifted off and become turbulent; now, more or less the entire length of the flame is turbulent now. The base is bluish and it is because, it is lifted off there is some pre mixing that is happening till the point of ignition and the flame stabilizes at a point where the turbulent flame speed is matched by the local velocity.

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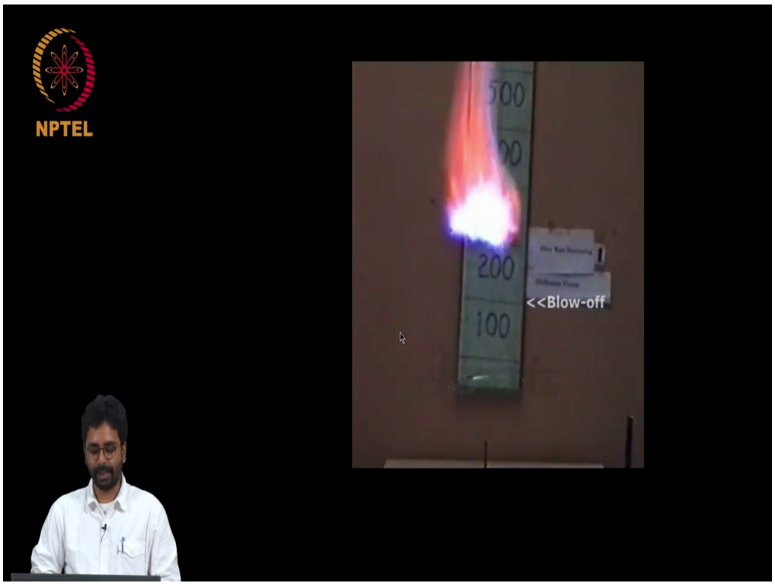

Now, we will also see blow off of this flame. I will play it one more time, yeah it is already playing (Refer Time: 01:57). You must have seen that it is the tip that becomes turbulent first and then the disturbances propagate to the base, and when the disturbance propagates to the base flame lifts off and you have lifted flame for a range of Reynolds numbers and then it close off.

Student: (Refer Time: 02:31), tell me what is happening at the time of blow?

At the time of blow off, there is no location that is available for the flame to stabilize, because there is no point where the local velocity is matched by the turbulent flames p. See because, the flame is lifted off, there is a region where there is no reaction happening, only mixing is happening.

So, premixed mixture is created, the flow is turbulent and by increasing the Reynolds number you are continuing to increase the; the by increasing the Reynolds number we are continuing to increase the turbulent flame speed, ok. So, we will come a point at which there is no point where the flame can stabilize, it goes off. I am not sure, I would guess that it is 10 millimeters; (Refer Time: 03:25), what is the diameter of the tube?

Student: (Refer Time: 03:28) 10.

10 millimeters, right, 10, ok. So, the simple result that we derived from a scaling analysis is confirmed by experiments yeah.

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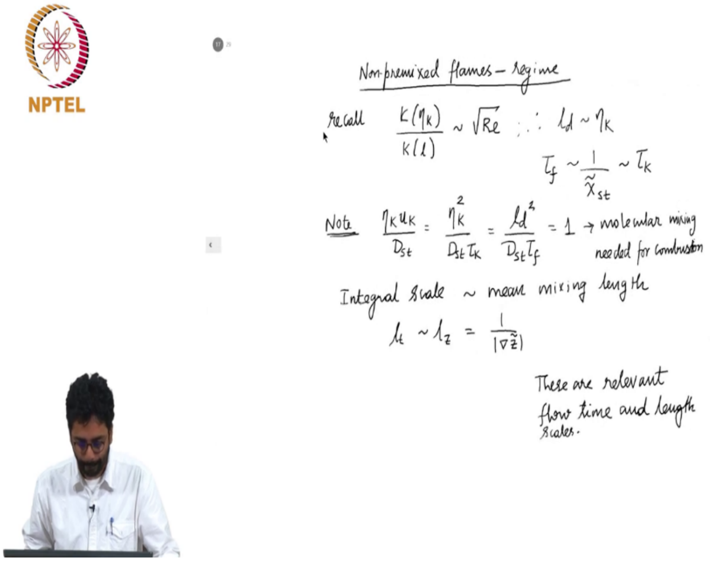

Non-premixed flames – regime

recall $\frac{K(\eta_K)}{K(l)} \sim \sqrt{Re} \quad \therefore \quad l_d \sim \eta_K$

$\tau_f \sim \frac{1}{\tilde{\chi}_{st}} \sim \tau_K$

Note $\frac{\eta_K u_K}{D_{st}} = \frac{\eta_K^2}{D_{st}\tau_K} = \frac{l_d^2}{D_{st}\tau_f} = 1 \rightarrow$ molecular mixing needed for combustion

Integral scale $\sim$ mean mixing length

$l_t \sim l_z = \frac{1}{|\nabla \tilde{z}|}$

There are relevant flow time and length scales.

So, now the diffusion flame can go through a series of transitions, 1 is it remains laminar the height goes up, the tip becomes turbulent, entire flame becomes turbulent and then it lifts off and then goes off. Till the point it lifts off the stabilization or the structure, the overall structure of the flame is controlled by mostly mixing. But, the reason it lifts off is that the mixing time is now shorter than the reaction time or the mixing time becomes comparable to the reaction time. So, the flame cannot stabilize at the rim. So, it moves downstream.

So, till the point that it starts lifting off, dynamics is mostly controlled by mixing ok, but if you have to capture lift off then you need to account for finite reaction rate effects ok. So, what we will do is use the ideas that we have discussed so far to classify the regimes; different regimes of turbulent non premixed flame. This we just saw that the stretch rate or the mixing rate at Kolmogorov scale is much higher than what it is at the integral length scale.

In fact, the ratio is proportional to the square root of Reynolds number. Therefore, the mixing scale that is of relevance is the Kolmogorov scale. And, the timescale of the flow that is relevant as the mixing time scale which we saw as the inverse of the scalar dissipation rate, ok. And, this also is significantly higher at Kolmogorov scale is compared to what it is at integral length scales and therefore, the flow time determined by the mixing time is proportional is comparable to the Kolmogorov scale, ok.

This of course, satisfies the condition for what should be the Reynolds number at the Kolmogorov scale, you can combine. The Kolmogorov scale Reynolds number is eta K u K by the diffusivity; I am assuming Lewis number and Prandtl number are 1 and it is indeed 1, ok.

What happens if the integral scale is overall mixing, ok, blobs of fuel and oxidizer come together. There is no molecular mixing, but there is overall coming together a fuel or bulk of fuel and oxidizer and that scale can be simply determined from the mixed fraction gradient ok, that is what is shown here. So, these are the scales that are relevant to the relevant time and length scales for the diffusion flame or the non-premixed flame, ok as far as the flow is concerned.

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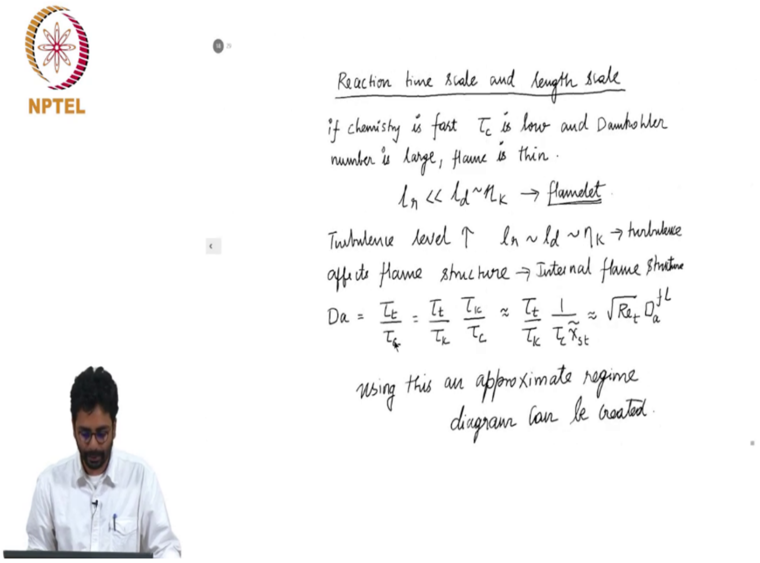

Reaction time scale and length scale

if chemistry is fast τ_c is low and Damkohler number is large, flame is thin.

$$l_n << l_d \sim \eta_K \rightarrow \text{flamelet}$$

Turbulence level ↑ $l_n \sim l_d \sim \eta_K$ → turbulence affects flame structure → Internal flame structure

$$Da = \frac{\tau_t}{\tau_c} = \frac{\tau_t}{\tau_k}\frac{\tau_k}{\tau_c} \approx \frac{\tau_t}{\tau_k}\frac{1}{\tau_c \tilde{\chi}_{st}} \approx \sqrt{Re_t}\, D_a^{fL}$$

using this an approximate regime diagram can be created.

The reaction time and length scales are dependent on reaction rate obviously. So, if chemistry is fast, then the reaction time is low and the Damkohler number which is defined as the ratio of the flow time to the reaction time is very very high. When the reaction is infinitely fast the Damkohler number is infinite; reaction time tends to 0, the Damkohler number tends to infinite.

And therefore, the flame can be considered to be thin, ok. This is expressed as the reaction zone thickness ok, is much much smaller than the zone over which the reactions happen is much much smaller than the mixing. The overall mixing length scale which is proportional to the which is comparable to the Kolmogorov scale. What this means is that the smallest scale of turbulence cannot affect the flame structure, ok.

The flame thickness or the thickness over which the reaction happens is smaller than the Kolmogorov scale, because the reactions are very very fast, ok and therefore, the internal structure of the flame. Remember that in reality, the flame has a finite thickness even though the approximation that it is thin; that means, it has 0 thickness is a theoretical construct, but in reality it has a certain thickness what we mean by that it is thin is that it is smaller than the Kolmogorov scale.

And therefore, the internal structure of the reaction zone is not affected by the Kolmogorov scale, but it is possible that as we you know we looked at an example where by increasing the strain rate we can quench a flame. Similarly, if we are increasing the turbulence level, we can make the reaction zone length scale comparable to the mixing scale and the Kolmogorov scale.

And therefore under these conditions, the turbulence will affect the internal flame structure and what can happen here is actually the smallest scale can actually shed the flame, ok. And when that starts happening the reaction zone, you do not have a distinct thin flame, because it is getting shredded by turbulence. You move into what is called a distributed reaction zone or typically what is find in a flameless or a mile combustor corresponds to a region where there is intense turbulence created by the recirculation of the hot products. And therefore, there is no distinct flame, the flame is shredded and distributed.

So, the Damkohler number one definition of Damkohler number is the timescale the integral time scale the ratio of the integral time scale to the reaction time scale which can be split into 2 factors. The first one which is a dependent only on the flow which is the ratio of the integral scale integral time scale to the Kolmogorov time scale multiplied by the Kolmogorov time scale to the reaction time scale.

And, we already know what the mixing time scale is going to be it is the inverse of the scalar dissipation rate and that is what is expressed here, which again if you plug in the relation scaling relations that we derived just now. You can show that the overall Damkohler number is the square root of the Reynolds number multiplied by the flame Damkohler number, ok.

Using this we can create an approximate regime diagram for the turbulent non-premixed flames, ok. Remember this criteria and this criteria, ok; reaction zone much much smaller than the Kolmogorov scale and when the in the case where the reaction zone thickness becomes comparable to the Kolmogorov scale, ok.

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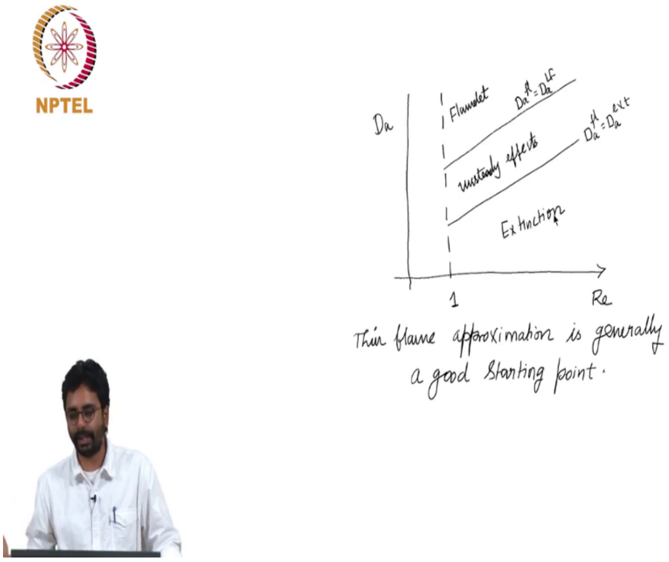

Thin flame approximation is generally a good Starting point.

Of course, it is because there is an intrinsic length scale and velocity scale for a premixed flame, it is much easier to create a regime diagram for premixed flames, diffusion flame regime diagrams are a hotly debated topic. So, this is only a simple representation of the diffusion flame regimes, ok. Till the point when Reynolds number is 1, we have laminar flames this part is laminar flames, ok.

And, when the Damkohler the flame Damkohler number is greater than the laminar flame Damkohler number the zone that is above this line, we have thin flame. The thin flame approximation, the flame reaction zone the internal structure of the flame is not affected by turbulence. So, we can assume that a turbulent flame in this regime is an ensemble of laminar flamelets. In fact, from the video, you would have seen that when the flame transitions to becoming turbulent it becomes brushy, ok. Those bristles are nothing, but laminar flamelets ok.

And, in this regime the reactions zone thickness becomes comparable to the Kolmogorov thickness and then the turbulence, the smaller scale of the turbulence starts affecting the reaction zone. And, when this stretching because of the turbulence becomes intense, there can be local extinction and re ignition, and when you go to this condition and combine it with recirculation of hot gases.

So, that it actually does not go extinct the flame is shredded by the turbulence, but the ignition source is constantly provided. So, it goes through extinction and re ignition, maintaining a more or less third conditions which is called the flameless combustion or mild combustion ok. Therefore, for a lot of applications that you may be working on, the thin flame approximation is a good starting point.

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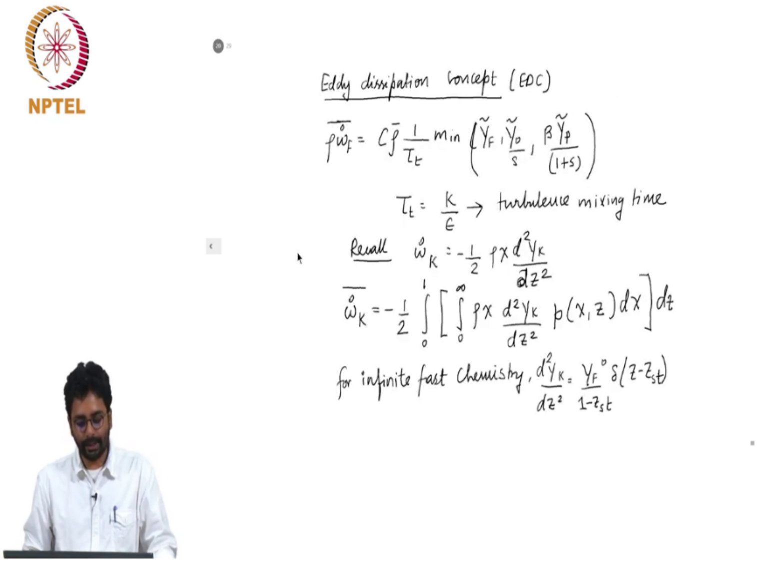

Eddy dissipation concept (EDC)

$$\overline{\rho \overset{o}{\omega}_F} = C\bar{\rho}\frac{1}{\tau_t}\min\left(\tilde{Y}_F, \frac{\tilde{Y}_O}{s}, \frac{\beta \tilde{Y}_P}{(1+s)}\right)$$

$$\tau_t = \frac{k}{\epsilon} \rightarrow \text{turbulence mixing time}$$

Recall $\overset{o}{\omega}_K = -\frac{1}{2}\rho\chi\frac{d^2Y_K}{dz^2}$

$$\overline{\overset{o}{\omega}_K} = -\frac{1}{2}\int_0^1\left[\int_0^\infty \rho\chi\frac{d^2Y_K}{dz^2}p(\chi, z)\,d\chi\right]dz$$

for infinite fast Chemistry, $\frac{d^2Y_K}{dz^2} = \frac{Y_F^{\,o}}{1-z_{st}}\delta(z-z_{st})$

And you may be familiar with the eddy dissipation concept model many of you may be using it. The basis for this is the assumption that the flame is very thin and the flame separates the fuel from the oxidizer, the reactions are infinitely fast. And therefore, the average reaction rate; remember, that to solve for the flow field in a turbulent non-premixed situation we need a measure or we need a way to calculate the average reaction rate. Here, the average reaction rate is simply controlled by the mixing timescale that is what is shown here; the average reaction rate is 1 divided by the timescale for the turbulence , this comes from here, ok.

This we have already seen is proportional to the mixing timescale and chemistry has no influence, and the mixing timescale itself we saw earlier is proportional to K by epsilon, ok. We saw that the scalar dissipation rate is proportional to epsilon by K, time scale is the inverse of the scalar dissipation rate which is K by epsilon. So, this simple idea is what is used in the so called eddy dissipation concept.

This minimum of these three quantities is just to make sure that the reaction does not continue to happen when one of the reactants is completely defeated. This is the simplest turbulence combustion model. The next level of description of course, comes from the idea of considering the flame to be an ensemble of laminar flow bullets. What is done here is you solve the flamelet equation which is shown here for several values of the scalar dissipation rate ranging from small values to a point where the flame goes extinct and it is tabulated.

And then, the reaction; the mean reaction rate is calculated from the of course, if it is a laminar flame. The mean reaction rate is simply equal to minus half rho chi d squared by K by dz square. So, for a given value of chi you can just look up that number, but remember that in a turbulent flow field you have fluctuations, right. So, at a given point in space as a function of time the value of the mixed fraction and the scalar dissipation rate will fluctuate, ok.

And therefore, to calculate an average reaction rate we need to know the probability density function from which the moment. The first moment would be the average reaction rate and that is what is shown here the average reaction rate is the first moment of the right hand side of this equation. And, for calculating this first moment we need the joint probability density function of the scalar dissipation rate and the mixed fraction conditional on Z being equal to Z s t, ok.

But, in the simple case where the reactions are infinitely fast the solution is the same irrespective of what value of chi is there in the local flow field and therefore, d square Y by dZ square becomes a direct delta function.

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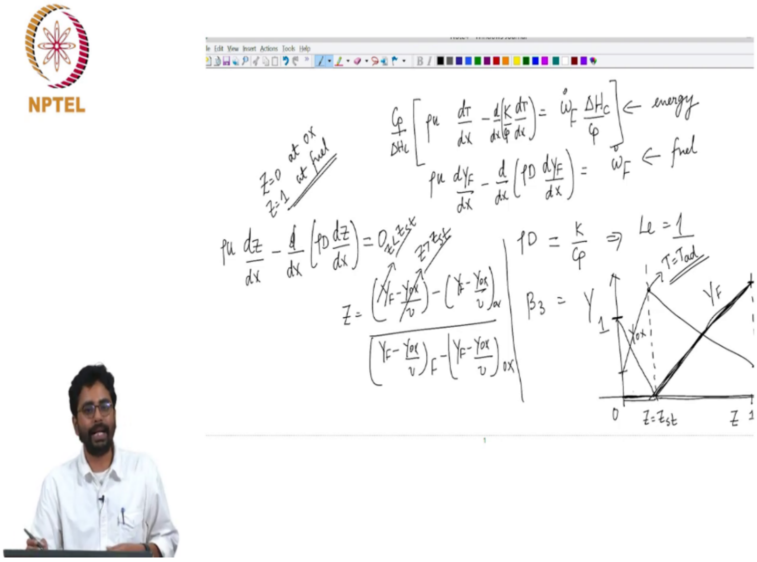

$$\frac{c_p}{\Delta H_c}\left[\rho u \frac{dT}{dx} - \frac{d}{dx}\left(\frac{k}{c_p}\frac{dT}{dx}\right) = \dot{\omega}_F \frac{\Delta H_c}{c_p}\right] \leftarrow \text{energy}$$

$$\rho u \frac{dY_F}{dx} - \frac{d}{dx}\left(\rho D \frac{dY_F}{dx}\right) = \dot{\omega}_F \leftarrow \text{fuel}$$

$Z = 0$ at ox

$Z = 1$ at fuel

$$\rho u \frac{dZ}{dx} - \frac{d}{dx}\left(\rho D \frac{dZ}{dx}\right) = 0$$

$Z < Z_{st}$ $\quad Z > Z_{st}$

$$Z = \frac{\left(\cancel{Y_F} - \cancel{\frac{Y_{ox}}{\nu}}\right) - \left(\cancel{Y_F} - \frac{Y_{ox}}{\nu}\right)_{ox}}{\left(Y_F - \frac{Y_{ox}}{\nu}\right)_F - \left(Y_F - \frac{Y_{ox}}{\nu}\right)_{ox}}$$

$$\rho D = \frac{k}{c_p} \Rightarrow Le = 1$$

$$\beta_3 = Y$$

What I mean by this is we saw this in the case of infinitely fast reactions Y F varies linearly in the fuel side ok, I am making that line thick, and it goes to 0 at the flame and it remains 0 on the oxidizer side, ok. So, if you have to write an equation that describes this profile, ok.

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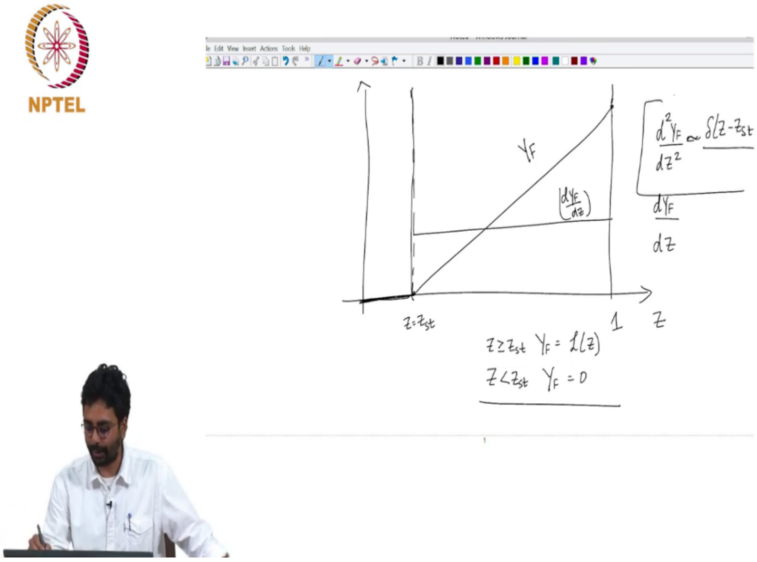

This profile this is Y F this is 0, ok. So, Z greater than or equal to Z s t, Y F is a linear function of Z ok, and for Z less than Z s t Y F is equal to 0, ok. So, this is how Y F changes, what we are looking for is d square Y F by d Z square because that is a term that appears in the reaction rate equation, ok.

So, d Y F by d Z is some number here; a constant value here ok, this is d Y F by d Z ok, and then it is 0 here, ok. And d square Y F by d Z square will be direct delta function centered at Z s t. It is 0 on both the sides, but it is reaction rate is not 0 at the flame, reaction rate is a finite value which is given by the integral of the direct delta function around that point, ok. In fact, we can show that it is simply the rate of mixing of the reactants or the rate of diffusion of the reactants towards the reaction zone or the flame, ok.

So, the second derivative of Y F will be a direct delta function that is what is shown here, d square Y F by d Z square is a direct delta function centered at Z equals Z s t.

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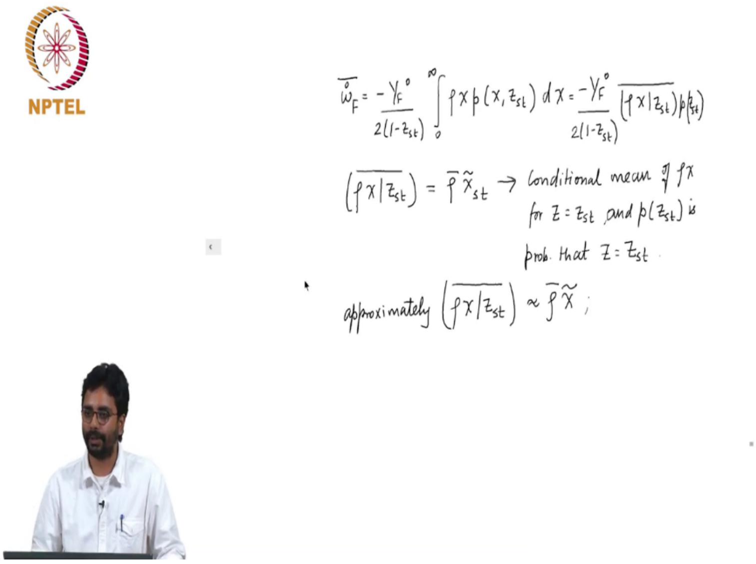

$$\overline{\dot{\omega}_F} = \frac{-Y_F^\circ}{2(1-Z_{st})}\int_0^\infty \rho\chi\, p(\chi, Z_{st})\, d\chi = \frac{-Y_F^\circ}{2(1-Z_{st})}\overline{(\rho\chi|Z_{st})}\, p(Z_{st})$$

$\left(\overline{\rho\chi|Z_{st}}\right) = \bar{\rho}\tilde{\chi}_{st} \rightarrow$ Conditional mean of $\rho\chi$ for $Z = Z_{st}$ and $p(Z_{st})$ is prob. that $Z = Z_{st}$

approximately $\left(\overline{\rho\chi|Z_{st}}\right) \propto \bar{\rho}\tilde{\chi}$;

You can plug this into the expression for omega dot F, remember that when the reaction rates are infinitely high for every chi you have the same solution and the flame locates itself at Z equal to Z s t. So, the probability density function you are looking for is only p of condition on Z equals Z s t and you can show that the reaction rate is proportional to the scalar dissipation rate as expected from the basic theory, ok. And, the approximation that is made is that the conditional value of chi at Z equals Z s t is taken to be the mean value of the scalar dissipation rate at Z equals Z s t; that means, you are taking only the first order term, ok. So, this is an approximation that was made.

So, the conditional mean of the density times the scalar dissipation rate for the location where the stoichiometry is met and the probability that Z equals Z s t is assumed to be just the mean value, ok. So, this is an approximation that is made, ok. So, this is what is used in a flamelet description, where the flamelet is taken to be controlled only by mixing, no reaction rate effects, ok.

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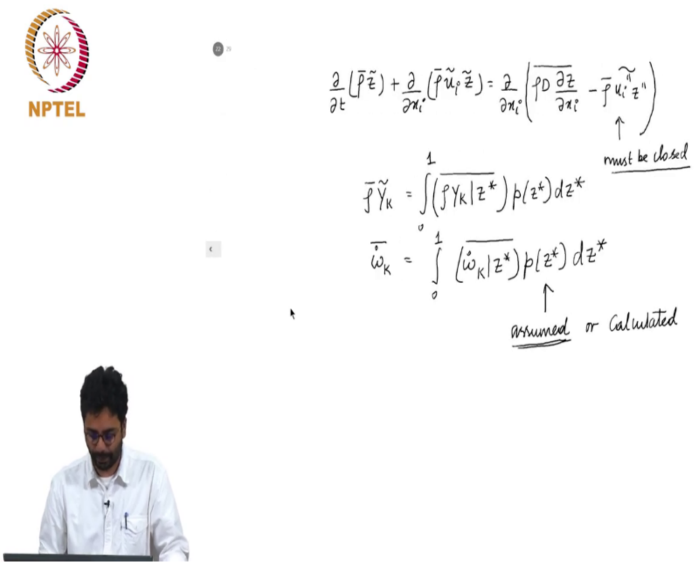

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{Z}) + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{Z}) = \frac{\partial}{\partial x_i}\left(\overline{\rho D \frac{\partial Z}{\partial x_i}} - \underset{\substack{\uparrow \\ \text{must be closed}}}{\bar{\rho}\widetilde{u_i'' Z''}}\right)$$

$$\bar{\rho}\tilde{Y}_K = \int_0^1 \left(\overline{\rho Y_K | Z^*}\right) p(Z^*)\, dZ^*$$

$$\bar{\dot{\omega}}_K = \int_0^1 \left(\overline{\dot{\omega}_K | Z^*}\right) \underset{\substack{\uparrow \\ \text{assumed or Calculated}}}{p(Z^*)}\, dZ^*$$

Of course, the next level of description is where you want to actually account for some chemistry effect for example, lift off, ok. So, at lift off you have a combustible mixture between the flame and the rim, it has a value of Z which in the case of infinitely fast chemistry must have a flame. But, in reality it does not have a flame, because the scalar dissipation rates are so high that the flame cannot stabilize there, ok.

So, that is a finite chemistry there is an effect because of the finite rate of chemistry and to capture that you need to account for extinction and re ignition in the code and some finite rate chemistry effects can be included by using the detailed flamelet library. I will not go into too much of the details of this. The average reaction rate is again calculated by the same strategy. But now, the difference in the value of scalar dissipation rate at different locations must be accounted for, you need both xi. So, for the probability density function of Z we do not know, ok.

So, what we do is we calculate the mean value for Z and the variance by closure equation and assume a probability density function that depends only on the mean and the variance; usually, a beta function is what is used ok. You can find more details in for instance book by point; so, called Theoretical and Numerical Combustion. I do not want to go into too much of details, I just want to this summarize quickly the hierarchy of approach.

First you assume that there is no flamelet structure whatever is mixed is reacted that is eddy dissipation concept model. And, the next level of description is you have a flamelet, but the flamelet is always there independent of whatever is the value of the scalar dissipation rate, that is second level of description. The third level of description is where you account for the fact that the structure of the flame is different at different scalar dissipation rates. And therefore, from the tabulated values of the flamelet equation at different values of chi, you calculate the local flame features.

Accounting for extinction and re ignition requires another level of description starting from here ok, and I will not go into the details of that, but you can refer theoretical and numerical combustion by point so, ok.

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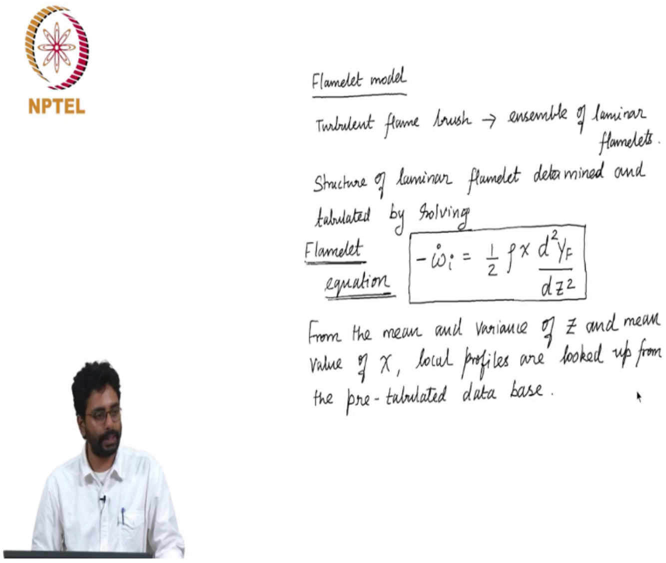

Flamelet model

Turbulent flame brush → ensemble of laminar flamelets.

Structure of laminar flamelet determined and tabulated by solving

Flamelet equation $$\boxed{-\dot{\omega}_i = \frac{1}{2}\rho\chi\frac{d^2Y_F}{dZ^2}}$$

From the mean and variance of Z and mean value of χ, local profiles are looked up from the pre-tabulated data base.

So, this I already explained, this is again summary of the flamelet model. So, the turbulent flame brush is an ensemble of laminar flamelets. The structure of laminar flamelet is determined and tabulated by solving the flamelet equation for different values of chi, but remember that in a turbulent flow field the at a given location in space.

The value of chi Z, the higher moments of Z everything will; I am sorry, the value of Z will fluctuate and therefore, you need to characterize the probability density function of Z with it is moments mean, variance etcetera. And, from the mean and variance of Z and mean value of the scalar dissipation rate, local profiles are looked up from the pre tabulated database, there are several approaches and ways of doing this, ok.

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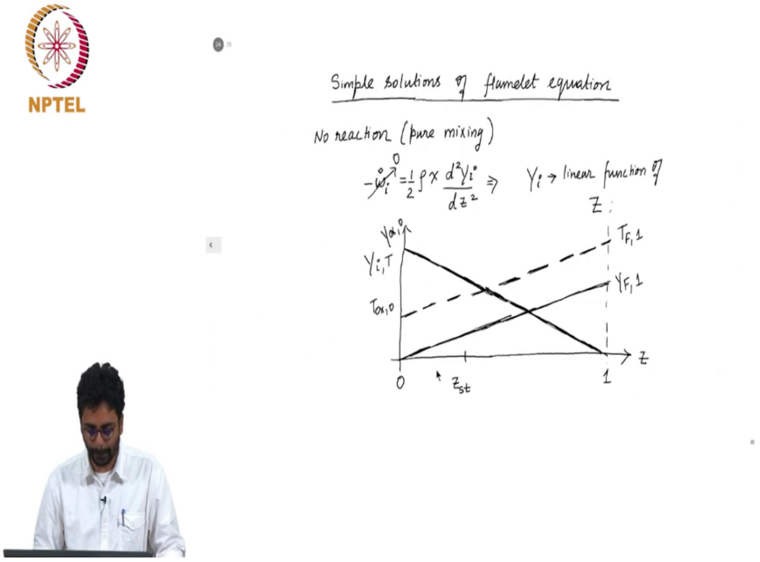

Simple solutions of flamelet equation

No reaction (pure mixing)

$$-\cancel{\dot{\omega}_i}^{\,0} = \frac{1}{2}\rho\chi\frac{d^2Y_i}{dZ^2} \Rightarrow \quad Y_i \rightarrow \text{linear function of } Z;$$

I will just show some simple cases which we have already seen; simple solutions to the flamelet equation; one case is where there is no reaction, there is only mixing reaction rate is 0. And therefore, you have a solution which is pure mixing all the fuel and oxidizer are mixing, and the Y and the Ts are linear functions of Z as expected from the definition of the scalar.

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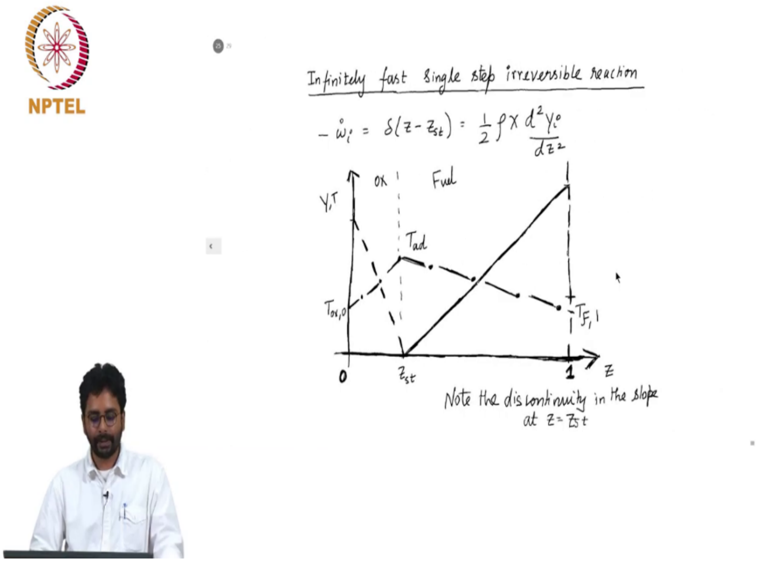

Infinitely fast single step irreversible reaction

$$-\dot{\omega}_i = \delta(z - z_{st}) = \frac{1}{2}\rho\chi\frac{d^2 Y_i}{dz^2}$$

Note the discontinuity in the slope at $z = z_{st}$

This is the, this is also this is the case with infinitely fast chemistry where the reaction rate is a delta function centered at Z equals Z s t is equal to the equal to this term, you can now for, ok. So, the react for every value of chi, the reaction rate is infinitely fast, ok. Therefore, it is not the left hand side is 0 everywhere else not because chi is 0 because reaction rate is 0. So, you can integrate this equation, you will get linear profiles on either side only that the slopes will have a discontinuity, because the left hand side is a direct delta term, ok.

Now, the discontinuity in the slope at Z equals Z s t ok, and this discontinuity exists because the reaction rate is finite, no fuel can cross over to the oxidizer side and no oxidizer can cross over to the fuel side. So, Y F must be 0 here and Y x must be 0 here. And, correction to the solution can be calculated by assuming that around the flame, the products go to equilibrium and that is a solution.

I showed earlier from the paper by bulger where the profiles were actually not discontinuous at Z equals Z s t. They were continuous the slopes were also continuous at Z equals Z s t, because it has been assumed that around the flame the composition is the equilibrium composition. This works very well for the stoichiometry and the lean side and a little bit on the red side, but if you go further into the red side. The equilibrium assumption does not work because reactions are not that slow, I am sorry reactions are not that fast; so, bit slow.

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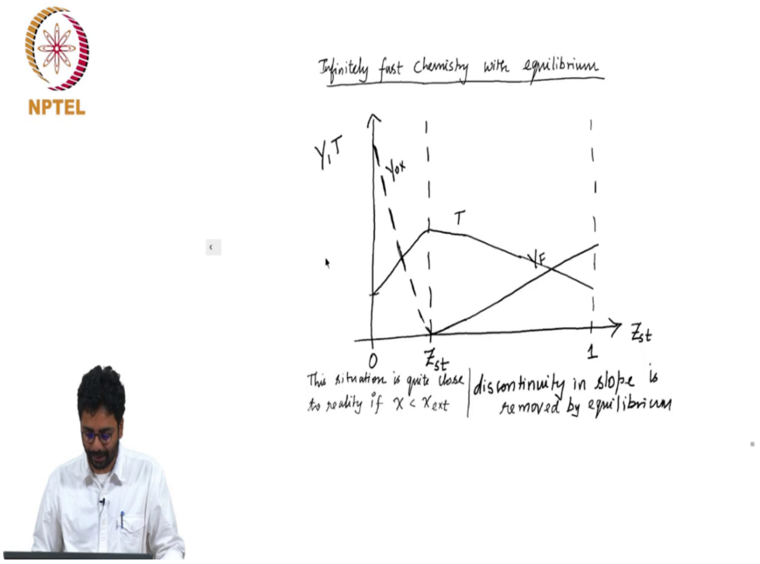

Infinitely fast Chemistry with equilibrium

This situation is quite close to reality if $\chi < \chi_{ext}$

discontinuity in slope is removed by equilibrium

Well, this is the profile that is infinitely fast chemistry, but corrected with equilibrium assumption; so, the discontinuity in the slope is removed. This we saw earlier in a real example that it is quite close to reality, if you are far away from the extinction point, ok. That completes the turbulent diffusion flame modelling related aspects you have any questions? No, ok.

Let us I will keep the premixed flame part short, because most of you are keen on or using diffusion flame or non-premixed configurations, but just for the sake of completeness.

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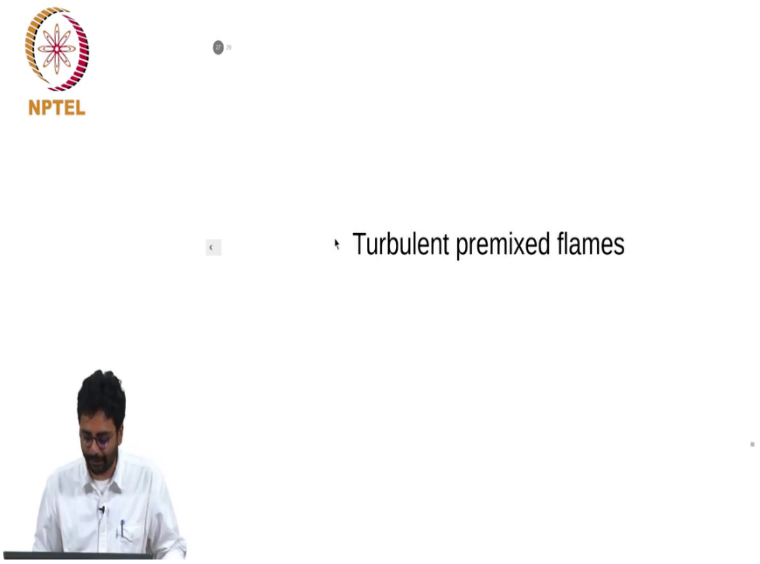

Turbulent premixed flames

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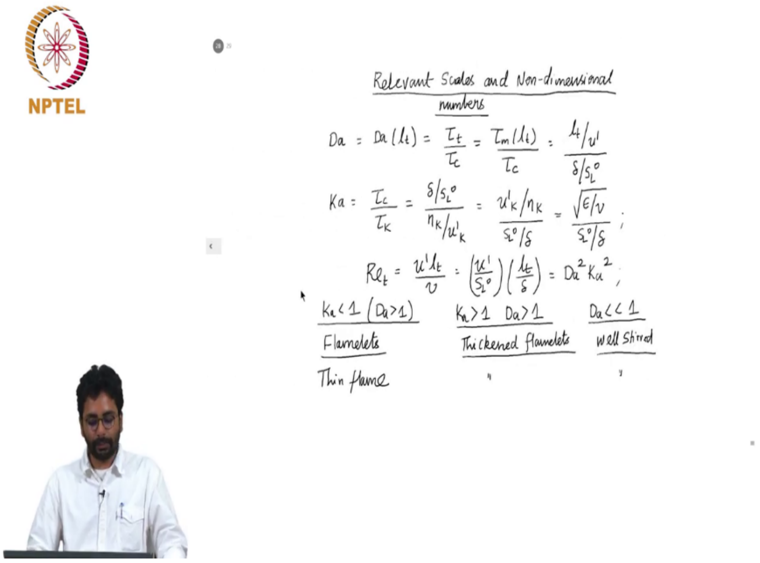


Relevant Scales and Non-dimensional numbers

$$Da = Da(l_t) = \frac{\tau_t}{\tau_c} = \frac{\tau_m(l_t)}{\tau_c} = \frac{l_t/u'}{\delta/S_L^0}$$

$$Ka = \frac{\tau_c}{\tau_K} = \frac{\delta/S_L^0}{\eta_K/u'_K} = \frac{u'_K/\eta_K}{S_L^0/\delta} = \frac{\sqrt{\epsilon/\nu}}{S_L^0/\delta};$$

$$Re_t = \frac{u' l_t}{\nu} = \left(\frac{u'}{S_L^0}\right)\left(\frac{l_t}{\delta}\right) = Da^2 Ka^2;$$

$Ka < 1$ $(Da > 1)$ — Flamelets — Thin flame

$Ka > 1$ $Da > 1$ — Thickened flamelets — "

$Da << 1$ — Well Stirred — "

I will quickly go over the premix claims. In fact, creating regime diagrams for premixed flames is much easier than for turbulent for non-premixed flames, because there are definite length and timescales. So, the Damkohler number here, everything that we have discussed about turbulence still holds here. The Damkohler number corresponding to the integral scale will be this ah; the integral length scale divided by the integral velocity scale and the reaction time scale is the delta divided by S L 0, ok. Again, we use this earlier also.

There is a new non-dimensional number called the Karlovitz number which is the inverse of the Damkohler number where the flow time scale is taken as the Kolmogorov timescale, ok. The Damkohler number is tau t over tau c, the Karlovitz number is the chemical timescale divided by the time scale of the Kolmogorov scale, ok.

So, the chemical timescale still remains the same delta over S L 0. The Kolmogorov time scale is eta K over u dash K, ok always time scale is length scale divided by a velocity scale, ok; similarly, for the chemistry also. Now, if you can rearrange it and use the equations that we derived earlier. We can show that it is square root epsilon by nu over s l 0 by delta and the turbulent Reynolds number, you can show as Damkohler numbers squared and Karlovitz numbers squared.

The idea of using Damkohler number and Karlovitz number to create a flame regime for premixed flames is simple when the when the Karlovitz number is much less than 1. Remember, that Karlovitz number is chemical timescale divided by the Kolmogorov timescale and this is much less than 1. Obviously, the Damkohler number is much is greater than 1, because, the timescales for the integral scale are much smaller; this means that; this means what means that the flames.

Student: Fast.

Not infinitely fast chemistry, we are looking at premixed flames. So, chemistry is still finite rate yeah, the reaction reactivity is still S L 0 is still a measure of the reactivity the reactions are happening at a finite rate, but the thickness of the flame is much much smaller than the Kolmogorov thickness ok. So, this is the thin flame limit of the premixed flames.

Here also what you can; here also the this assumption or this regime offers the following simplifications, you cannot you need not solve for the structure of the flame. Because, a laminar flame including a strain laminar flame, you can pre calculate the structure of the flame using a approach that is similar to the opposed jet flame for a non-premixed flame. And, from that all you need to do is depending on the conditions inside the flow which can be calculated independent of the chemistry, you have to embed the flame and let the flame transport at the laminar flames flame, ok. So, this is the thin flame limit of the laminar premixed of the turbulent premixed flame.

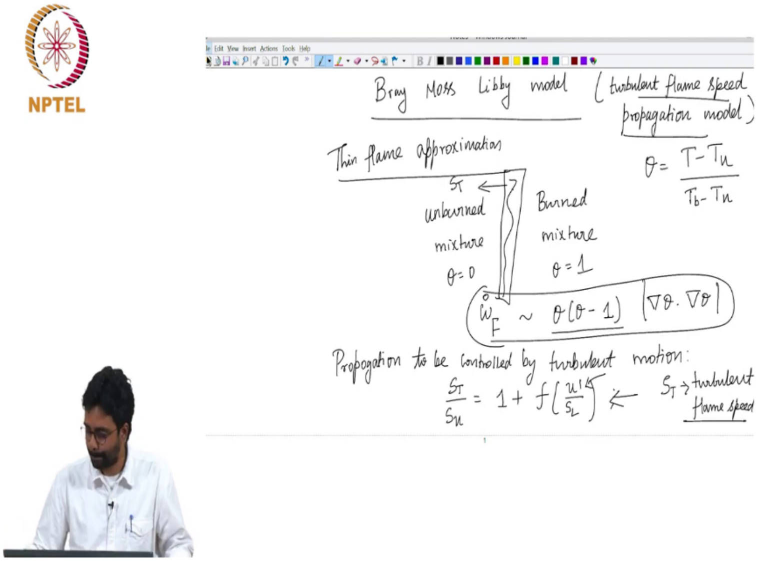
The next situation is when the flame thickness is becomes comparable to the Kolmogorov scale or the flame thickness is actually bigger or larger than the Kolmogorov scale. Now, the smallest length scales can actually affect the flame what it does is to thicken the flame. So, this is the thicken flame regime and when the Damkohler number when you further increase the turbulence levels, the Damkohler number becomes much less than 1 and this is the condition of the well stirred reactor, ok.

Under these conditions, it does not actually if you have a combustion system working in this regime, it does not really matter whether it is pre mixed or non-pre mixed. The behavior inside the combustion chamber is essentially the same, ok.

Student: (Refer Time: 28:24).

Yeah I will (Refer Time: 28:27), any questions.

(Refer Slide Time: 28:43)



Bray Moss Libby model (turbulent flame speed propagation model)

Thin flame approximation

S_T

unburned mixture $\theta = 0$

Burned mixture $\theta = 1$

$\theta = \frac{T - T_u}{T_b - T_u}$

$\boxed{\dot{\omega}_F \sim \underline{\theta(\theta - 1)} \, |\nabla\theta \cdot \nabla\theta|}$

Propogation to be controlled by turbulent motion:

$\frac{S_T}{S_u} = 1 + f\left(\frac{u'}{S_L}\right) \leftarrow$ $S_T \rightarrow$ turbulent flame speed

Yeah So, the I will just quickly explain one simple version of the flame flamelet model for the premixed flame called the Bray Mass Libby model. Well, there are generally two approaches, this belongs to the ok, this is the thin flame approximation is valid. Since, the flame is thin the flow zone essentially has only can be in either of the 2 states; one is the unburned state separated from a flame that is at the burned, which is a burned mixture, ok. You do not have to resolve the flame, because the flame is thin compared to the other length scales, ok.

So, the flame separates the unburned mixture from the burned mixture. So, similar to a well similar to mixed fraction this is not a conserved scalar, but still this is a measure for example, you can define theta as T minus T u by T b minus T u. So, in the unburned mixture the theta value is 0, on the burnt side the theta value is 1, ok. And, starting from the energy equation you can construct a conservation equation for theta, but more convenient variable is theta times theta minus 1, because it is directly related to the reaction rate.

I will not go into the details of this, but the reaction rate can be shown to be related to the scalar dissipation of theta which will look like this ok and this will come out of a conservation equation for theta times theta minus 1, ok. All this details are there in the book by point. So but, what I want to emphasize is that either you can calculate the reaction rate from an approach like this or the other approach is to simply take the propagation to be controlled; propagation to be controlled by the turbulent motion ok. So, this follows from the simple idea that the turbulent flame speed is, ok.

Well, there are other correlations which account for the length scale effects, but this is something that we discussed earlier that the turbulent flame speed can be related to; in this case I have written u dash, but there are other correlation which accounts for both intensity as well as the length scale, ok. So, from the local turbulence state of the turbulence, we can calculate a turbulent flame speed from the correlations, ok. And, the flame moves this entire block of wrinkled flame moves into the unburned mixture with the velocity of S T, ok. This is a simple model for simulating premixed flame situations.

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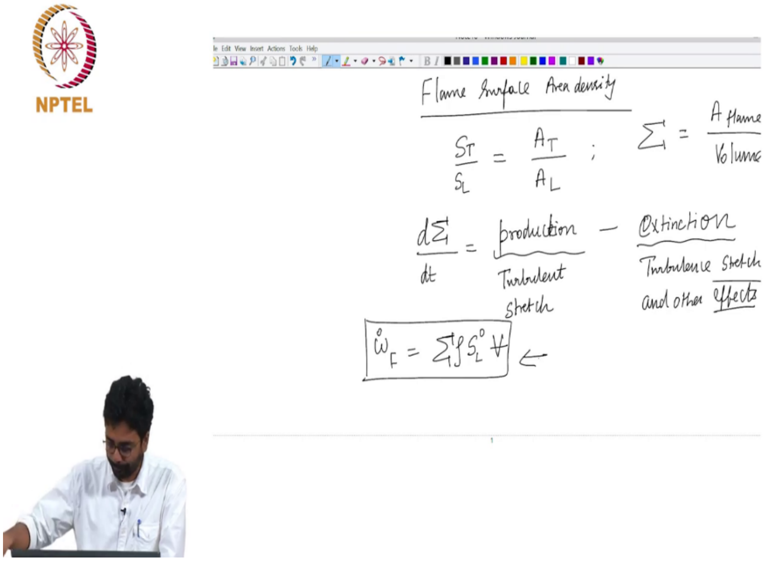

Flame Surface Area density

$$\frac{S_T}{S_L} = \frac{A_T}{A_L} \; ; \quad \Sigma = \frac{A_{flame}}{Volume}$$

$$\frac{d\Sigma}{dt} = \underbrace{\text{production}}_{\text{Turbulent stretch}} - \underbrace{\text{Extinction}}_{\text{Turbulence stretch and other effects}}$$

$$\boxed{\dot{\omega}_F = \Sigma \rho S_L^0 \forall} \leftarrow$$

Another approach is based on the flames surface area density which is equivalent to the Bray Mass Libby model. This is based on the idea that locally the flame retains the laminar flame structure, but it is wrinkled by turbulence. Therefore, the turbulent flame speed is simply the ratio of the turbulent flame, area of the turbulent flame to the area of the laminar flame, ok. So, this is the 1 d projected area, this is the total area of the corrugated or the wrinkled flame, ok.

So, conservation equations or transport equations are returned for what is called the flame surface area density which is the area of the flame per unit volume, ok. And, and the equation for sigma will have terms that can produce flame surface area the production terms. This is mainly because of the turbulent stretch minus the extinction, cross of again cross of turbulence stretch other effects, ok.

So, this is a transport equation for the flame surface area density which has production and extinction terms and from the flame surface area density average reaction rates are calculated. Assuming that within the flame structure reactions still proceeds at laminar flame speech, ok; times volume will be the average reaction rate ok. This can be plugged into the species conservation equation and we can solve for the flow field, ok. Thing that is about all that I have said anything I should heard (Refer Time: 35:17), that is about all that I have to say about turbulence modelling.

Of course, this is just an overall picture for your reference, I will just write down the name of the book that has more details, ok.

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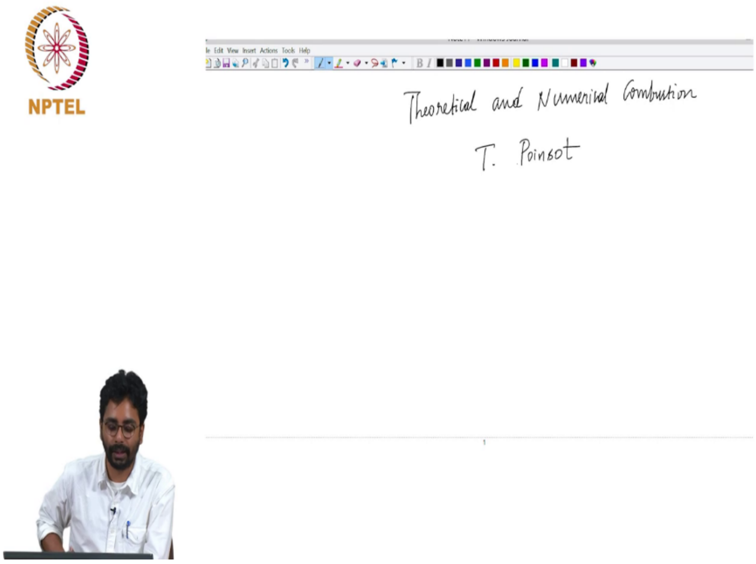

Theoretical and Numerical Combustion

T. Poinsot

This has a lot more details and in fact, a lot of interesting data on DNS and LES on specific configurations that have been performed, ok.

Thank you.