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COMBUSTION

Lecture 48
Turbulent Combustion

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So we have these definitions for pursuing the idea of regime diagram for clinics turbulent flames of course in this process we have assumed somewhere along here that the Schmidt number = 1, so let us suppose that for scaling purposes.

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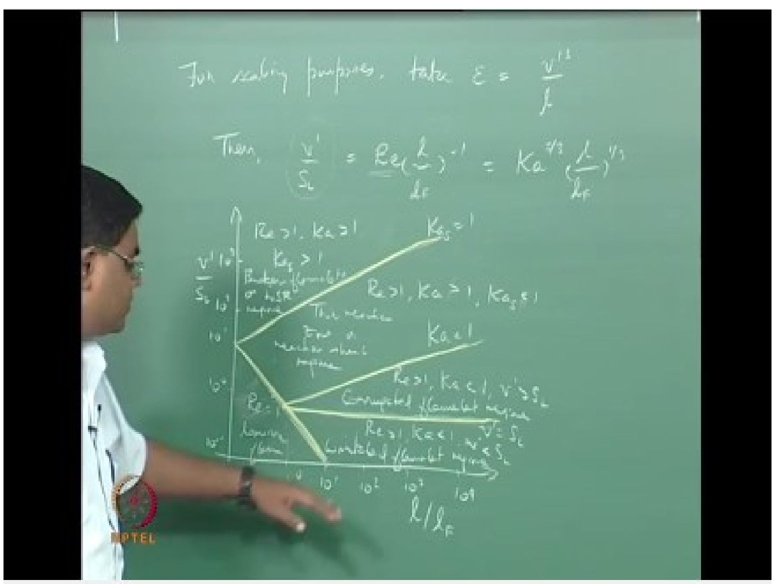

Or take the turbulent dissipation V `$^{3}$ developed by the integral length scale, could only show typically that it is of the order of but let us suppose that big take it is = to then putting things together way essentially what you are looking for is an expression for V` / S_L in terms of non dimensional quantities, so the non dimensional quantities actually what we are looking for is expressions for V `/ S_L in terms of L / L_F with the non dimensional quantities involved in there and we should now be able to show that this is = to retimes L / L_F to the - 1 and it is also =to Carlo words to the two-thirds / sorry times L_F.

L times L / a left turn to the 1/3 why are we doing this because that is what the regime diagram is all about their regime diagram is 1 on the V` lower SL on the vertical axis plotted against l_{olf} what this basically means is that when you want to talk about turbulence you talk about it in by characterizing in two ways, 1 what are the length scales involved in the Indy turbulent flow that we are talking about the other 1 what is the intensity that is involved okay. So these are these are two things essentially it is sort of like in a time a signal kind of thing what you are talking about is what are the frequencies involved and what are the amplitudes involved right.

So these two things essentially indicate that and in both the cases and for both the parameters what you are looking for is to compare these two with their corresponding flame related quantities, that means we are saying can we now look at the turbulent length scales in comparison with the flame length scale like the flame thickness right. So are we having typical Eddie sizes that are all that are bigger than or smaller than the flame thickness right that is on the 1 side as far as the scales is concerned and as far as the intensity is concerned.

When you now have a flame that is trying to propagate at a particular speed if the flow that is out there is now fluctuating right, I read a certain intensity if the fluctuation is very small that as a flame is beginning to propagate it does not really go through any jitter, it just the this is so small that the flame can just go through without even realizing that it went through a fluctuation right. Then you do not really have a turbulent flow at all in other words if you now had significant amount of intensity flux it either means the amplitude is a very large right.

Then the flame is going to now go through fluctuations correspondingly, therefore how is these fluctuations the fluctuation in turbulent fluctuation intensity, and how is it comparable to the flame speed itself right. So these are the two things by which we want to compare characterizes, so we will now have values thrown in on a log-log plot this is actually logarithmic diagram, so we will now look at 10 to the - 1 10 to the 0 10 to the 1, 10 to the 2, 10 to the 3 etcetera oh maybe just 1 more s phase 4, 10 to the 4.

And similarly / here could actually look for something like a squares picture 10 to the - 1 10 to the 0 10 to the 1 10 to the 2 10 to the3 and so on okay and what we want to point out here is the relationship between V`/ SL and L/ L F through Reynolds number is 1 of a inverse relationship right that is this goes is 1 / that and with a Reynolds number as a coefficient and therefore we would actually like for a normal plot it should actually be like a rectangular hyperbola that is forming the relationship between V ` / s L to L / L F for constant Reynolds number.

But this is actually a log-log plot so in a log-log plot this actually shows up as a negative nail straight line with a negative slope and in this particular exercise what we are trying to do is to have for example in this case this involves like the scaling and we are using a which number or value of about 10 and that is something that we have stocked we have seen long ago when we are trying to scale the pre-mixed flame thickness to find out, how much is the reaction zone thickness is going to be relative to the preheat zone thickness.

And so correspondingly we now expect that a Reynolds number of 1 a constant Reynolds number of 1 line is going to be a straight line in the log plot with a with a slope that is inclined downward for R = 1 and this regime, now is essentially what we call as laminar flame the things with the turbulent Reynolds number defined this way this line corresponds to R = 1 anything > or = 1 forms this region to the right off and above of this line and anything that is to the left off and bottom below this line is laminar right.

So that means for turbulent flames you are essentially interested in all of this regime that is there is power point number 1, then the next thing that we have to look for is how is V ` / S_L related to L / L_F through caller wits number, so can we now plot constant car of its number lines and the answer is this is actually going is 1 third of that and therefore in a log-log plot it is going to be a straight line with a slope of 1 / 3 all right and then the line is going to go upwards. So we start the start doing this at this point corresponding to 1 over here and now draw a line that is k_a = 1 and carol bit is =to 1.

We now start from this point, so we now have this entire turbulent combustion regime at the moment divided into two parts right, 1 which is having a core of its number < 1 and another 1 that where the car love it is number > 1 and in both the cases the Reynolds number is > 1 within this regime, we now want to further differentiate between it well she could use actually a straight line in continuous straight line this is an horizontal line, this is a horizontal line corresponding to v ` / $S_L$ = to 1 that means V ` =to S_L right.

So this is a regime where r e >1k < 1 but V ` is > itself this is a regime where r e is >1k < 1and V ` is also < S_L right and finally we want to now look at the situation where the second curl of it is number is >1 right. So we now have a boundary and that is also going to go the same way because Carlo its number that this is basically ∇ 2 collar wits right, so they are directly related so V ` / S_L in terms of Hollywood's Δ Ka Δ is going to also have a 1-third relationship for the lof all right.

With simply a different coefficient Δ square, therefore you will have the same slope but then it starts at around ten because we are not looking at as which scaling of 10 and so mainly these things could be a little bit off this way that way okay but essentially we are getting the picture like this depending upon the value of your number and this line corresponds to k Δ =to 1therefore this is re there for you, now go back and say re >1 Carlo it is lake is >1 but Carlo it is Δ < 1 and here we now have re >1k a > a Δ let us just use the space k Δ >1.

So that means we now have four regimes that we have marked 1 based on Carlo it is < 1 but V` >or < S_L gave you got to and when Carla which is >1 we still have caller with Δ < or >1, so that is how we are splitting this so what is the significance of doing it this way the answer is we are now going to, now call this the wrinkle flame lit wrinkle flame lit regime and we are going to call this the corrugated frame lit regime we are going to call this thin reaction zone regime or reaction sheet regime you can call it either way so again Satan reaction zone or reaction sheet regime.

And this is what this is what you would call as broken flame let us regime or the well stirred reactor regime it is differently called in different textbooks in this way well. So that is kind of interesting so just to make it a little clearer we could probably use like a different colored sharpies cool lines that we lock talking about that demarcate these five regions and so why are we the question is why are we calling these what they are right, so now let us think of think about what happens in each of these cases.

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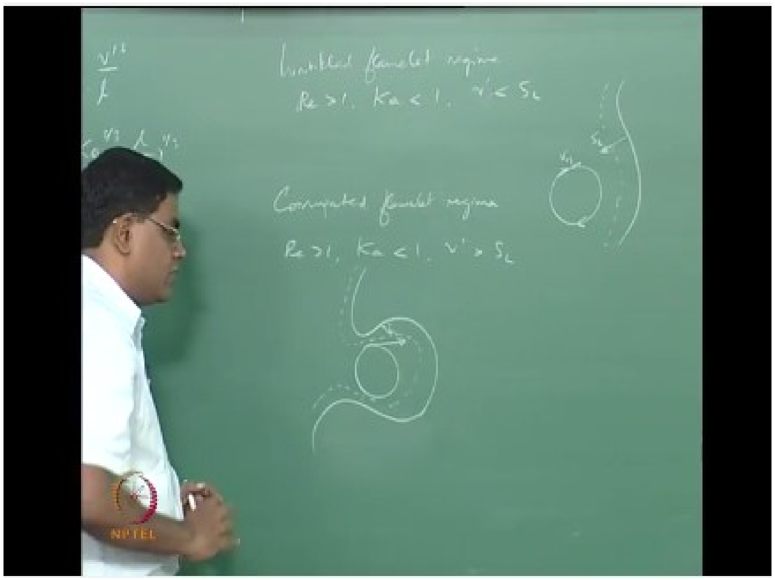

So the first 1 is the wrinkle flame lit regime and here we are having situation of re >1k a < 1 and V ` V ` < S_L so when we say ka is < 1 and look at what is k_a is essentially the flame time to the time all right so essentially it is comparing the flame scales with the Collar scales or essentially what it basically says is we are still looking at the flame to be significantly thinner than the turbulent scales right. So that is what that is what it basically means, so you now have a flame let us say marked by two lines that is we will try to do this for quite some time.

And then the point essentially is we will be able to do this for quite some time and that is what I would like to impart here these two lines are essentially this does this line like the reaction zone and the Technical including the thickness of the reaction zone and the dotted line is actually the upstream edge of the preheat zone. So the preheat zone is spanning the thickness corresponding to this distance between these two lines and the thickness of this continuous line itself represents the reaction zone right.

So effectively in a 1-dimensional flame you would have the reaction zone an upstream of it you will have the preheat zone, so the upstream edge of the preheat zone is what is marked by this broken line but we are now talk showing it as curved because what we are basically saying is this is now interacting with an eddy that is going around like this, so it is tangential velocity is Vn depending upon the ad size and this flame is now propagating locally normal to itself with a flame speed S_L right and since you are having a situation where V` is still < S_L the intensities are significant to make the turbulence felt by the flame.

Unlike in a laminar flow but still not enough to penetrate the flame or do anything more all it does is to basically make the flame wrinkle around the right the flame is 210 and then so the whole of the flame is too thin okay, we will now progressively get to the point where the any sizes are smaller when compared to the flame thickness or the flame is becoming thicker when compared to the ad sizes whichever way right and then things are going to get a little bit more complicated.

So the next regime for example would be the corrugated frame it regime where the Reynolds number is > 1 all right the curl of its number is still < 1 all right but V ` is >S_L so this means the intensity is now larger than the frame speed, so the theories are now going to make their presence felt on the flame a lot more. So what this basically means is the velocity here is going to be large and correspondingly the flame has to give ways that is how the flame was always tries to do things right it.

Now when the flow is locally large it gives way by inclining itself to the flow such that only a comp1nt of the flow direction is balanced by the flame speed right, so what then happens when this now begins to increase is so if you now think about a Eddie that is now having a larger V_N and I now have a flame that is interacting with it now actually begins to curl up to encompass that, so which means in fact it should you should you could exaggerate this a little bit more by saying strictly speaking you could say.

That means you know the corrugation in the flame can now house and Eddie comfortably right previously we do not have the flame corrugated so much but now you have a corrugation of the order of the any size right, so that is reason why it is called a corrugated flame. Then we now get into the thin flame thin reaction zone or the reaction sheet regime.

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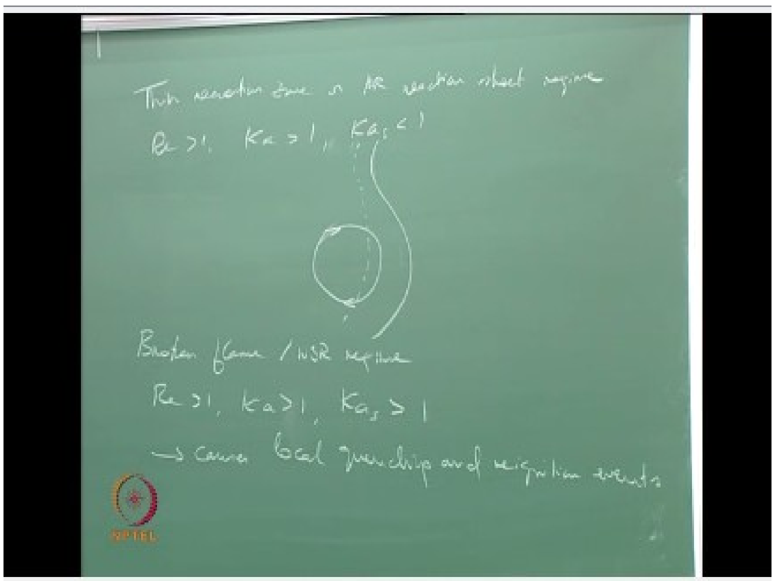

So here Re is > 1 and Carlo obits is also greeted at 1 and of course V ` is > S_L be aware we have long passed we are going to pass that long back right and therefore what we are talking about is Carlo obits is >1 and that means the turbulent scales are now bigger than the third that the turbulent look at this if Carlo which is > 1 then the flame thickness is now getting to be bigger than the turbulent scales right. So what that really means is you are now going to have a flame that is having a preheat zone starting out like that.

But you now have an ad that is that is big enough to penetrate the preheat zone and then the preheat zone, why does the preheat zone thicken is because you now have a turbulent transport of heat and mass the job of the preheat zone is essentially transported okay, where heat from the reaction zone is being transported upstream to the reactants and mass from the reactants is being transported downstream to the to the reaction zone right.

So you have a heat and mass transport that is happening in the preheat zone which is now in addition to the molecular transport that happens because of temperature and concentration gradients is also additionally happening because of the eddy, that means this Eddie is now taking the reactants and putting it into the preheat zone for the reactions to consume and taking the heat from the preheat zoom and bringing it a priori ahead to the reaction zone and heating it up right.

So if you want to think about this in a statistical manner it is as if like you had a fairly thick preheat zone the Eddie was doing the job of taken in the preheat zone right, so you know can only talk about a reaction zone that is now trying to give accommodate the DD Eddie but the preheat zone has been breached that is that is essentially, what is going on so therefore that is the reason why we are calling this a reaction sheet regime that means all that we can talk about as a characteristic of the original premix laminar flame is the remnants of it is only the reaction zone the preheat zone is now marred right.

So effectively the way we are thinking about this is can I hold on to my laminar knowledge right and that is just beginning to get breached here by the turbulence until then it is okay right and there is a reason why we have been using this there is this term called flame that all the time and there is this basic idea of what is called as laminar flame. Let us the pins you can now think about in these regimes we can still continue to think about the turbulent flame or the turbulent combustion zone as being made of laminar flame.

Let us write so locally where you have these things satisfy you can now say it is essentially a laminar flame but it is now interacting with an eddy and therefore it is getting curved or corrugated wrinkle de corrugated right, so you can you can continue to preserve your idea because the original local structure of a 1-dimensional laminar flame how we extend it from a 1-dimensional pre-mixed flame to let us say for example a Bunsen burner the shoulder of the flame there or the base of the flame there or the tip of the flame there in all these things we try to accommodate the 1-dimensional idea.

Locally the flame is trying to match the flow right or it is shaping itself to match the flow and that happens everywhere still right, so you could you could you could hold on to that that means locally if you now look at these gradients you can draw exactly the same pictures that you drew there is the concentrations are now falling down the temperatures is now growing up and all that stuff, that structure is they are right but hear that structure is breached okay.

Except only for the reaction zone and then finally you now get into the WSR or the broken flames the well stirred reactor WSR regime here course the Reynolds number is >1 of course the caller wits is > 1 when we got to go back and point out that we still have Carla with Δ < 1 therefore the previous case that means the airy sizes are still not big enough to act sorry small enough to breach into the reaction zone, but that is no longer the case here. So here we have caller with Δ is also > 1 right.

So in this case what happens is the even the reaction zone is torn apart, so that means you now have the flow getting into the reaction zone and coming back again and locally it constrain the reaction zone and cause local quenching Andrei ignition and so on so, that means you now have the flame torn apart into shreds because of these are right so this is this causes local quenching and Ray ignition events.

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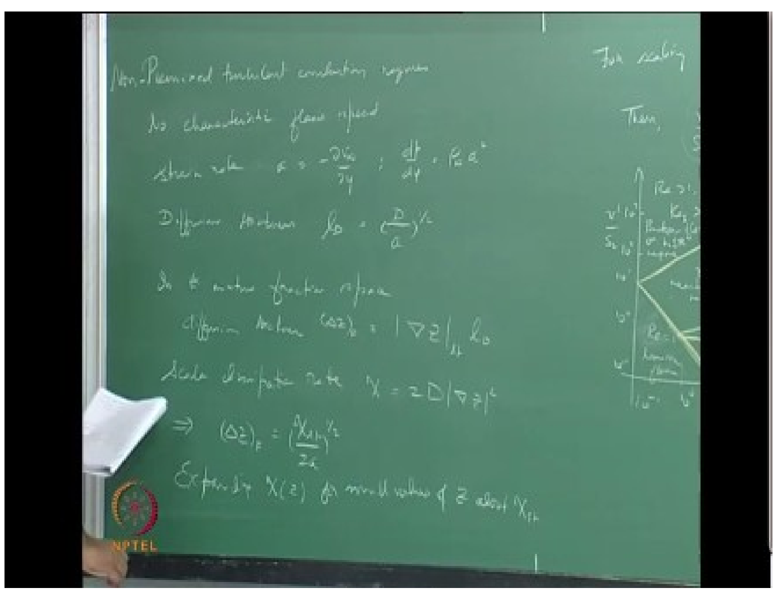

Let us now talk a little bit about non climax combustion so non premix turbulent flames I am following Peters here and there is more work that is being d1 further out and more in more recent past but I am nothing that material as far as this is concerned, now the problem with non premix combustion regimes is we do not have a characteristic flame speed here right but instead what we want to actually look at is if you are looking for velocity gradients in the flow and of course turbulent flames will have velocity gradients in the flow.

So if you are now looking at something like a strain rate strained rate, let us say it is given by symbol a and you have like let us say something like go infinity we do be infinity by ∂ Y for the flame it is also related to the pressure gradient in the flow that is like you can say dy = r ρ infinity a 2 where a is the strain rate and so if you now have a strain rate then the strain rate actually has dimensions of time okay, so this is meters per second this is meters right so it is all explained it has a damage to the 1 / time right.

So then with this we should now be able to come up with a diffusion, thickness diffusion thickness or le = to / a the whole three half so that is like meter 2 per second divided by 1 / second so the 1 / second gets canceled you get me two 2 per sq meter, so now we are we are basically looking for something like a characteristic dimension associated with there is a flame in order to be able to compare with the turbulence, that is what we were doing for the premix flame there it was rather easy to think about a time and space relationship through the flame speed.

But here we did not have a flame speed, so we are going through this, the next thing that we want to do is we do not want to actually think in terms of physical space because in diffusion flames the mixed refraction actually comes up as a very handy tool and we went through this when we did when we did the fusion flames you see. So when you have diffusion flames it is 1 thing to actually get the flame shape in physical space but if you want to actually look at the flame structure you are better off looking at the mixture fraction space.

Because in the mixed refraction space all the concentrations and temperatures are all related to the mixed refraction and if you now supply the local mixed refraction you can find out how the how these things very right. So in the in the mixed refraction space we can now have a corresponding diffusion thickness that is corresponding to the diffusion thickness that we have defined L_D diffusion thickness in the mix of fraction space now is let us suppose we call this Δ Z F again the subscript F is corresponding to here.

Because we are looking at the diffusion thickness around the stoichiometric surface right because you have the frame and then you now have a certain length scale associated with the flame that the ad wants to interact with right. So the in the mixture fraction space it is always about the stoichiometric mixed refraction where the famous, therefore what you are saying you know what you are looking for is the conversion from the physical space to the mix diffraction space goes through the modulus of the mixture fraction a map modulus of the gradient of the mixed refraction at stoichiometric condition X_{LD}.

And we also have the scalar dissipation rate so scalar dissipation rate K_Y we did design never define this and that is twice d grad Z quiet so obviously we can get an idea no we want to try to put these two together, so that means ∇ hazard if the diffusion thickness in mix diffraction space is ξ st divided by 2a the right. Now if you want to just make this bit simpler what you can do is you can now expand ξ st about ξ about ξ st for small values of Z and then approximate let us say let us not say or let us say the sod is not varying too far out from Z st right.

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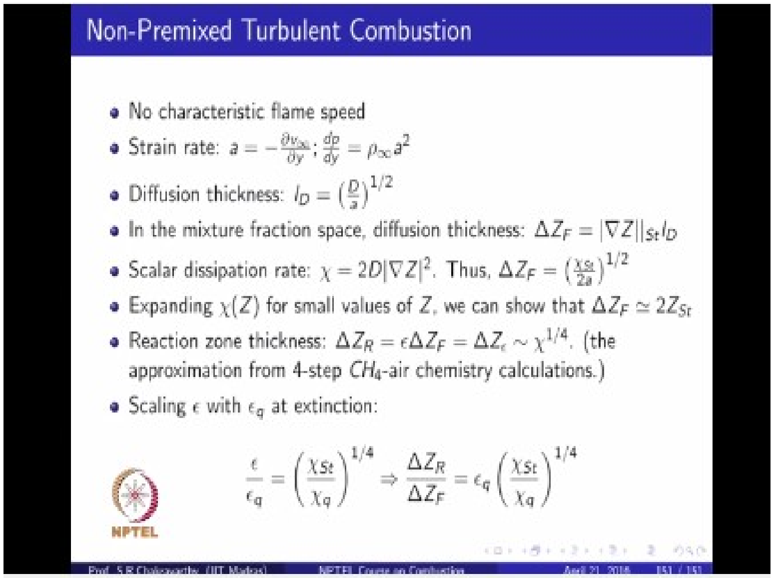

And then ξ depends on Z therefore expand ξ about ka stay for small values of Z that is like a Taylor series approach, so expanding ξ of Z for small values observed about ξ st and when you say small values observed that means we are approximating, so we can show that Δ 0 is approximately 230 right.

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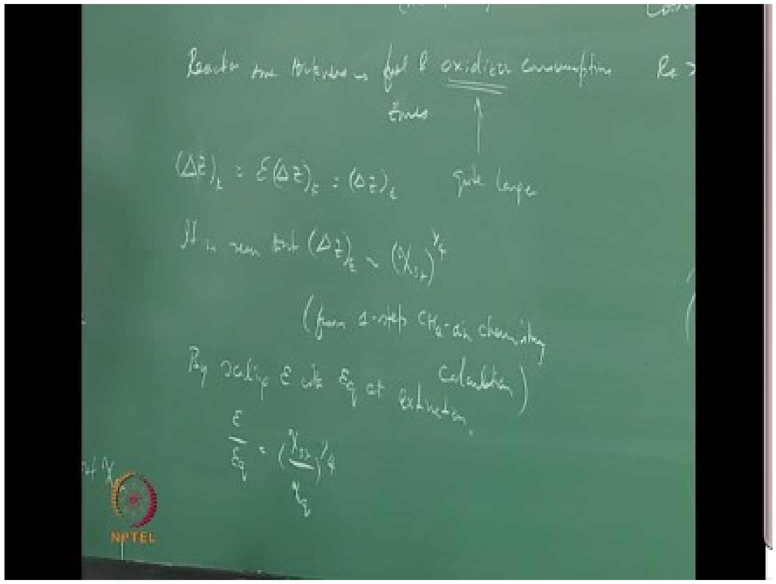

So this is effectively the counterpart of counterpart of L_F in premix flames right and should be basically point out that this is mostly the preheat zone and we did point this out when we were doing diffusion flames if you recall right. So when we did the laminar diffusion flames what we pointed out was the Burke Schumann assumption was essentially saying that the flame is a sheet along the stoichiometric surface but that was essentially the reaction sheet right.

So it is sort of like saying in the pre heat lean in the premix flame you know if you now think about only the reaction zone as a sheet but consider the thickness of the preheat zone like the way we have been drawing pictures here right, then what happens in the appeal in the shire minh problem you have a flame that is a sheet which is like a reaction zone and you do have the transport going on that is mixing of fuel an oxidizer and our heat all these things are going on outside of this sheet and if you want to think about what happens the reaction rate, the infinite reaction rate assumption is the 1 that says that the reaction rate is almost infinite here.

But if you now try to zoom in and then clarify this reaction zone like we would we would do in the parade preheat premix a flame then we would find that it is essentially the reaction rate there is going to be peaking only at this sheet similar to how we did in premix flames right. So effectively in most of these we have been mainly interested up to here we have been mainly into spit in the premix flamed regime diagram watch the preheat zone doing relative to the eddies right.

So similarly if you are now thinking about a corresponding diffusion thickness for the flame we should be worried about this in the mixed refraction space this which is this how is that going to actually interact with the 80 and that is like the counterpart of mostly the pre heat zone of the premix plane, and here again the laminar radius or coming back to help us. Now the reaction zone thickness on the other hand right, so this is the 1 where you have the fear and oxidizer consumption zones right.

And we would like to point out that the oxidizer consumption zone is actually quite larger in reality, that is that is what we are saying is if you, now do actual chemistry right the detail chemistry for that same attain our flames or something what you should find is the oxidizer significantly leaks out of the reaction zone to a farther distance outside into the field region okay. So keep that in mind and we would like to now call this Δ Z are this is the counterpart of l Δ that we had in the preheat zone in the pre-mixed flame sorry.

And we would now like to relate this to a ε Δ Z left that means it is a it is a fraction of the diffusion thickness, now what we know from literature on detail kinetics like or diffusion flames up detail kinetics is so we will just take this empirically here, so it is seen that so let us just call what we wrote here as Δ Z ε Δ ε is going with respect to kst power 14 this is actually from for step with inner chemistry calculations.

And then we try to relate the ε hereto the extinction ε, so by scaling ε with ε q @ extinction then we can show that ε 0 ε q is ξ st / kike you to the 1/4 and therefore Congress right here Δ Z are divided by Δ Z F s ε cube high st / yq to the ¼, now the reason why we want to do this is this is actually the 1 that gives you l Δ/ l that is a counterpart in the premix flames that we saw which is what is the length scale corresponding to 1 either reaction zone thickness, sorry LDL Δ/ LF we are so as i said this is the counterpart of LF and that is this and this is the counterpart of l Δ okay.

From pre heat zones, so we are kind of doing something very similar here is what we did for the preheat zone so premix flames.

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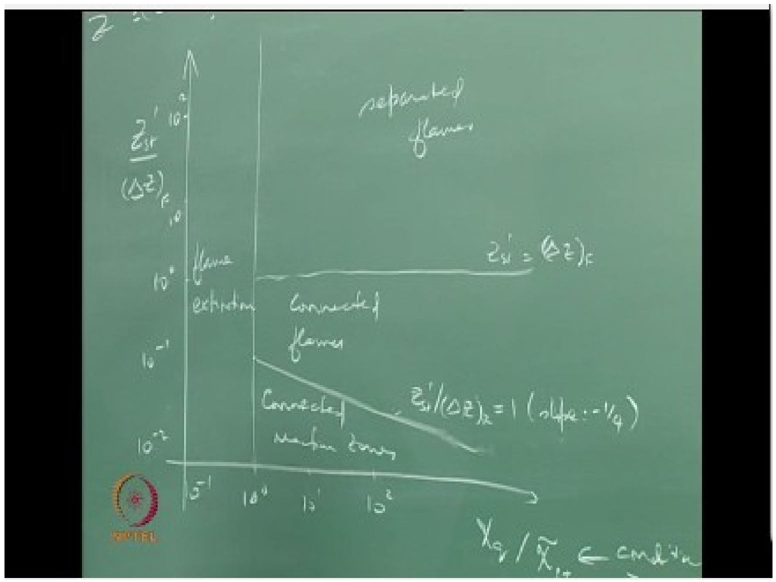

So what we want to plot here is a fluctuation amplitude z ` divided by the diffusion thickness in mixed refraction space and on the right, answer on the on the x axis or the Arizona Lexus we want to plot something as a measure of turbulence which is now going to be the scalar dissipation rate at extinction / scale of dissipation rate at stoichiometric, now strictly speaking we got to actually average this to indicate a far average in fact this is what is called as a conditional for average scalar dissipation rate.

Let us not worry about what are doing what it exactly means for the moment we will simply take it as of the order of the same order dress the scalar dissipation rate at its lucky metric condition and in fact I should also point out, what is what is meant by this Z ` so Z ` is nothing but Z what's called as its ∂ble` 2 tilde the half ∂ble ` essentially indicates a father averaged fluctuation so this is a essentially af lower or MS okay so it is a root-mean-square of the fabric fluctuation okay so that is what it means.

And similarly you now say sub` st what we really mean is the root mean square fabric fluctuations obtained at the stoichiometric condition right. Now if you are so now let us put some numbers here, so we can say 1 or 10 to the 10 to the 0 10 to the 120 the 2etc there and then let us say so this is 10 to the - 1 let us start with 10 to the - 2 in the y-axis 10 to the - 1 10 to 20 10 and 10 2 and so on and what we should be interested in is a region that is > ξ q by ξ is t >1 because when you now have a region that is <1 this is the extinction ξ.

So essentially this corresponds to flame extinction right and then what we should be interested in is when you have actually we should show this so we have Z ` st / Δ Z F going as ξ q / $K_Y$ as he again see that here you have a this is opposite so you have a - 1 / 4 in a log-log scale, so starting from here you know go through a line that is like this so this is sub` in fact I should say that st divided by Δ that are = 1 and this is slope - 10 4 we are we are taking as approximately same as kst here.

As i said and then you also have 1 more situation where you are looking at similar to previously where we had u ` is comparable to SL and zesty ` is comparable to Δ s so that is here, so this is Zst ` = Δ Z F, so that now breaks up things into four parts 1 is so the flame extinction is, 1 region then we have what is called a separated flames connected flames and the connected reaction zones right. So let us again explain these things so when you now have so where you now have for example.

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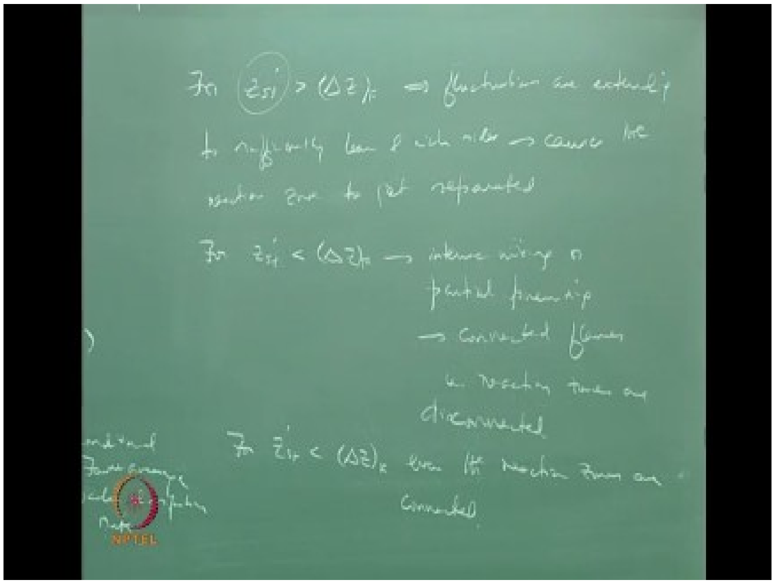

Z to see >Δ F right now what this means is you now have fluctuations that are actually >the Δ Zeta and ΔZ_F is actually corresponding to like the preheat zone and this basically means that fluctuations or extending or to sufficiently lean and rich sides and therefore what this means is that you are now taking in taking some amount of so the fluctuations are, now causing some amount of lean side of the flame to go to the rich side and vice versa.

So this actually begins to now separate the flames because the flames are effectively dictated by the what is near the stoichiometric surface for the reaction zone and if now you have these things going on you will now create intermediate regions of stoichiometric surfaces, so the original flame is essentially broken, so this begins to cause separated flames so causes the reaction zone to get separated now for zs t < Δ Z def right.

We do have intense mixing but not enough to cause separation and sometimes you can also get partial pre-mixing, so what does what this means is you can have the reaction zone move around without really getting disconnected but you will now have the preheat zone gig have the flow since the fluctuations. So effectively then you do not you do not really have disconnected reaction zones. So this is essentially connected flames that is a reaction zones are connected and finally for Zst $< \Delta z$ are this is now beginning to look like fluctuations are still smaller than the reaction zone thickness itself then even the reaction zones should say your reaction zones are disconnected but here even the or connected. Now what it turns out is actually you can sense these things completely in a diffusion flame.

So if you now think about a jet diffusion flame along its axis then the D_J diffusion flame axis actually goes through these different regimes, as you go along this and come down along here so you can now see these different regimes exist in a jet diffusion flame corresponding to this will stop here and pick up from here somewhere on some other day you.

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