Combustion in Air Breathing Aero Engines

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Lecture - 42
Turbulent Premixed Flames I

Hello friends, welcome back. In the last class we have seen that we did turbulent non premixed flames. So, in this class we will start with turbulent premixed flames and go into several aspects of it. In this class on turbulent premixed flames will mainly go into lot of the physical aspects of it like the structure of turbulent premixed flames which will explain in terms of things called regime diagrams, which we did on little bit for non premixed flames also. And then we will introduce some modeling approaches in the sense which we will call this g equation approach as well as the Bray-Moss-Libby models.

And subsequently we will introduce a very important quantity for turbulent flames premixed flames all the turbulent flames speeds. So, as such you have seen that for laminar premixed flames the most important quantity that determines that the most important property of a turbulent of a laminar premixed flame is a laminar flame speed. Similarly with the most important property for a turbulent premixed flame is the turbulent flame speed. So, we will go into that and towards the end of this class ok.

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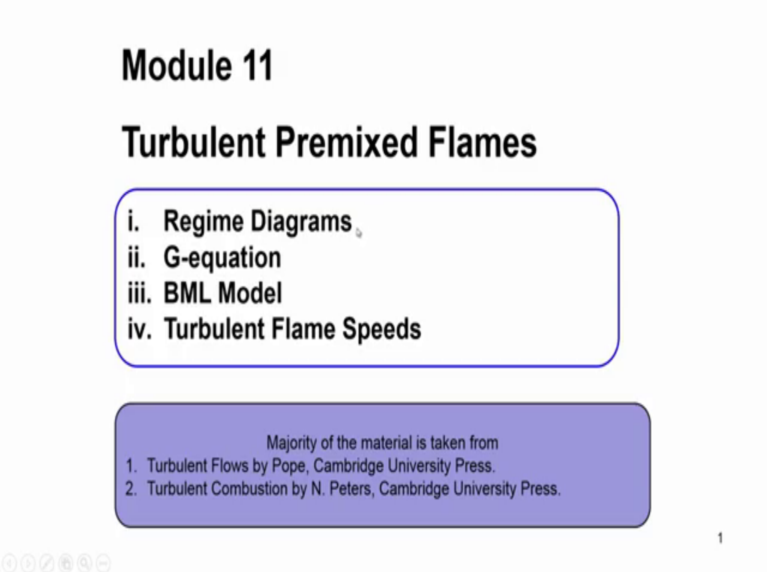

Module 11

Turbulent Premixed Flames

i. Regime Diagrams
ii. G-equation
iii. BML Model
iv. Turbulent Flame Speeds

Majority of the material is taken from
1. Turbulent Flows by Pope, Cambridge University Press.
2. Turbulent Combustion by N. Peters, Cambridge University Press.

So, first we will go with basically this things called the will go with this regime diagrams. And then we will go with this g equation model Bray-Moss-Libby models. And turbulent flame speeds and the majority of this material is mainly taken from the turbulent combustion book by Norbert Peters. And little bit from turbulent flows by pope also.

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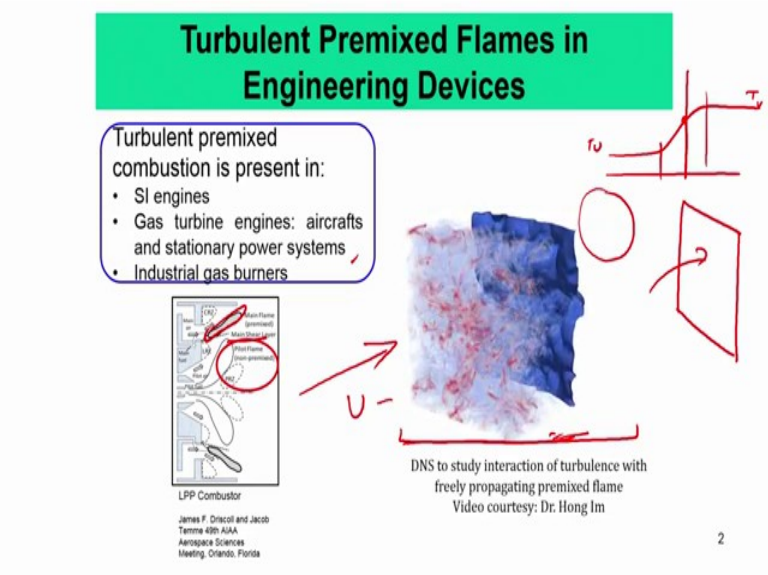

Turbulent Premixed Flames in Engineering Devices

Turbulent premixed combustion is present in:

- SI engines
- Gas turbine engines: aircrafts and stationary power systems
- Industrial gas burners

LPP Combustor

James F. Driscoll and Jacob Temme 49th AIAA Aerospace Sciences Meeting, Orlando, Florida

DNS to study interaction of turbulence with freely propagating premixed flame
Video courtesy: Dr. Hong Im

So, where do we find turbulent premixed flames in engineering devices? Turbulent premixed flames are found in SI engines spark ignition engines in car engines which are used in car engines. And in gas turbine engines of course, and mainly in stationary power plants and industrial gas burners you find turbulent premixed flames.

Now, in gas turbine engines as we have discussed in last class that mainly because gas turbine engines use liquid fuels, the flames that are formed are mainly non premixed flames, but still as you have seen that in non premixed flames you really cannot control the temperature as such the temperature of the flame though you can control the exhaust gas temperature by dilution with the excess air. But the temperature of the flame really cannot be controlled for non premixed flames, and that leads to formation of this pollutants and stoichiometry combustion and near stoichiometry combustion reach combustion leads to formation of this suit. So, you really cannot avoid pollute information in non premixed flames.

Now, whereas we have seen that for the premixed flame of course, the premixed flame temperature is totally controlled by this stoichiometry, that is if you have a fuel lean mixture of course, the temperature is less if, you have a stoichiometry mixture the temperature is high. So, that is why you have a better control on the on the flame temperature if you have a premixed flame. So, that is why it is we in the gas turbine engine 7 for the aircraft engines to with the stringent with the stringent emission norms, that are coming the aircraft engine industry is moving more.

And more towards premixed flames and as such you have seen in the last class also, that this very modern engine this g and x engines which they use for powering the boeing 7 8 7 aircraft and the taps combustors that they use to in a (Refer Time: 03:35) premixed solar combustor and that is essentially a lean premixed pre vaporized combustor. So, it is a large fraction of the flame that is formed in this taps combustors or this g and x engine combustors. They are essentially premixed flames. So, as you see in the industry the arriving the aircraft industry is moving towards premixed flames. And the reason is simply the following that you can have much less pollution for pollutant formation in this kinds of in this kinds of a combustor.

So, that is why the gas turbine industry is shifting more towards burning premixed flames. And then of course, it has you have to have the additional process of premixing. So, we are we are moving towards that and that is why it is important to understand. How turbulent premixed flames behave. So, here on the right hand side you see this image of this video of a of turbulence like a turbulence impacting on a on a initially flat premixed flame. So, this is this blue surface initially is a flat it is essentially a laminar premixed flame and then turbulence comes on impinges on that. So, this surface is actually a representative surface of the premixed flame.

So, it is essentially an ISO surface of temperature of about 500 Kelvin which is selected from the premixed flames. So, you see that premixed flame has this kind of a structure right. The temperature increases like this is unburned this is burnt. And this is this is the burned gas temperatures this is unburned gas temperature. So, you can select actually one particular temperature inside that which is a 500 Kelvin. And you can we can when you when you basically look it in 3D. It is essentially a flat surface like this if it was a laminar premixed flame right. Planner laminar premixed flame. Now then this turbulence comes and on it and impinges and it create this sort of different things.

But what this does this actually you see the different vortex this actually beautiful visualization of the turbulence also, this essentially you get this vorticity structures this fine scale vorticity structures, that are forming on the premixed flame. So, you see that in this premixed flame what it happens when as soon as it impinges on this on this on the surface it essentially folds, and wrinkles the surface at a multitude of length and time scales. And this length and time scales are controlled by both turbulence as well as the intrinsic flame properties. And then after it folds and wrinkles the premixed flame at a multitude of length and time scales, you see that this surface essentially annihilates in this straining regions of the flame.

So, the flame this turbulence essentially stretches folds and wrinkles the surface at different length and time scales, and then the surface is actually destroyed this ISO surface of temperature is actually destroyed. So then; that means, there is a continuous generation of surface also. So, a premixed flame structure that you have a turbulent premixed flame is this complex this convoluted wrinkled structure that you see, is actually characterized by continuous generation and annihilation of the turbulent of the flame of the surface of the flame surface by turbulence.

So, this is how turbulence actually interacts with the premixed flame, and this interaction between turbulence and combustion and the flame, is what gives the result in structure. So, the result in structure of this turbulent flame that you see is not a property only of the flame or a property only of the turbulence, it is a property that emerges due to interaction between the turbulence and the flame. So, you have to understand this one has to know the turbulence as well as combustion very well. So, that is why we have so we have spent in this in this class in the previous classes we have spent so much time on understanding the basic properties of flames ok.

So, you have to understand the basic properties of the flame you have to understand both the basic properties of turbulence and then only you can understand this kind of a turbulence flame interaction, but this is what is some form of this is what is happening in a gas turbine engine right. So, this is a very simplified version of what is unit version not a simplified version it is an unit it is an unit building block of what is happening in the in the gas turbine in is happening in the gas turbine engine. So, it is important to understand this. So, there is it is a as you see it is a beautiful phenomena it is a it is a very complex phenomenon also.

And that is why it is makes challenging and that is not makes the scientific study on turbulent premixed flame were enriching. So, it is a continuous interaction between turbulence and the flame. And of course, as you see that that the turbulence interacts with the flame at a different at different length scales that is captured in this in this video. Now as I said that this of course, in an engine the flame can be more complex is to presence of shear etcetera, here just it is a is a turbulent flow which is carried by the carried by a main flow into this main flow carry this turbulence onto this un to this premixed flames which impinges on this premixed flames. Of course, in an engine as you see here.

That this main flame branch it is it is actually stabilized in this the shear layers, in this main shear layer as you see shear layer. So, the presence of the shear also adds one more complexity to the flame structure, but nevertheless this we need to this these are complex phenomena, but this complex complicated phenomena is what this complex interaction between turbulence and flame, is what determines what will be the final heat release rate output from the engine, what will be the where the flame will be stabilized if it can be ignited and what will be the final temperature profile at the exit of the combustor ok.

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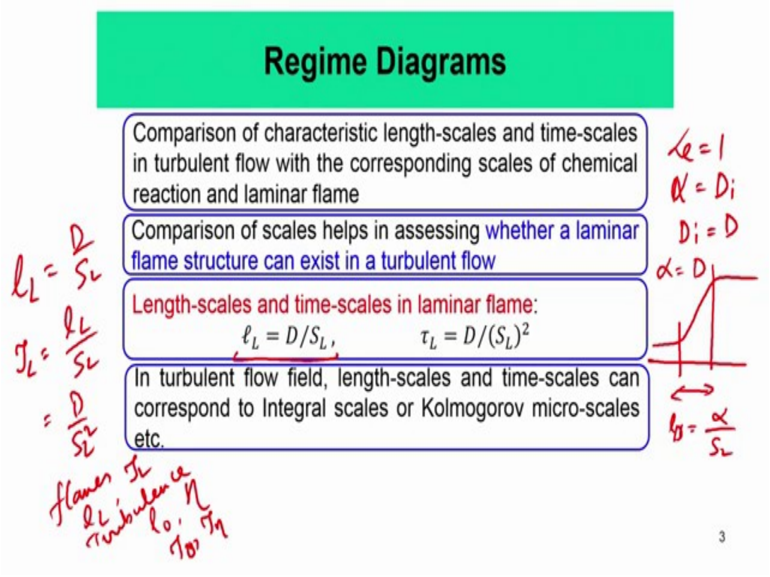

Regime Diagrams

Comparison of characteristic length-scales and time-scales in turbulent flow with the corresponding scales of chemical reaction and laminar flame

Comparison of scales helps in assessing whether a laminar flame structure can exist in a turbulent flow

Length-scales and time-scales in laminar flame:

$$\ell_L = D/S_L, \qquad \tau_L = D/(S_L)^2$$

In turbulent flow field, length-scales and time-scales can correspond to Integral scales or Kolmogorov micro-scales etc.

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$l_L = \frac{D}{S_L}$

$\tau_L = \frac{l_L}{S_L} = \frac{D}{S_L^2}$

flames τ_L, l_L

turbulence η, l_0, τ_η, τ_0

$Le = 1$

$\alpha = D_i$

$D_i = D$

$\alpha = D$

$\delta = \frac{\alpha}{S_L}$

So, many things that is what determines this is emerges from this turbulence flame interaction. So now, to understand that how does turbulence interacts with the with the with the flame, and we need to basically compare that the characteristic length and time skills in a turbulent flow, with the corresponding scales of chemical reaction and laminar flame. So, that is that is important. And we need to consider basically length and time scales of the of the of the flame of the of the turbulent flow, and compared with the corresponding length and time scales to the flame. And then we find out under where turbulence will win where the flame will win and where both can be at a competitive can compete with each other ok.

So, the comparison of the scales helps in assessing with the laminar flame structure can asses exists in turbulent flow. So, that is one very important, that we have understood we have taken up the structure of the laminar flame in a great details. Now the question is that is this when you have turbulence is this laminar flame structure whether this structure is reasonably well preserved and only bends and folds that is all. So, is it what is a turbulent flame just a bended form of a laminar flame under what conditions can that kind of a structure exist of course, you can expect you can expect that if the turbulence is extremely strong ok.

So then the inner structure of the turbulence of the of this laminar flame will be destroyed. So, in that case it may not exist like this. So, we need to find out under what regimes this laminar of structure of this flame can be preserved under what regimes this laminar structure of the flame will not be preserved and it will be in something entirely new. So, the length and time scales of a laminar flame we can define like this. So, this is actually just a new notation this l L is nothing but the flame thickness. So, if you remember that we discussed laminar flame structure like this and this was the diffusion length scale we defined that l D is equal to alpha by S L.

So, here what we is do is that we assume the Lewis number to be 1. The Lewis number is equal to 1 and hence our alpha is equal to D i and our D i is equal to a common diffusivity like D. So, we do not assume any distinct diffusivities we do not assume any distinct non unity Lewis number. So, Lewis number is a unity our diffusivities are all same. So, alpha is equal to D i and D i equal to D this means alpha is equal to D. And then we can replace alpha with D. So, our l L which is a characteristic laminar flame thickness; this is a characteristic laminar flame thickness is essentially D by S L. So, this is what we already obtained before from the laminar premixed flame class.

So, if it is D by S L the corresponding time scale is essentially l L by S L, and which we can write by a D by S L square. So, that is what we have done. Now in a turbulent flow field the length scales and time scales. So, we have got we have got 2 essentially character can be other scale length also, but in you have got essentially 2 2 bordering length and time scales. One is at the beginning of the inertial range you get this integral length scale and the light at the end of the initial range after that in the dissipative range you have got the Kolmogorov of scale. So, both the time scales and the length scales can correspond to integral on Kolmogorov of integral or Kolmogorov of time scales.

So, we have essentially then for flames you have the length scale as l L. For turbulence you have l 0 or eta and similarly the time scales for this you have tau l whereas, for this you have tau 0 and you have tau eta. So, these are the different of the length and the and the time scales that you have ok.

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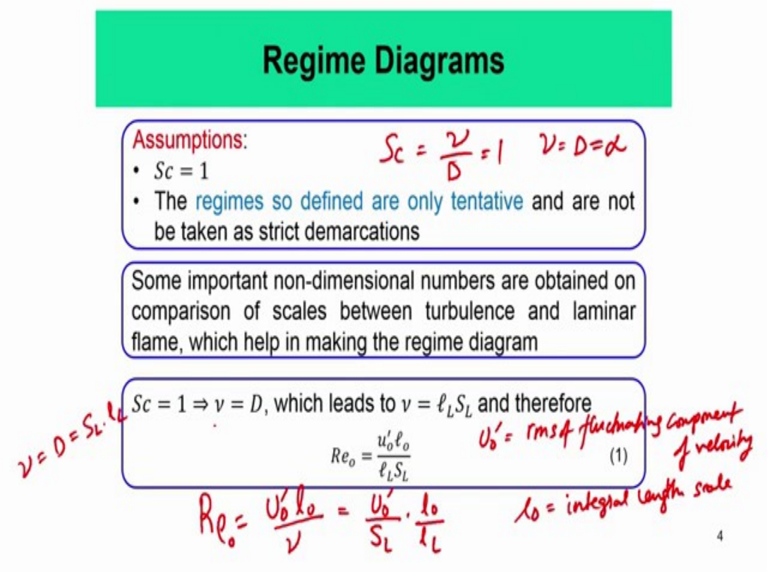

Regime Diagrams

Assumptions:

- $Sc = 1$
- The regimes so defined are only tentative and are not be taken as strict demarcations

$Sc = \frac{\nu}{D} = 1 \quad \nu = D = \alpha$

Some important non-dimensional numbers are obtained on comparison of scales between turbulence and laminar flame, which help in making the regime diagram

$Sc = 1 \Rightarrow \nu = D$, which leads to $\nu = \ell_L S_L$ and therefore

$$Re_o = \frac{u'_o \ell_o}{\ell_L S_L} \quad (1)$$

$\nu = D = S_L \cdot l_L$

$U_0' =$ rms of fluctuating component of velocity

$Re_0 = \frac{U_0' l_0}{\nu} = \frac{U_0'}{S_L} \cdot \frac{l_0}{l_L}$

$l_0 =$ integral length scale

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So, these are the different length scales and time scale of a, now of course, we also assume that the Schmidt number that is Schmidt number is nothing but nu by D. So, that is also equal to unity. So, essentially all our Schmidt number, Prandtl number everything is unity and our Lewis number is also unity. So, all this non dimensional thermo physical properties are essentially same.

So, all this non dimensional numbers are same and all the thermo physical properties are essentially same. So, nu essentially nu is equal to t is equal to D is equal to is equal to alpha; so when this regimes that we will define if it is important to remember that this regimes which will define our only tentative and should not be used as to take as strict demarcations. So, it is not that this regime that will define is just only it exists only this kind of structure only exists within this regime strictly and it cannot be found outside.

Because the regimes this boundary is a little bit blurred what I mean will become apparent very soon. Now some important a non dimensional numbers are obtained on comparison of scales between turbulence and laminar flame which help in making the regime diagram. So, what are this non dimensional numbers? So, the first one dimensional number of course, you can understand in a turbulence class of course, is important or the non dimensional number is Reynolds number. Now since our Reynolds number our nu is equal to D our Reynolds number which we essentially define as in terms of the U 0 prime which is essentially the U rms right. So, it is the U prime it is the root mean square of the fluctuating of the fluctuating component of velocity ok.

So, that that is defined as U 0 prime. And that is used in our definition for Reynolds number l 0 is my integral length scale. So, U 0 prime is the rms of fluctuating component of velocity. And l 0 is the integral length scale if you have any questions you can go back to the previous notes of turbulent flows where we defined all these properties. And this is of course, divided by nu now since nu is equal to D and D is equal to S L times l L we can replace nu with S L times l L and we get essentially U 0 prime by l 0 divided by S L times l L. So then it becomes the Reynolds number essentially becomes a ratio of your characteristic velocity scales turbulent velocity scale to the flame velocity scale or flame speed scale to the ratio of the turbulent length scale to the flame length scale, ok.

So, that is what it becomes, you can clearly see here that the numerator in this and this one is essentially this guys essentially the ratio of this first term is the ratio of your this is the ratio of your U rms to flame speed and this is the ratio of l 0 by l L, ok.

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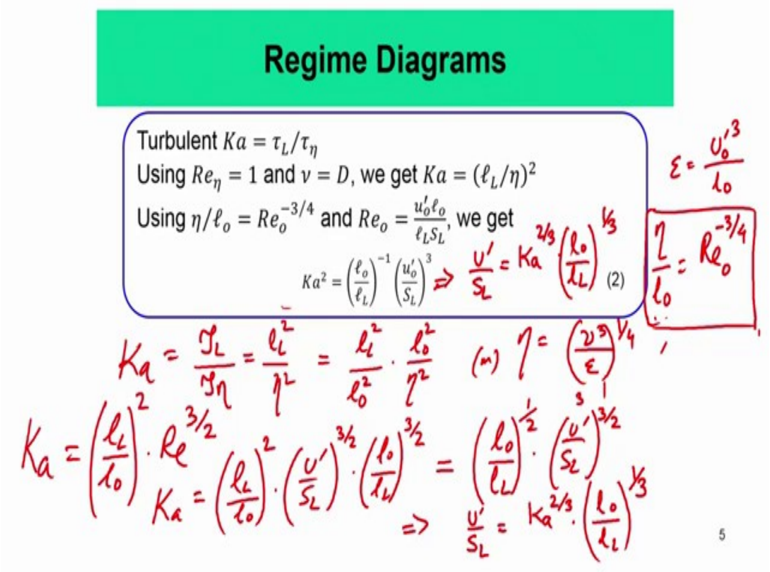

Regime Diagrams

Turbulent $Ka = \tau_L/\tau_\eta$

Using $Re_\eta = 1$ and $\nu = D$, we get $Ka = (\ell_L/\eta)^2$

Using $\eta/\ell_o = Re_o^{-3/4}$ and $Re_o = \frac{u_o'\ell_o}{\ell_L S_L}$, we get

$$Ka^2 = \left(\frac{\ell_o}{\ell_L}\right)^{-1}\left(\frac{u_o'}{S_L}\right)^3 \Rightarrow \frac{u'}{S_L} = Ka^{2/3}\left(\frac{l_o}{l_L}\right)^{1/3} \quad (2)$$

$$\varepsilon = \frac{u_o'^3}{l_o}$$

$$\boxed{\frac{\eta}{l_o} = Re_o^{-3/4}}$$

$$Ka = \frac{\tau_L}{\tau_\eta} = \frac{l_L^2}{\eta^2} = \frac{l_L^2}{l_o^2}\cdot\frac{l_o^2}{\eta^2} \quad (\nu)\ \eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

$$Ka = \left(\frac{l_L}{l_o}\right)^2 \cdot Re^{3/2}$$

$$Ka = \left(\frac{l_L}{l_o}\right)^2 \cdot \left(\frac{u'}{S_L}\right)^{3/2} \cdot \left(\frac{l_o}{l_L}\right)^{3/2} = \left(\frac{l_o}{l_L}\right)^{\frac{1}{2}} \cdot \left(\frac{u'}{S_L}\right)^{3/2}$$

$$\Rightarrow \frac{u'}{S_L} = Ka^{2/3}\cdot\left(\frac{l_o}{l_L}\right)^{1/3}$$

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So, clearly this tells you that how strong the turbulent sees as it is that in all turbulence should tell. There are other numbers also and there are other numbers like something that is something called a Karlovitz number. What is the Karlovitz number? Karlovitz number is essentially I will just show that derivation here clearly Karlovitz number is the ratio of flame time scale to the Kolmogorov time scale. Now I can write that tau l which is the unit of second ok In terms of the characteristic diffusivity which has the unit of meter square per second and the length scale which is the unit of meters.

So, I can write this tau l as l L square by D. So, this is meter square this is meter square per second. So, tau l is equal to seconds similarly I can write tau eta as eta square by nu, why because we remember by Kolmogorov first similarity hypothesis the small scale should be determined only by nu and if required by epsilon. So, of course, in the definition of eta you have a definition of epsilon. So, here we can just form this tau eta by eta and epsilon and nu now we can replace this by D because nu is equal to D.

So, you can write this as D. So then this big I becomes nothing but l L square by eta square you can just erase. This it is only becomes just simple l L square by eta square. And then I can write l L square by l 0 square which is my integral length scale to l 0 square by eta square. So, it is becomes then the ratio of the square of the ratio of the flame length scale to the integral length scale and the integral length scale to the Kolmogorov length scale. Now what is the ratio of integral length scale to the

Kolmogorov length scale that we should derive. Now for that if you remember then we have to find out essentially what eta is ok.

If we remember the definition once again going to Kolmogorov first similarity hypothesis eta should be only based on, nu there is a kinematic viscosity and turbulent kinetic energy dissipation rate. So, if eta has a length of meters and epsilon has a unit of eta has a dimension of our unit is of meters, and epsilon has this turbulent kinetic energy dissipation it has a dimension of meter square per second cube, and nu has dimension of meter square per second. Then eta must be defined they have to eliminate s. So, it is essentially defined as nu cube by epsilon to the power of one fourth, and that is a definition of Kolmogorov of length scale fine.

So, if I write eta by l 0 what I get is nu cube by epsilon to the power of one fourth by 1 by l 0. Now what is epsilon? Epsilon is nothing but nu prime cube by l 0. So, we can just substitute. So then this becomes now this l 0 can go inside and this will have con coincide here this will have cube once it because it is inside. So then it becomes nu cube by U 0 cube times l 0 cube to the power of one fourth. What is this? This is essentially Reynolds number to the power of 3. So then this becomes Re 0 to the power of 3 by 4. Now this is a very, very important thing. So, this tells you the how the scale separation looks like.

So, eta by l 0 is equal to Re 0 to the power of minus 3 by 4. It is a very, very important expression. So, as the Reynolds number increases the scale separation increases. So, that is why when in a turbulent Reynolds number increases the largest length scale remain same, but the smallest length scale it becomes finer and finer and the smallest length scale decreases. So now, we can then put this thing here. So, essentially my Karlovitz number becomes. Or we over this is one way to write it, the other way would be we have just stop substituted the nu by with S L times with S L times l L that is the substitution.

We have done and then this becomes to be equal to, this is minus because this is inverted of times prime by S L to the power of 3 by 2. So then this implies sorry, this can not be seen here. So, that is what we have got here also. So, or we can just write this here So, U prime by S L that is a ratio of the turbulent velocity scale divided by the flame speed scale is equal to Karlovitz number to the power of 2 thirds times l 0 by l L that is the integral length scale by the flame thickness to the power of one thirds.

So, we can define another non dimensional number. Now this is based on based on the integral time scale to the flame time scale remember Karlovitz number is the ratio of the flame time scale to the Kolmogorov time scales.

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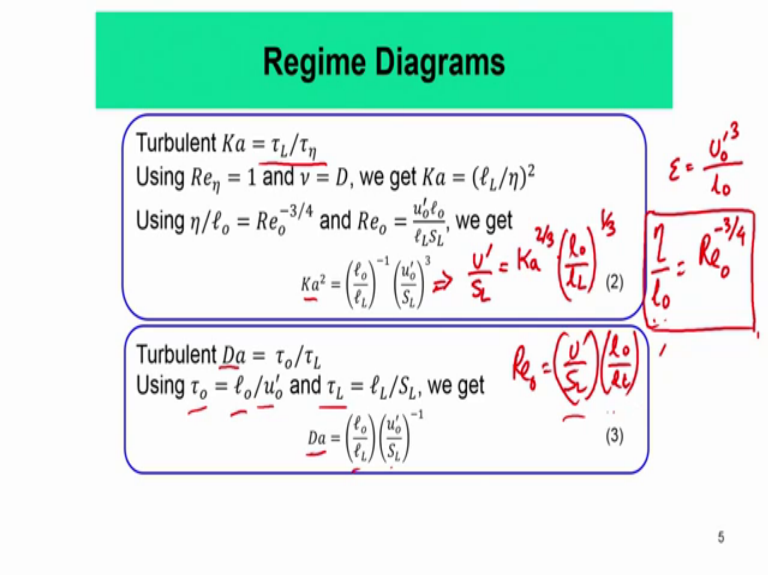

Regime Diagrams

Turbulent $Ka = \tau_L/\tau_\eta$

Using $Re_\eta = 1$ and $\nu = D$, we get $Ka = (\ell_L/\eta)^2$

Using $\eta/\ell_o = Re_o^{-3/4}$ and $Re_o = \frac{u_o' \ell_o}{\ell_L S_L}$, we get

$$Ka^2 = \left(\frac{\ell_o}{\ell_L}\right)^{-1} \left(\frac{u_o'}{S_L}\right)^3 \Rightarrow \frac{u'}{S_L} = Ka^{2/3} \left(\frac{l_0}{l_L}\right)^{1/3} \quad (2)$$

$$\varepsilon = \frac{u_0'^3}{l_0}$$

$$\boxed{\frac{\eta}{l_0} = Re_0^{-3/4}}$$

Turbulent $Da = \tau_o/\tau_L$

Using $\tau_o = \ell_o/u_o'$ and $\tau_L = \ell_L/S_L$, we get

$$Re_0 = \left(\frac{u'}{S_L}\right)\left(\frac{l_0}{l_L}\right)$$

$$Da = \left(\frac{\ell_o}{\ell_L}\right) \left(\frac{u_o'}{S_L}\right)^{-1} \quad (3)$$

So, the turbulent Damkohler number is based on the ratio of the integral time scale to the flame time scale. And we can define integral time scale is nothing but l 0 that is the integral length scale divided by the U prime rms that is the rms of the fluctuating velocity. And the flame time scale is of course, l L by S L. So, we can write this simple Damkohler number as l 0 by l L at time c prime by s n inverse.

So, you see we have got numerous non dimensional numbers, that Reynolds number is essentially if I just Reynolds number here we have written U prime by S L times l 0 by l L. So, you see these groups, U prime by S L that is a non ratio of the turbulent rms velocity divided by the flame speed and the ratio of the integral length scale to the flame thickness these 2 groups these 2 non dimensional groups appear repeatedly and these are basically used to combustor the different non dimensional numbers ok.

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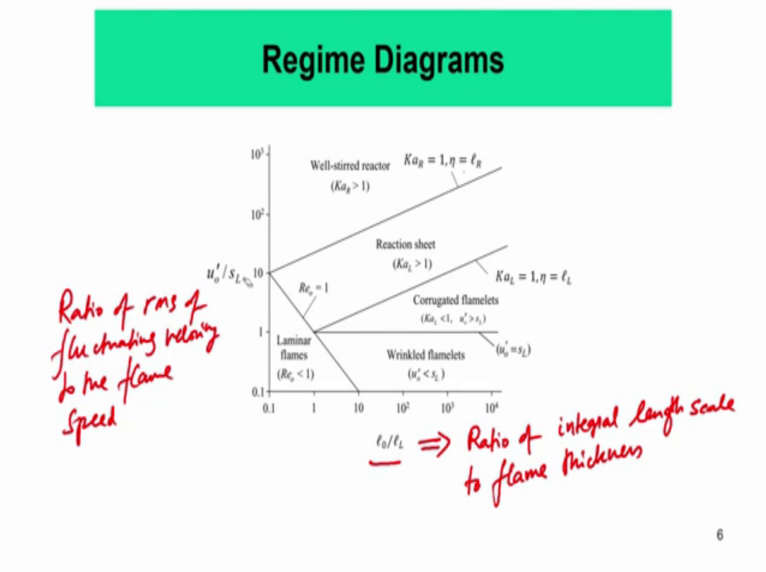

Regime Diagrams

So then we can use this 2 groups U prime by S L and l 0 by l L to essentially construct or something like a regime diagram.

So, we put l 0 by l L that is the ratio of integral length scale to flame thickness. We put this on the x axis and we put ratio of rms of fluctuating velocity to the flame speed on y axis. So, this is U prime by S L is that the ratio and this is the other ratio. So then we can construct this regime diagrams. Now we will discuss the different regimes. So, you see that the parameters that we had ok.

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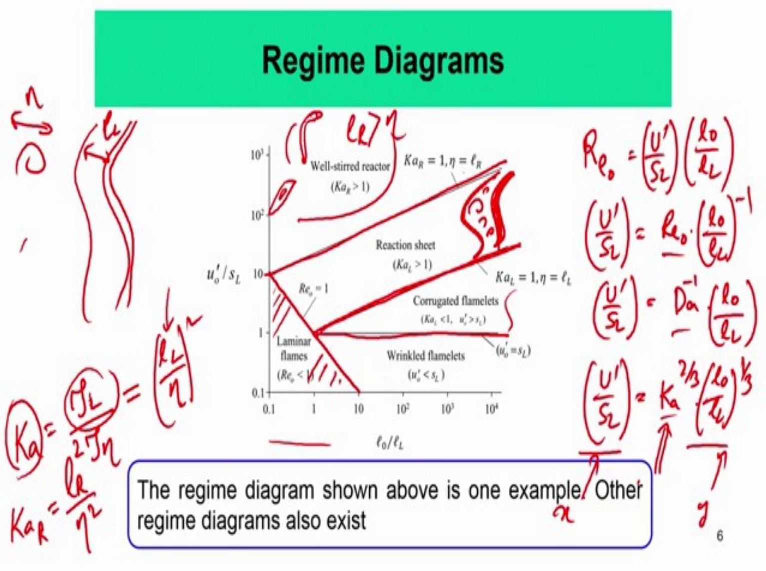

Regime Diagrams

The regime diagram shown above is one example. Other regime diagrams also exist

So, the parameters that we had was essentially Reynolds number was U prime by S L times l 0 by l L. Or U prime by S L is equal to Re 0 times l 0 by l L to the power of minus 1. The other parameters was Damkohler number is equal to U prime by S L was equal to Damkohler number inverse times l 0 by l L ok.

And Karlovitz number is U prime by S L is equal to k to the power of 2 thirds times l 0 by l L to the power of one third. So, this do you see the important thing is that in the log plot this will be appeared just like straight lines, U prime by S L and So, if this is we choose this as x and this as y. So, it is essentially x is equal to some constant times y to the power of one thirds. So, in a log plot the one third will just become come on the come on the left hand side, come on in as appears a coefficient and it will appear just straight lines ok.

So, this regime diagram is essentially on a log plot both the axis are on log scales one log with logarithm base 10, and all these lines these different lines are essentially this lines is constant all number constant number constant Karlovitz number this will appear as essentially as straight lines. So, the Reynolds number equal to 1 line is basically what demarcates between a turbulent flame and a laminar flame. So, this is this line that the Reynolds number is equal to 1 line. So, of course, you see the Reynolds number this is x y is equal to constant, and your log plot this rectangular hyperbola will appear as a straight line with a negative slope ok.

As you see here. And so anything beyond this regime is a is a laminar flame regime. So, we are not interested in this regime. Now if the U prime by S L is less than 1. So, if the U prime S L is less than 1; that means, that flames flame speed is much faster than the than U prime then the fluctuating velocity. So, the flame will propagate even before the fluctuating velocities can cause in a disturbance to the flame the flame will cross them. So, this will be mildly this site of the flames will only mildly wrinkled by the only we all will be just mildly wrinkled with the will only be just mildly wrinkled with the by the by the turbulence. So, this regime is essentially called the wrinkled flame regime.

So, this regime this U prime by S L is equal to 1 which is less than 1 this will be on this will be called the wrinkled flamelet us regime, because the flame speed is smaller than the fluctuating velocities all right. Now comes the two interesting regimes called the corrugated regime and the 3 interesting regimes essentially the corrugated regimes the reaction sheet regime and the well stirred reactor regime. Now the corrugated regime is essentially the boundary between U prime by S L equal to 1, and the Karlovitz number the flame Karlovitz number equal to 1 line. So, this Karlovitz number equal to 1 line will appear. So, if we put in this expression if you put Karlovitz number equal to 1, the Karlovitz number equal to 1 if you remember the Karlovitz number was essentially the ratio of the flame time scale to the Kolmogorov time scales.

So, if the flame time scale is equal to the Kolmogorov time scales then that essentially becomes Karlovitz number equal to 1, and this also boil down to the fact that your this your the it boil down to the fact that your flame thickness by the Kolmogorov by the Kolmogorov by the by the Kolmogorov length scale was also can be defined as a Karlovitz number. So, it is l L by eta whole square. So, when Karlovitz number is equal to 1 it means your flame time scale is equal to your you have to Kolmogorov time scale all right. All right now also it means that your flame length scale is equal to your Kolmogorov length scale.

So, the flame time is equal to the Kolmogorov time and your flame thickness that is if this is a flame, so then if this is the flame thickness. So then it the smallest eddies of turbulence which are the Kolmogorov of eddies which is also of the same size. So, this is the idea. So, this regime is essentially composed of means this line essentially means this limiting condition is reached when the flame time is equal to the Kolmogorov time and the flame thickness is equal to the Kolmogorov of eddies. In this regime in this beyond in this smaller than this regime the Kolmogorov of eddies are essentially much larger than the flame thickness. So, the flame actually in all these regimes that we have discussed the flame actually remains undisturbed. The flame structure or the preheat zone remains undisturbed by turbulence.

But now in this regimes greater than the Karlovitz number equal to 1 regime, once the flame time or the flame thickness becomes bigger than the Kolmogorov of length scale; that means, when the flame thickness is bigger than the smaller scales in turbulence then idea is that then the smallest scales of turbulence can enter into the pre heat zone and distort the structure there, as such it can enhance the molecular diffusion with turbulent diffusion in the pre heat zone. So, this is the structure. So, in this regime So, if I just draw So, this regime is just simple wrinkled flamelet us regime, this flame in this regime the corrugated flamelet us regime the flame can be strongly wrinkled like this ok.

But it is internal structure will still be very much preserved, even the pre heat zone and the and the reaction zone even it will be preserved. But in this reaction sheet regime what it means is that because the flame time is now greater than the Kolmogorov of time or the flame length scale the flame thickness is now greater than the Kolmogorov of length scale. The Kolmogorov of eddies can now penetrate into the preheat zone and distort the flame structure there. So, this structure will look something like this. The actual laminar flame structure will not be perfectly preserved and you can have eddies inside this preheat zone in this reaction sheet regime and it can distort ok.

But you still see that now only the flame thickness is bigger than the Kolmogorov of length scale. There is one more length scale associated with the flame which we have not discussed in turbulent combustion, but we did discuss in laminar combustion there is the reaction zone thickness you remember the reaction zone thickness and the preheat zone thickness they were given by a ratio of 1 by zeldovich number. So, the reaction zone thickness is still greater than is still much smaller than the preheat zone thickness. But now if the reaction zone thickness, if you replace the Kolmogorov of that this Karlovitz number definition

Now, instead of the flame time scale instead of the flame time scale which is based on the preheat zone thickness and the flame speed if you put the reaction zone thickness and the flame speed, then correspondingly you will get essentially the reactions zone thickness we can define a Karlovitz number based on the reaction zone as your l r square by eta square. So, if now the l r square that is or the or the l r that is reaction zone thickness becomes bigger than your pre heat than your than your Kolmogorov of length scale, then what will happen is that then the Kolmogorov of eddies will even penetrate inside the reaction zone and can distort it ok.

So, this is this can lead to this kind of a broken flame length structure where this even this reaction zone has essentially has broken up. So, once again to I will I will summarize this. So, here these 2 are very for turbulent combustion actually gas turbine combustion or ISO engine combustion happens in basically in this reaction sheet limit. Which means that why do we call it by the reaction sheet limit we call it reaction sheet limit, because here in this in this in this structure eddies the Kolmogorov of eddies can distort the preheat zone thickness. But since the reaction zone thickness is still much smaller than the Kolmogorov of sized eddies the reaction zone structure remains undisturbed ok.

And the reaction zone structure resembles to that of a laminar flame which is not disturbed it can be bent, but it is not the structure is not disturbed and as such we can still approximate it using a in the reaction sheet limit. So, that is why it is called the reaction sheet zone and whereas the previous part whereas, the previous whereas, the part which is proceeding in that is a preheat zone that is now totally disturbed with the by the Kolmogorov of sized eddies. So, these are the different regimes that we have and as you see that these lines are obtained essentially with the with this is the U prime by S L is equal to 1 line.

And this line is very important, which is essentially the Karlovitz number equal to 1 line. And the importance of Karlovitz number was essentially found out by of course is an end of the Karlovitz, but this was found out by Williams. So now, this is of course, very important that in this there is the distinction between these 2 regimes, but as I said that this regimes the boundary should not be taken to be extremely like very sacrosanct as such there can be flames which exist in the corrugated flamelet us regime which can have a structure which is similar to the reaction street structure and vice versa.

But mainly in this regime when you see the turbulence is also weakened because the Karlovitz number is essentially small is less than 1 it belongs to the corrugated flamelet us regime, whereas in this reaction sheet limit which is also called the thin reaction zone regime it is actually a very, very important regime for practical purposes. So, here basically as you have seen that because the Karlovitz number has become greater than 1, which means that your preheat zone thickness has become greater than the than the Kolmogorov length scale, and that means, essentially now and also your flame time scale has become bigger than the Kolmogorov of time scale.

So then it means essentially the Kolmogorov of eddies can penetrate into the preheat zone and distort the structure actually it can even broaden the preheat zone in certain circumstances, and it can essentially distort the structure it adds to the diffusion processes, it now the molecular diffusion can be overtaken by turbulent diffusion and the preheat zone structure is really affected by turbulence in this reaction sheet limi. But still because as you know because the reaction zone thickness is still reaction zone thickness by the preheat zone thickness for a normal laminar premixed flame is essentially given by the 1 by zeldovich number, the reaction zone thickness is still smaller than the preheat zone thickness.

And if it is substantially smaller in the sense that this now the still the reaction zone thickness is smaller than the Kolmogorov of eddies Kolmogorov of eddies sizes then the Kolmogorov of eddies sizes can only distort the preheat zone structure and it cannot distort the reaction zone structure. So, that is why this is called the reaction sheet limit and you still basically have a little bit of our distorted now you have a convoluted reaction zone, but the internal structure is not disturbed. But if you have a situation which you have in this well stirred reactor situation that is if you have a situation where your (Refer Time: 41:47) or Kolmogorov of sized eddies have become essentially smaller than the reaction zone thickness ok.

So, l r is of an larger than eta. So, this region is essentially means that l r is essentially larger than eta. So, if that is the situation; that means, the Karlovitz number is very, very large I mean it is if in the reaction Karlovitz number is larger greater than 1. So then what happens is that the flamelet us structure is completely destroyed. So, when the reaction zone structure does not behave like that of the laminar flame. And it is a well to behave like a distributor flamelet us the flame becomes distribute into several parts, and it becomes approximately that of a well stirred reactor. So, this part is essentially call the well stirred reactor of this. This region there can be other regime diagrams also exist that was is just one example.