Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 47
Turbulent Combustion

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So far we have been looking at spray combustion we try to put a set up a formulation for how to spray combustion we looked at spray statistics, and so on this is actually coming from droplet combustion and we also mentioned a little bit about coal combustion and maybe biomass combustion and so on. So essentially we have covered something about heterogeneous combustion in this realm.

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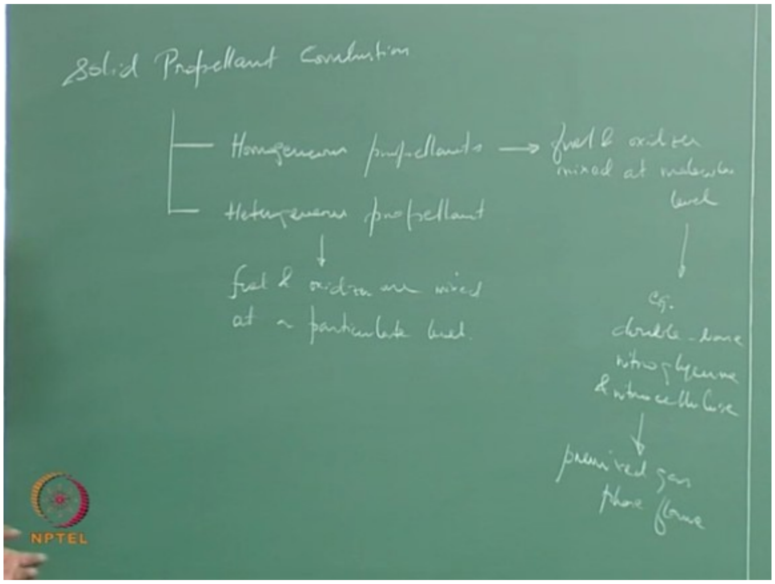

Solid Propellant Combustion

Homogeneous propellants → fuel & oxidizer mixed at molecular level
↓
e.g.
double-base
nitroglycerine
& nitrocellulose
↓
premixed gas
phase flame

Heterogeneous propellant
↓
fuel & oxidizer are mixed
at a particulate level.

We should probably just touch upon a little bit about solid propellant combustion as well so we will just quickly talk about this the reason why we are actually going through all these things in quick succession is to essentially point out as far as this course is concerned that whatever we have learnt on lamina premix flames and lamina diffusion flames are actually applicable as we speak pretty much in the context of more complicated application oriented areas except that the situation is complicated by a lot of other things.

For example in sprays it is complicated by the spray statistics the diameter distribution and so on in the case of solid propellant combustion we will see what, what else happens and then we will move on to turbulent combustion also to show that the basics that we have learnt will be applicable there and, and how it is complicated by the turbulence and so on so in the case of solid propellant combustion.

What we are what we need to understand is essentially we have to look at two cases one is homogeneous propellants and, and the other one is heterogeneous propellants the term propellant actually means that both the fuel and oxidizer are actually available in solid form together and the question basically is to what is the level to which they are really mixed together so in the case of homogeneous propellants.

They are actually mixed up to the molecular level so fuel and oxidizer mixed at a molecular level here that means when, when you now have a source of heat that ignites it and then these the combustion keeps going under steady state conditions essentially what happens is the solid gets heated up and it, it is thermally unstable so it decomposes into the in the gas phase products the gas phase products are essentially a gas phase fuel molecules.

And oxidizer molecules which then in turn break down further to react in the inner gas phase flame and the gas phase flame releases a lot of heat that goes back to giving rise to the Colonel's phase decomposition products of fear and oxidizer molecules in the gas phase so that's how it happened in a matter of fact when we are looking at liquid droplets that are also I mentioned monopropellant liquid droplets okay.

So where you now can actually have a privet flame that is surrounding maybe monopropellant liquid droplet and it paralyzes the droplet in the drop that decomposes in the gas phase fuel and oxidizer molecules that react in the gas phase plane so a similar idea essentially provides for homogenous propellants example of this fridge is a example, example you can think about is the most common thing is what is called as double base, double base propellants it calls double, double base.

Because it is actually a combination of nitro-glycerin and nitrocellulose so they are mixed together such that they actually form a, a mixture at the molecular level and then they willed compose into a gas phase fuel and oxidizer on the other hand so obviously before we move on to heterogeneous proponents.

Obviously what we are looking at is essentially is this should give rise to a pre-mixed gas phase flame and so you can think about a premix gas place flame where the preheat zone now extends into the solid all right because the preheat zone essentially is where the heat conduction happens and the heat conduction now happens into the solid heats up the solid from its initial temperature up to a surface temperature that needs to be determined as part of the problem by supplying interface boundary conditions between the solid and the gas phase.

And in addition to that you call you still have the same problem essentially of an Eigen value problem which is you have to find out the, the burning rate of the solid or what is this is what is the rate at which the surface regresses this is that is essentially similar to the way we did the gas phase plane one-dimensional flame structure associated analysis in the case of heterogeneous propellants essentially the fuel and oxidizer or, or mixed at a particulate level.

That means you typically have this is very typical it does not have to be exactly followed this way but typically we have a solid oxidizer powder which means like it is typically assault chemical salt and the, the most typical one that we use is what is called as a what is called as ammonium per chlorate and so you can use these ammonium per chlorate salt so it looks like the common salt particles.

But you come in very various particle sizes and so essentially you have these particles that are now embedded in a, in a polymeric fuel so this is essentially starting out with a polymer that is there is a highly viscous liquid into which you know makes things and then you set this polymer to become a solid and so the polymer the fuel is essentially a polymer that is that also acts, acts as a binder that binds the particles.

And you can also of course threw in metal particles to act as further fuel to do this entire mixture but the metal combustion actually happens outside of the combustion between the fuel and oxidizer all right so effectively the binder and the oxidizer so effectively what we are looking for is the combustion that that propagates the flame into the solid that is caused by a flame that is between the fuel and oxidizer.

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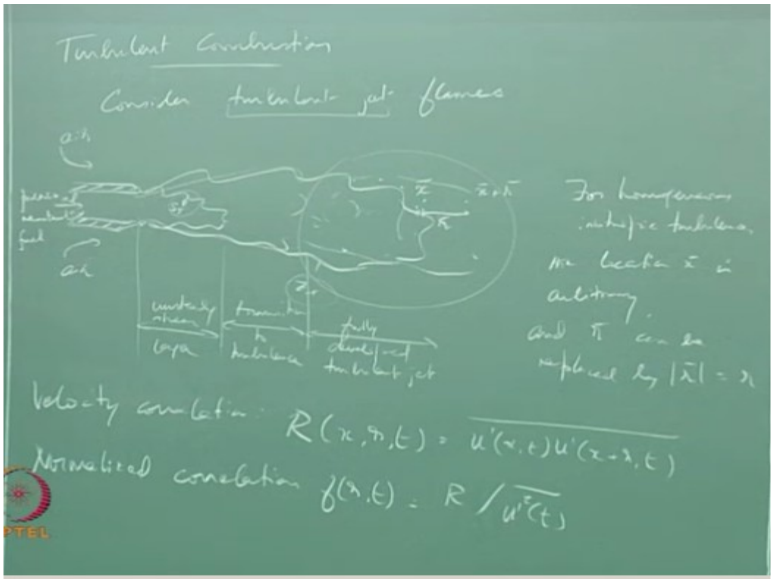

Turbulent Combustion

Consider turbulent jet flames

For homogeneous isotropic turbulence, the location $\bar{x}$ is arbitrary. And $\bar{r}$ can be replaced by $|\bar{r}| = r$

Velocity correlation: $R(x, r, t) = \overline{u'(x,t)\,u'(x+r,t)}$

Normalized correlation $f(r,t) = R / \overline{u'^2(t)}$

So if so this is going to actually look like now have a lot of solid particles so typically these are like about 200 microns to 300 microns in size the finer ones could be as fine as even 5 microns or even one micron in very extreme cases but typically it is of the order of about 50 to 70 microns 80microns maybe at the most 100 microns and so on.

So essentially you try to have a very tight pack of a lot of large solid particles and then you now try to pack further in between the crevices of form formed in between the subway big solid particles with further smaller particles and so now you get these particles and then you now have a binder that is binding the whole thing together so microscopically when you now have a flame that is trying to eat into this it is obviously not going to be a pre-mixed flame right.

So even at the microscopic level what happens is let us suppose that we can begin we can hypothetically say we just cut it with a surface like this and we now say that is now the burning surface obviously the burning surface is not going to be as flat as what it is and we will try to see what happens how the non planarity develops as we, as we speak but let us suppose that this is what we want to think about and now you have like an exposed area of oxidizer that is giving rise to oxidize the vapor.

And there is exposed area of binder that is giving rise to binder so this is actually let us say fuel here oxidizer here fuel here and this is if you now look at it like this within this region that is sort of like the inverse of the Burke-Schumann problem the Burke-Schumann problem is where we now had a fuel in the code and oxidizer on the sides but if you did not really care about exactly what chemicals that are that are being used we are essentially looking at two different constituents reactant, reactant species.

That are coming out in this fashion so we expect to actually have a, a diffusion flame over here that's associated with this recall we had talked about flux boundary conditions so we can we can deliberately talk about where exactly the stoichiometric surface is going to attach is it going to be at the contact between the oxidizer and fuel or away these kinds of issues remain to remain to be discussed in these in these problems but we also talked when we talked about diffusion flames we talked about finite chemic emissary effects particularly near the leading edge.

And then we found that we need to have something like a leading edge flame or a triple flame structure and that is pretty much expected in these propellants because it turns out that the oxidizer actually is a monopropellant by itself it can burn by itself but we need the binder to hold oxidizer particles together and then push it closer to a stoichiometric situation therefore you are essentially having a oxidizer rich reactive mixture.

And in fact it can also go through a self deflation so you do have a, a self differentiation flame of the oxidizer very close to the oxidizer particle out of which you now get oxidizer rich products of this flame which now makes within the binder fuel gaseous species and then obviously since you now have a oxidizer rich species you are now going to have more like a, a triple flame there are other than rather than a diffusion flame.

That that extends all the way so typically modelers have identified that you know have like a, a monopropellant flame for the ammonium per chlorate then you car what is called as a primary flame in the diffusion flame that that is coming from the, the triple flame kind of idea there the corners and then the trailing diffusion flame so a typical idea of multiple flames prevails for compo what is called as composite propellants heterogeneous propellants are also generally to turn this composite propellants because is the composite of particulates in a, in a binder similar to composite materials and structures.

And the popular idea is you have essentially multiple flames of different structure that prevails on top and of course as I said you also have aluminum metal particles that are embedded aluminum is thermally very stable therefore as it comes out it is going to accumulate on the burning surface because it is it is just barely getting melted there that is that at that time it is not ready to actually get evaporated.

So it and then so as it gets accumulated it now forms interested web and it is getting heated up by this gift this gas place flame complex and ultimately it now reaches an ignition temperature by which it gets ignited and then it does this a sintered web actually rolls out and then goes up and then starts burning as a bigger agglomerate than the individual particles that we originally had so that is, that is a complex problem that has a lot of ramifications in solid rocket performance where these kinds of propellants are used.

So all I want to point out is we have discussed many of these issues in trying to do laminar flames earlier on and all these ideas actually remain here as well so we now want to also do a similar kind of overview of turbulent combustion and do say that we want to just give an overview of turbulent combustion is extremely unfair.

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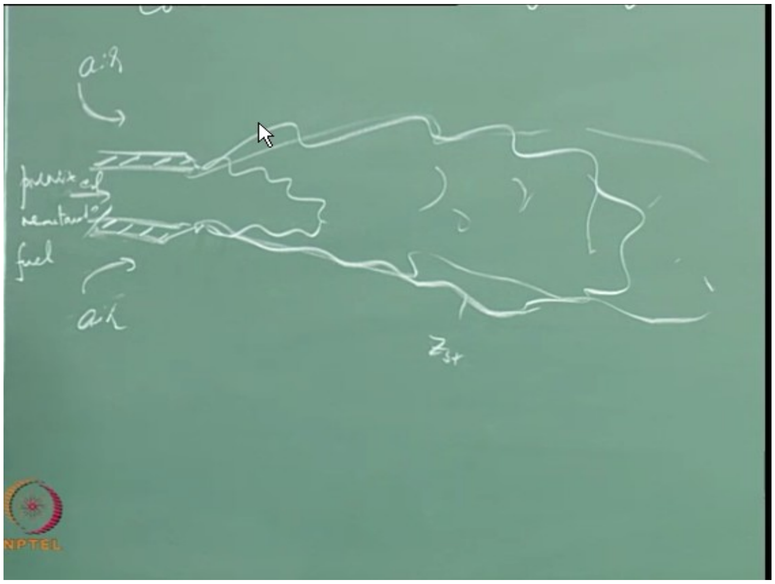

Because there is a subject that has actually spawn a huge amount of literature a lot of scientists have been working and turbulent combustion is one of the things that that has funded a lot of combustion research if you will in the last many decades that is primarily because most of practical combustion boring let us say some of these things that we talked about which are happening in very, very microscopic scales so that the Reynolds numbers are so small except for this most of the other kinds of combustion situations are turbulent, turbulent in nature right.

So we are, we are, we are looking at let us say gas turbine combustors or liquid rocket combustors or furnaces or boilers and so on many of these things you are actually wherever you are going through most, most combustion situations you have trouble official so effectively what you have to do is here again just like how we did sprays first we have to get a hang of turbulent flows.

Before we can actually get into the combustion so when we did sprays you remember you we had to first talk about Sperry statistics how do you characterize sprays how do you describe space and then we will worry about the combustion so similarly we have to actually go back a little bit and then get a quick overview of what is, what is turbulent about turbulent combustion right.

So that means we have to look at what is turbulence in general we will we will try to restrict what, what we are trying to do here to the context of turbulent jet flames and when I say turbulent jet flames I will talk about both premix flames and non premix flames and let us see what, what, that means so when we say turbulent jet flames consider turbulent jet flames is what we want to do this is this is very, very generic.

Because what you can think about essentially is if you now have a little nozzle from which you now have a gas that is coming out at turbulent speeds and, and you now he is use out like a, like, like a jet right so and then you have a lot of Eddie's here and there and so on so it is a caricature that I do not want to really elaborate too much so, so you now have a large turbulent jet so you can think about this is like, like coming out of a burner that is fitted to a combustor or a furnace and so on.

So this is every practical situation that comes that you come across in many applications when you now say turbulent premix flames you can now think about a reactant mixture that is coming out of here and then letting in air from besides entrain into the jet so or if you want to think about a turbulent non pre-mixed flame you could now say I have only fuel coming, coming through this its entry it is in training air around and then you now have a flame so either way.

So depending upon how that is going to happen right so if you now have a pre-mixed, pre-mixed reactants you are now going to have a highly wrinkle a pre-mixed flame that is going to burn and consume all the all the reactants within a very, very short distance and once again recall or if you now have or, or okay or if you now have only fuel right you now going to have a, a diffusion flame the picture.

That I am drawing there is essentially something like the stoichiometric surface so what your Redemption just like how we did the book Burke-Schumann problem if it is possible for you to actually now mark the mixed refraction corresponding to the contour corresponding to the stoichiometric mixed refraction right you now get a turbulent friend of thing and what is turbulent about it.

Because you now have fluctuations that keep happening the next snapshot that you draw try to go through you are now not going to exactly follow the same contour this is an instantaneous picture so the next part next one is going to be slightly different and, and the third one, is going to be slightly different then we keep on taking these snapshots and then put on top of each there you know get lots of these kinds of curves which, which you now kind of form a, a bang and that is what you would call it a turbulent flame brush okay.

So it essentially causes a brush like structure on an ensemble averaged a manner similarly for the premix flame you again let us go back and think about what happens in a laminar situation we talked very significantly about the Bunsen burner experiment where you could now have the hole at the bottom that allows for the air entrainment open and set up a pre-mixed flame and then start closing the a whole very gradually and then convert the supreme exclaim into a diffusion flame.

And we now find that the diffusion flame is a lot taller than competitive premix flame right a very similar situation would exist for, for turbulent flames as well simply because in the case of diffusion flames the, the, the combustion is actually diffusion controlled we are so they say heat release is not going to be as intense or the chemical reactions are not going to be as intense because they are waiting for the mixing to happen right whereas in the premix flame you do not have that kind of a constraint.

So the heat release is kinetically controlled and so you now have a lot of heat release that happens within a very short region so the volumetric heating load that you come out come out where the premix flame is not a higher when compared to that of a diffusion flame for this reason for the same kind of thermal loading that means amount of fuel that you are trying to burn at a particular rate your prime extremes are really typically very compact when compared to diffusion flames this is true as well and laminar as in turbulent flows.

So if you are now thinking if you want to think about how so just us like how I said you know you can now look at the stoichiometric surface for the diffusion flame also meant to point out you could now think about a local turbulent flame speed that is trying to match the DD, DD flow and then trying to set itself up right and there we have little problem you know am I going to actually say this instantaneous flame is the one that is traveling at a turbulent flame speed or is it like it a turbulent premixed flame brush .

That is traveling at a turbulent flame speed so that the notion of what is a turbulent flame speed is a little bit difficult to think about and we will have to talk about a little bit in greater detail shortly maybe the first thing that that I am hinting is first of all for if you are completely ignorant we will now have to talk about something called a turbulent flame speed a supposed to a laminar flame speed we go a hint to fit the moment we actually used s l where l is a subscript indicating laminar.

I pointed out that when we do when we think about turbulent flames we will have to alter that and so we will discuss this the point again I am trying to make is the ideas that we had like the flame, flame speed balances the normal common with the flow those ideas will remain okay that is not going to change so if you want to now think about all these things the first thing that we have to do is forget about the flames for a moment.

We will now look at only the term turbulent jet right so for the sake of looking at the turbulent jet let us not worry about whether this is pre-mixed reactants or the fuel we will simply say it is just a jet of some gas right maybe air itself and in, in acquires entire ambience essentially looking at a jet and in a jet you now have a region that is like where you have a unsteady shear layer where you now have two mixing layers.

We are talking about momentum mixing as well as species mixing and thermal mixing if there if it is not isothermal so all these things are happening with in this region in an unsteady manner you could hope to actually view this part as essentially an unsteady laminar case if you are if you are trying to resolve these scales in your in your computation or whatever it is but pretty quickly you are now going to get into a region where you transition to turbulence right.

And then beyond this point you now have a fully developed turbulent jet when you are now having a fully developed turbulent jet we are now looking at a lot of Eddie's we would hear which, which are which are primarily a homogeneous isotropic so we are looking at situation where if you now pick a point which is given by X and another point which is given by X plus Ra distant, distant or apart then we now characterize this by having a cross correlation between the two.

Now if you are now looking at this region where it is fully developed turbulent for a homogeneous isotropic turbulence on the location X does not matter location, location X’s are arbitrary, arbitrary and, and all you are looking at is essentially the actual distance rather than the displacement so that that means you do not have to look at this vector, vector form it so the direction did not matter because it is isotropic so the location did not matter.

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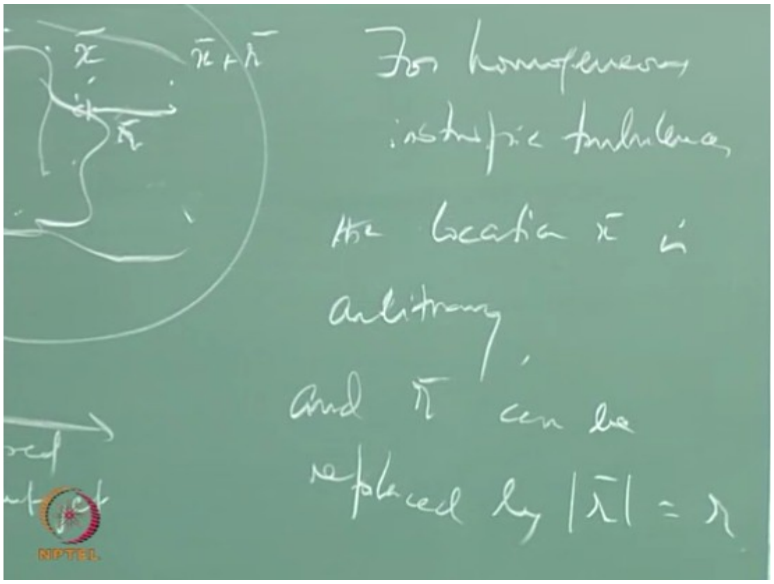

For homogeneous isotropic turbulence, the location $\bar{x}$ is arbitrary, and $\bar{r}$ can be replaced by $|\bar{r}| = r$

Because it is homogeneous therefore and R can be replaced by modor which is let us say simply or without the vector and then what you are looking for is a velocity correlation so the starting point of thinking about turbulent flows is to think about a velocity correlation here that is a spatial correlation that means you are essentially looking at turbulent fluctuation at X, T correlated with the turbulent fluctuation that X + or comma T as a as an average right and then DD then you normalize this so the normalized, normalized correlation F,T then is just take the correlation R and divided by the RMS.

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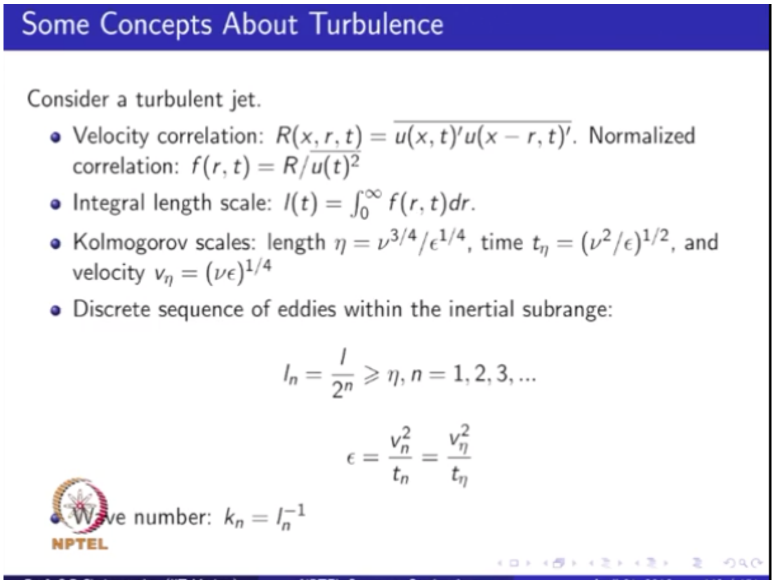

Some Concepts About Turbulence

Consider a turbulent jet.

- Velocity correlation: $R(x, r, t) = \overline{u(x,t)' u(x-r,t)'}$. Normalized correlation: $f(r,t) = R/\overline{u(t)^2}$
- Integral length scale: $l(t) = \int_0^\infty f(r,t)dr$.
- Kolmogorov scales: length $\eta = \nu^{3/4}/\epsilon^{1/4}$, time $t_\eta = (\nu^2/\epsilon)^{1/2}$, and velocity $v_\eta = (\nu\epsilon)^{1/4}$
- Discrete sequence of eddies within the inertial subrange:

$$l_n = \frac{l}{2^n} \geqslant \eta, n = 1, 2, 3, ...$$

$$\epsilon = \frac{v_n^2}{t_n} = \frac{v_\eta^2}{t_\eta}$$

- Wave number: $k_n = l_n^{-1}$

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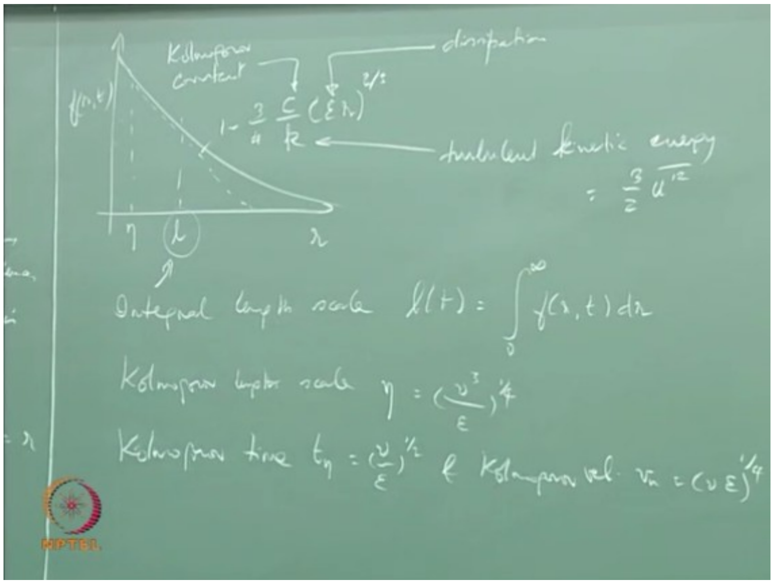

$1-\frac{3}{4}\frac{C}{k}(\varepsilon r)^{2/3}$

turbulent kinetic energy $= \frac{3}{2}\overline{u'^2}$

Integral length scale $l(t) = \int_0^\infty f(r,t)\,dr$

Kolmogorov length scale $\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$

Kolmogorov time $t_\eta = \left(\frac{\nu}{\varepsilon}\right)^{1/2}$ & Kolmogorov vel. $v_\eta = (\nu\varepsilon)^{1/4}$

So U prime squared T the whole bar and so why are we why are we bothered about this because we want to now step into how this looks like so if you now look at how the f of R, T looks like then it is going to be the verses are let us say so how does it look like with verses are it typically goes it is normalized so we do not have to worry about the magnitude it goes asymptotically 0 as you go further out in our and with respect to this.

We could now say somewhere along here we have a length scale ξ which we would now call as the kolmogorov length scale and somewhere in here we would now have a length scale L which we would call it the integral length scale we will talk about these things a little bit more carefully so let us not worry about them at the moment are trying to write down but what we are what I am interested in is if I can actually have a function that approximates this to good measure and that would be 1 -3/4th's C over K ε or to the 2/3rd's where K what we are talking about is K is what is called as a turbulent kinetic energy turbulent kinetic energy which is equal to for isotropic turbulence.

You can say this is equal to u prime three half U prime squared where U prime of course is the fluctuation over the mean of the velocity and ε is the dissipation and, and see of course is what is called as equal Mauro constant, Mauro constant and then we want to talk about what is the integral length scale integral length scale L of T then is integral 0 to infinity f of r, t that is essentially the normalized correlation integrated over all, all distance.

Then you now get a measure of a, a, a scale that kind of caps the log scale large-scale structures so and we will see what that means pretty soon and then you now have what is called as the kolmogorov length scale which is the smallest length scale in your flow essentially what is happening is you now have a turbulent flow in which you now have a cascading that happens that, that goes all the way down to the colon comma grove length scale so ξ place new cube divided by ε the whole to the 14where μ is the kinematic viscosity.

And of course epsilon is what we call as the turbulent dissipation sometime back all right we would also talk about aka coma group time associated with the length scale and we will talk about these time scales and length scales and the velocity associated these for many of these scales but we are discussing at the moment we are just discussing the Cullman grow scale so let call number of time d ξ is anew over ε to the half and kolmogorov velocity, kolmogorov velocity V n is μ ε to the 14 right and between a between the large scale and the kolmogorov scale.

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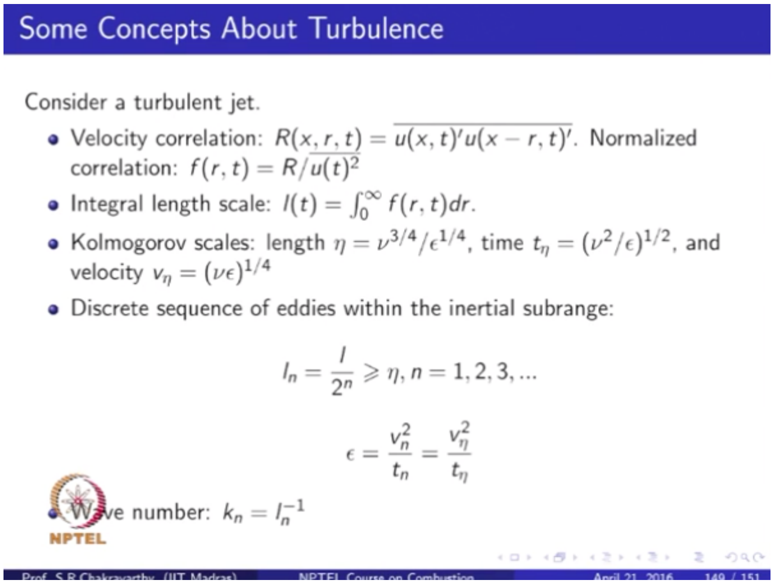

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We could now think about a discrete sequence of eddies and leave the reason why we are talking about these things is because ultimately we want to compare these things with a laminar flame thickness okay so when you now talk about combustion we now have length scales associated length scales and time scales associated with the flame and the and a flame speed that is associated with it.

So we want to be able to compare these scales with the those orders of the flame so we will now talk about a discrete sequence of Eddie's discrete sequence of Eddie is but then what is called as a inertial sub range I am going to explain this soon with it with a spectrum with the energy spectrum but let us first I mean it is kind of like a chicken and egg thing so we first have to talk about the Cascade and then the spectrum or vice versa.

So, so this is basically L /2n whereof course until we reach ξ where n goes as 1, 2 etc., that means for every Eddie sighs it is, it is half the size as the previous the ready essentially that is how we keep on looking at a discrete sequence and what we can find out when in this, in this inertial sub range essentially the dissipation remains constant you have a constant dissipation mechanism that, that works on the d, d, d cities therefore we could now say that epsilon is essentially like we n^2/Tn where the N is actually the Bessel velocity associated with the nth Eddie and the TN is the time associated with the tempter.

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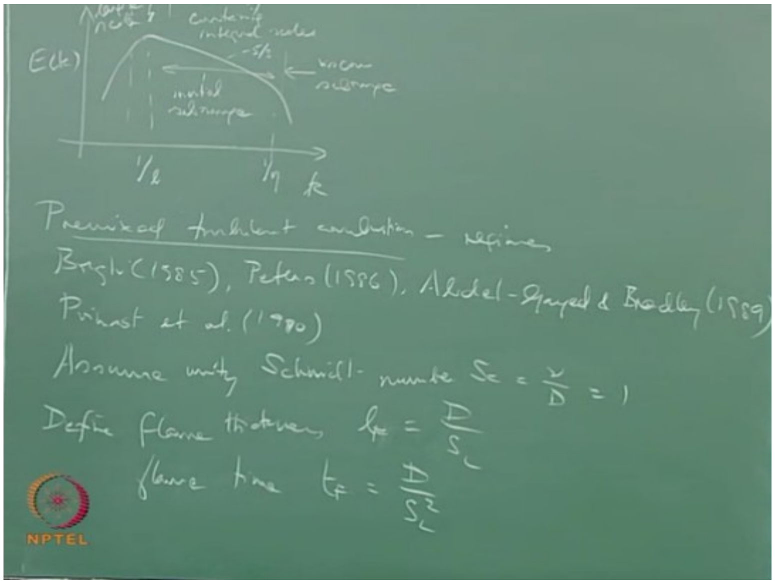

Premixed turbulent combustion – regimes

Bray (1985), Peters (1986), Abdel-Gayed & Bradley (1989)

Poinsot et al. (1990)

Assume unity Schmidt number $Sc = \frac{\nu}{D} = 1$

Define flame thickness $l_F = \frac{D}{S_L}$

flame time $t_F = \frac{D}{S_L^2}$

And Eddie and this would be this would be the same as ξ a square by D ξ however a very ξ essentially the kolmogorov skills so then the next thing that we want to think about is what is called the wave number? For some reason a turbulent to the turbulence community is very fond of K maybe because kolmogorov like kolmogorov a lot so they keep using k for the turbulent kinetic energy as well.

As the wave number and so on so, so this is typically like 1 over 1 over the length scale and what you are looking for is the energy density which is the kinetic energy density the density per unit wave number K so we can now think about a spectrum right versus K and usually we are looking at a room that kind of looks like, looks, looks like this and you can now think about a division here where you are looking at this is the large-scale diseases lost scale and this corresponds to 1 over L which is the integral length scale and this corresponds to 1 over e to the kolmogorov length scale.

And we are looking at this region as the energy containing a DS or energy containing can say integral scales and this region is now referred to as the inertial sub range where you now have a constant slope of minus 5third there is a famous law there and then below the kolmogorov scalars the viscous sorry so essentially what is going on is turbulent flows are of such high Reynolds numbers on the whole based on the large scale that you have a predominant inertial effect over the viscous effect as you keep on going down further and further to smaller and smaller scales until you reach the kolmogorov scale beyond which the viscous effects begin to be important right.

So this is this is how did this thing pans out so it is kind of like a 10, 15 minutes of turbulence or less, less than that may be right just about enough to for us to think a little bit about what happens when you know throw in a flame on top of this right so we and then we want what we want to do is to think about pre-mixed premix turbulent combustion right now the first thing that I would like to point out as an empirical factor or, or, or an observation is when you know how a turbulent flame it.

Now propagates a lot faster than a laminar flame corresponding laminar flame how do I get there right how did I how did I get to that point essentially what it means is now you have a lot of these Eddie's in the flow that are trying to wrinkle or corrugate this flame and you now have on the whole the flame that looks thicker and wants to reach ahead of itself so it is like a very, very crude way of thinking about this.

And then we have to think a little bit more refined manner but effectively it now gives rise to a larger flame speed when compared to the laminar flame and if you now taught that the laminar flame speed under typical conditions or of the order of a few tens of centimeters per second the turbulent flame speed or three speeds are about an order, order magnitude more so they are actually on the range of meters per second right still quite smaller when compared to most of the flow speeds.

That occur in let us say let us say a gas turbine engine so if you now think about a gas turbine engine where you are still looking at subsonic flows we are not talking about supersonic combustion here maybe not in this course we are looking at subsonic flows highly subsonic we went through this long ago when we wanted to show that the pressure remains more or less constant in low mach number conditions and we said that the mach number is of the order of 1.1

and since the temperatures are pretty high in the combustion zone your speed of sound could be like off the order of thousand meters per second for the kind of temperature.

That we are looking at and so we are looking at flow velocity sort of the order of a several min or many tens of meters per second 200 meters per second that kind of 100 that is kind of speeds we are talking about as a post which the, the turbulent flame speeds are still quite low right and this is obviously nothing, nothing to do with detonation speeds okay and they are like about three orders magnitude about.

So you can know you know how to think about the ideas that we cared about flame shapes that are getting that are attained like for example if you had like block body V gutters the flames still with the turbulent flame propagation it still tries to align itself at an angle to the flow such that the component of the flow velocity will match this flame speed so what you are talking about is a flame speed, is a flame speed here is kind of like a time average flame speed.

So what happens in reality without, without having to average right so for which what we want to do here is to actually look at the physics of what is going on instead of thinking about like let us say empirical correlations on how the turbulent flame speed a very, very slit of the laminar flame speed and so on that is for maybe a special course and turbulent combustion itself where you get quantitative about it but here we just want to qualitatively look at the different regimes of turbulence.

So the idea of turbulent flamed regimes comes from several investigators in the late 80’s so the, the first of which is bourgie1985 in fact the early researchers used to call this regime diagram as a boggy diagram but it is been also put forward by Peters and defined further and Bradley in coworkers it is like NT 1989 site at all many of these people are still active researchers in the community and so you can see that this is not very, very old it is about only about 20 years old idea.

So what we are going to do here is to assume a unity Schmidt number that means we do not want to make a big distinction between viscous mixing and molecular mixing SC which is new over D will now take this as one and we now go through a few definitions here so we define or flame thickness flame thickness a left capital F refers to fling not fuel and we will stick to this when we are when we are doing diffusion flames as well equal to do over yourself and you are using SL you see and that means we are actually thinking about essentially a laminar flame that is going through a fate of twinkling and so on when it is subjected to the turbulent Eddie's right.

And then we want to now construct an idea of what I turbulent flame looks like from essentially what solemnity right so we are using a laminar flame speed and then you have a flame time which is a $TF=d^2/S^2$ magnitude expression that you would get there.

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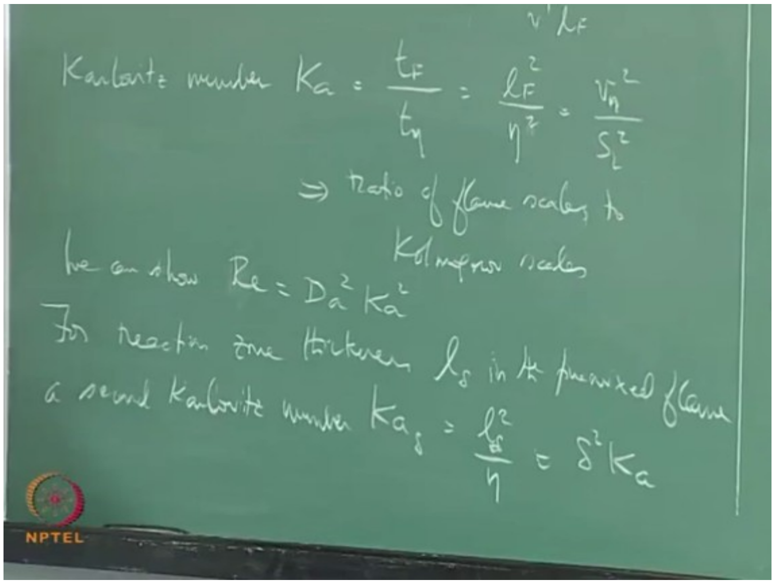

$v' l_F$

Karlovitz number $Ka = \frac{t_F}{t_\eta} = \frac{l_F^2}{\eta^2} = \frac{v_\eta^2}{S_L^2}$

$\Rightarrow$ Ratio of flame scales to Kolmogorov scales

We can show $Re = Da^2 Ka^2$

For reaction zone thickness l_δ in the premixed flame a second Karlovitz number $Ka_\delta = \frac{l_\delta^2}{\eta} = \delta^2 Ka$

So we want to define a turbulent Reynolds number turbulent Reynolds number which is defined as or e equal to let us say V prime elbow over new where V prime is the turbulent intensity it's a measure of the theater fluctuation rather to the turbulent velocity fluctuation it comes from how you can define your kinetic energy that means you can you can say are you looking at something like this under square root that means this is basically two thirds okay power, power half okay.

So that is how the turbulent intensity comes from and Ellis of course the integral length scale and new is the viscosity and the force since we are using Schmidt number equal to one we say this is actually V prime /V prime L /D and we just define the flame thickness as L F equals D 1 SL, SL f SL so this is going to look like V prime L biller SL LF it is sort of like a velocity ratio times the length scale ratio right.

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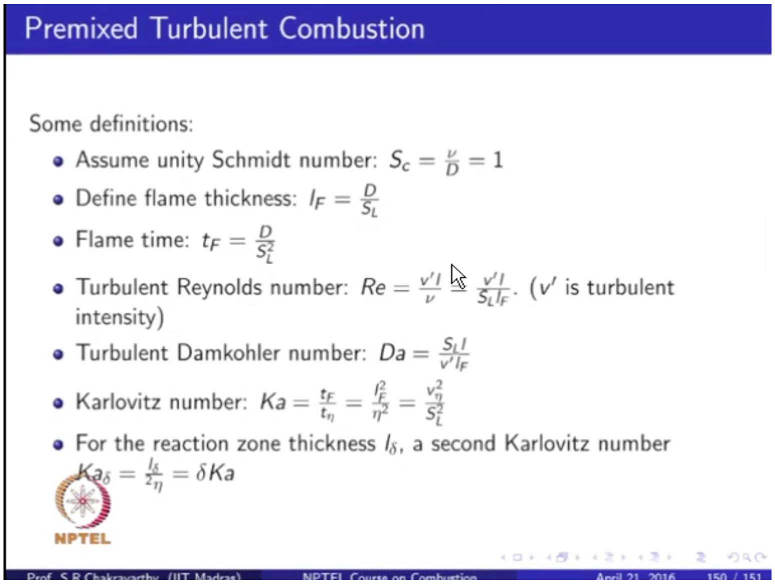

Premixed Turbulent Combustion

Some definitions:

- Assume unity Schmidt number: $S_c = \frac{\nu}{D} = 1$
- Define flame thickness: $l_F = \frac{D}{S_L}$
- Flame time: $t_F = \frac{D}{S_L^2}$
- Turbulent Reynolds number: $Re = \frac{v'l}{\nu} = \frac{v'l}{S_L l_F}$. ($v'$ is turbulent intensity)
- Turbulent Damkohler number: $Da = \frac{S_L l}{v' l_F}$
- Karlovitz number: $Ka = \frac{t_F}{t_\eta} = \frac{l_F^2}{\eta^2} = \frac{v_\eta^2}{S_L^2}$
- For the reaction zone thickness l_δ, a second Karlovitz number $Ka_\delta = \frac{l_\delta}{2_\eta} = \delta Ka$

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So the velocity ratio here, here is we are comparing the turbulent intensity versus the flame speed we are comparing the integral length scale of the turbulent Eddie's with the flame thickness right so I am trying to sort of implant this idea right here because that is kind of the way we are going to think about this the next thing that we want to think about is a turbulent damkohler number damkohler number is something that we have come across earlier on which is essentially a, a flow time by reaction time.

So it compares your flow time scale by the reaction time scale and so typically it is quite large because it takes a lot of time for the flow to make a significant moment like over a characteristic length scale of the geometry when compared to the time it takes for the reactions to happen so damkohler number is now defined based on this but you know you will find that it is a little bit different from the way Reynolds number turns out to be this is essentially time scales right.

So this is actually SLL divided by V Prime LF so it is actually coming from for the flow time divided by LF over SL for the chemical time so, so it sort of like saying this does this looks like this and this looks like that they, they kind of look work very closely similar but by then they are not like so keep in mind okay look good do not get confused about this and we now have a car robots number so damkohler number as the symbol corrodes number has a symbol ka which is effectively TF the flame time divided by the turbulence time so this is you can or you can say you can say LF^2 / ξ^2 in terms of length scales or you can say vie, vie squired or v^2 sorry v^2/ sl^2 whichever way you want to say this is essentially in all these cases.

We basically ratio of flame scales to kolomograv scale flame scale to total you can say flame scales because it could be time scale length scale whatever called ma grow scales right and with these we should be able to show ka sorry Ari equal to D is quiet k square so that kind of sounds like Dhaka is they call the square root that is that some way by which you could remember now what we what have you been thinking about a laminar flame is pretty much the same.

As what we thought earlier which means it has a preheat zone and the reaction zone right and then the preheat and largely the flame thickness is mostly preheat zone for a typically a high dumb call number or a high activation energy situation your reaction zone thickness is quite small when compared to D they did the flame thickness itself and it is given by what is called a Zelda which number right orders elevates the scaling.

So you can scale this scale the flame thickness by the Zelda which number in order to get you get the reaction zone thickness we have done this earlier when we were when we are talking about laminar flames so we can now form a second color its number based on the reaction zone thickness alone the reason why we are thinking about this is first of all recall we had we were talking about these things as well.

As the, the turbulence length scales because we want our now begin to compare how the turbulent length scales are going to be relative to the flame thickness right and what you are thinking about is and you now keep on changing your regime you are now going to have a situation where the turbulent length scales are typically much larger than compared to the flame yes but as you know keep on changing the regime your now get in the situation where the turbulent scales are going to be small, small enough to be able to enter into the preheat zone.

But not the reaction zone right and then ultimately can we get it to be even smaller than the reaction zone and so on so this I show we want to go through so therefore we also want to keep a track of the reaction zone thickness alone rather than just the flame thickness on the whole so for reaction zone thickness reaction zone thickness LΔ in the, the priming trim explain a second color which number K subscript Δ can be defined this $L\Delta^2 / \xi$.

We are still comparing this with a kolomograv length scale and of course we can show that this is equal to Δ^2 where Δ^2 is essentially the Zel dovih scaling coming between the flame length and the flame thickness and the reaction zone thickness LΔ we will just stop today with showing or this is probably a good time to stop well think we finish these definitions will pick up from here tomorrow.

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