Fundamentals Of Combustion (Part 1)
Dr. D. P. Mishra
Department of Aerospace Engineering
Indian Institute of Technology, Kanpur

Lecture – 40
Introduction to Turbulent Combustion

Let us start this lecture with a thought process from learned hand.

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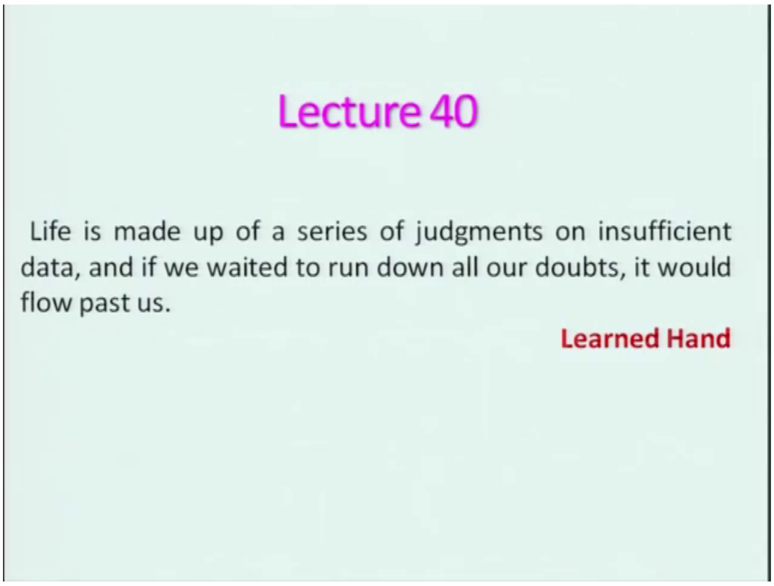

Life is made of series of judgments on insufficient data, and if you waited to run down all our doubts, it would flow past us right. You need not to be too worried about you know like the things, but; however, you should take a consent decision before doing something. So, that is the meaning of this.

So, in the last lecture what we did we basically looked at the governing equations for the laminar and 2 dimensional unsteady flow, later on steady flow right, we consider and we looked at little bit about boundary layer very briefly, but I would suggest that we may not use very much in our course.

But however, some touches or some feeling you should have and very important that we derived what we call equation one dimensional equation of force for mass mixture fraction right mixture fraction governing equation, which is basically a conserves scalar.

So, and those equations is valid basically for laminar flow and keep it mind that we will have to deal with what you call the also turbulent.

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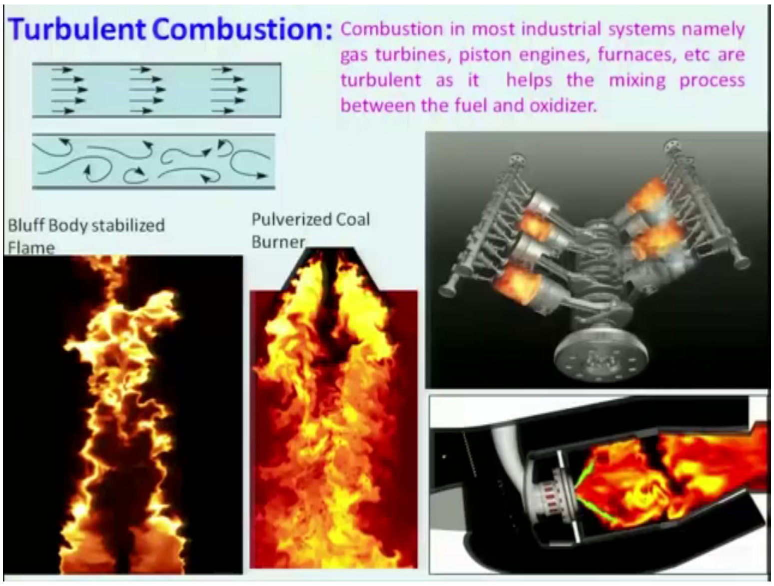

The laminar flow means the flow will be layer by layer. If you look at this is being shown here in this case is a flow through a pipe right is a layer by layer. That means, there would not be any mixing across the things, but where as in the turbulent right the flow will be not layer by layer it will be intermingling with each other right are you getting.

So, therefore, we need to look at that and turbulent combustion is plays a very important role why? Because the most of the combustion devices is basically turbulent in nature except few exceptional cases right. For example, if you consider your LPG burner is it laminar or turbulent combustion.

Student: (Refer Time: 02:49).

It will be.

Student: (Refer Time: 02:51) Laminar.

Looks to be laminar, but if you look at the candle light is it laminar or turbulent or transition what it would be?

Student: (Refer Time: 03:05).

It will be not laminar it will be basically transition right. So, but most of the a combustion system in industries namely gas turbine, piston engines, like furnace etcetera are turbulence at it helps in mixing process between fuel and oxidizer why you will go for turbulent.

Student: Mixing.

Not only the mixing we want to have a high rate of it release; that means, mixing should be as fast as possible right. Therefore, we need to go for turbulent combustion if you look at this is I say internal combustion is this are the combustion taking place and if you look at this is intensely mixed right means the combustion will be turbulent. And this is your gas turbine combustors right where it is having a lot of mixing is going on and this also some injection fluid like secondary air flow is coming over here is and then.

And liqui let us look at this is a coal combustion which is pulverized means particles right and combustion is taking place what he could observed the characteristics feature of a turbulent combustion. Let us look at the a combustion from a bluff body stabilized flame of course, you might be knowing the bluff body is been (Refer Time: 04:46) in fluid mechanics, am I right always you want to have a streamlined body is not it in a row dynamics other places, but in combustion we will be using bluff body why because we want to have a mixing better mixing you know which ever the disadvantage in fluid mechanics and it will be you will be using as advantages you know.

So, and this is the combustion which will be taking place and which is quite convoluted and turbulent in nature. Now, therefore, it is very important to look at the fundamental sub combustion, what I will do I will be only touching up an certain terminologies we may use I will be not getting detail into that.

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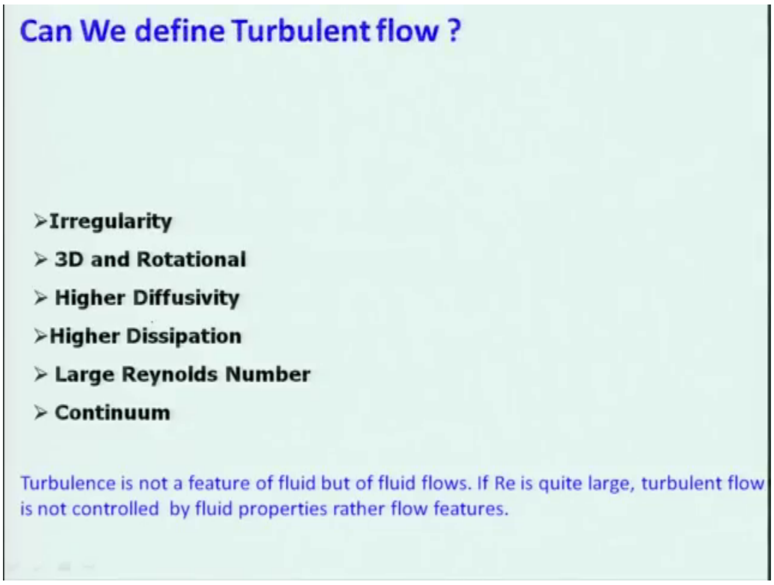

And so, can we define turbulent flow like the way we defined the laminar flow how we do right?

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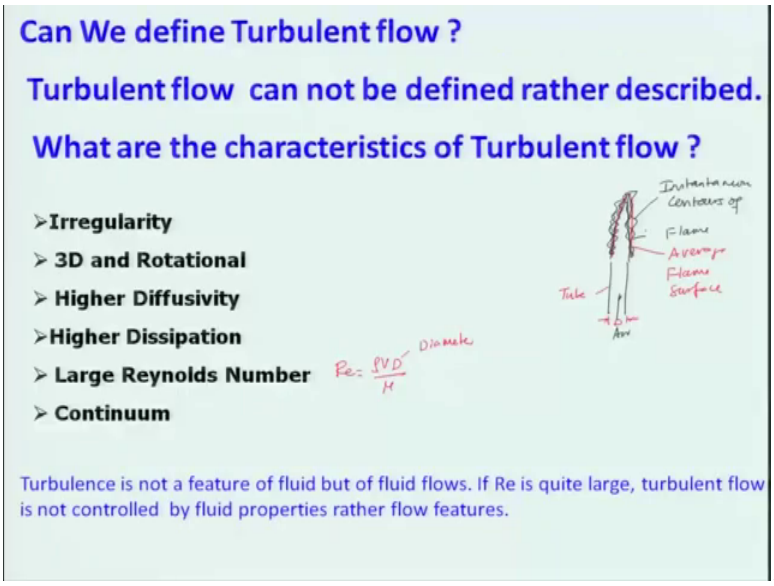

There will be some characteristics let fuel will layer by layer and then we can say whether it is laminar or turbulent right kind of things, but can we define turbulent flow. And we use the viscosity you know like diffusivity mass diffusivity or molecular diffusivity and other things those are properties of fluid which one is not it, like if I will say it is air the viscosity will be different if I say water it will be different right, but whether we can define the turbulent you cannot really define the turbulent flow you will have to describe the turbulent flow right. And now how will describe the turbulent flow; that means, we will have to use some characteristics. What are those characteristics any idea?

Student: (Refer Time: 06:54) irregular.

It will be irregular right it will be; that means, the flow will be convoluted, it will be mixing; that means, that will be intervening of the fluid element or the bulb which will be taking place right.

The molecules will moving he here and there and there some fluid packets will be moving up and down in the adjacent layer right. And as a result if I consider right a jet let us say. If I look at this is my air jet and there is a flame here right. If it is laminar my flame will be looking like that if it is laminar some shape particular shape you know, but if it is turbulent right it will be like that some kind of it will be intermingling surfaces and this is each one of this instantaneous contours of flame.

So, this will be here my average flame surfaces right and these will be very irregular in nature, but if you say look I have taken a photograph of the flame and it looks to be very small it is not, because the it will be average (Refer Time: 08:46) you would not see it unless it is highly turbulent and these flow will be 3 dimensional in nature you cannot say I will consider 2 d ok.

It will be 3 dimensional in nature and rotational means, the fluid will be rotating in the sense you know rotational flow like in visit flow is rotational or irrotational, that will be irrotational right, but here it will be rotational you cannot really consider invisit no then turbulent can you consider no.

So, and as a result there will be higher diffusivity, what do mean by that we have seen various diffusivity. Like conductivity, thermal conductivity, molecular diffusivity right and viscosity this are all diffusive process diffusivities right.

So, those will be much higher than the molecular one are you getting. And it will be diffusing moving around intervening kind of things and of course, we always use a Reynolds number to say, whether laminar or turbulent or transition right. That is a what you call high Reynolds number generally known as a turbulent flow. And as we had defined earlier basically that is Reynolds number. With d by mu if d is a diameter of the tube this is your diameter right, diameter of a tube this is a tube right from which the flow is going out right fu both fuel layer mixture we can say.

And question arises whether it is a continuum or not, because all are mixing is taking place you know we call it as a continuum or not continuum it will be definitely coming under continuum, because there will be instance mixing is taking place. It is not that the means free path is far away from each other, you know it is the far greater than the length scale of the where it is moving you know lengths of the other flow.

So, therefore, it will be continuum in nature and now how to deal with that, because as I told in this image or this flame there will be the flame surface or the velocity or the temperature or the species right mass fraction will be all changing rapidly with time right. Now you will deal with that is the question, before doing that let us look at how we can describe basically as I told turbulence is not a feature of the fluid I have already told like a diffusivity mo molecular diffusivity, conductivity, and then what we call viscosity, these are all properties of fluid not properties of the flow ok.

And keep in mind that if the Reynolds number is quite large of course, not in the transition range the turbulent flow is not controlled by the fluid properties rather flow features, it will be how the flow it is and.

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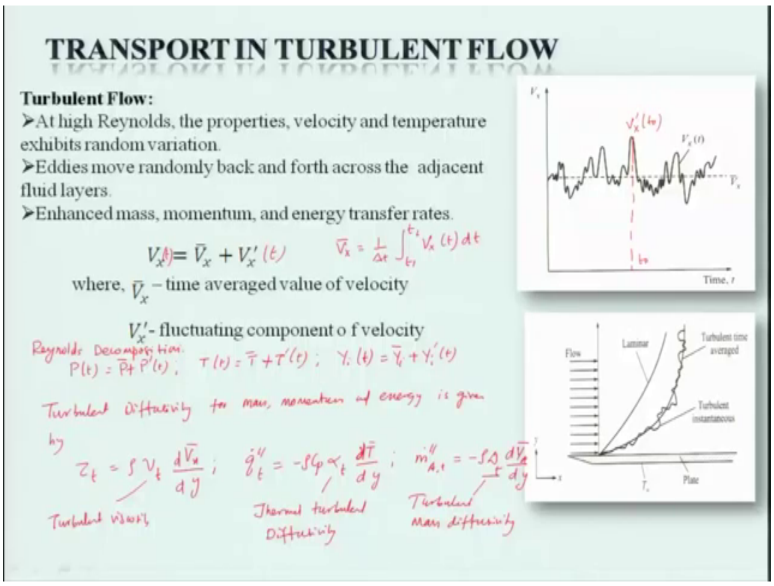

Now, we will be looking at how we will take care on some other terminology, I will be talking about it. So, at high Reynolds number like properties like velocity, temperature, mass fraction exits, random variations right. Now how we will deal with this, because if it is varying randomly then we will have to use some statistical tools or we will have to make some average quantities.

And keep in mind that eddies moving randomly back and forth across the adjacent layer let us say there is a bulk fluid which is moving, but in between the it will be also moving the fluid elements. A unlike in laminar flow where the flow will be moving very nicely see if you look at turbulent flow you can look at your traffic in Kalyanpur. All this car will be not in a line they will not following the line they will be moving here and there the way they want are you getting in Kalyanpur of Kanpur right.

But if you go to the western countries there car will be moving in a their own path taking. So, it will be laminar you know, but here you will be moving here and there. So, it will be losing a lot of energy and also it will be causing some problem. So, and, but there is a as a result you know of this fluid moving in the in a turbulent way or chaotic way. I can say like or turbulent flow need not to will be chaotic, but all chaotic flow need not be turbulent there will be enhancement of mass momentum and energy transfer rates.

So, that is why it is being used and now what will be looking at let us look at a velocity profile you know velocity fluctuates along with time V x. If you look at this is your average velocity V x and this is V x at any instant of time if I consider these as let us say this is a straight line.

As t naught this will be V x dash at T 0, let say some other time instant it will be different this is the fluctuating quantities this is the maximum fluc or you can say fluctuating quantities; that means, I can write that V x it would be what it would be V x at any instant of time right is equal to V x dash that is average velocity along with the x direction right and V x dash is the fluctuating quantities.

So, what is this V x dash if I look at that is nothing, but one over delta t t 1 t 2 this is V x over 1 dt, to integrate over the certain time which is the very las a time skill right it is not a very small you should not consider only this portion you should consider certain a considerable time then this is the average velocity you will. And there will be of course, fluctuating quantities we will be looking at.

And similar way I can also talk about what you call pressure P t is equal to P and I can talk about this temperature also dash T and similarly mass fraction of I is spaces I dash of t and this is basically known as what we call Reynolds decomposition, having 2 component 1 is fluctuating other is average quantities.

And if you look at that when you will do this things right you will find as I told earlier that in terms of when we will consider the laminar and the velocity over a flat plate, we can look at as basically this is the laminar velocity profile. And this is a instantaneous turbulent velocity profile this one right this fluctuating one and this a smooth line is basically turbulent time average velocity compounds right.

And as I told that when we will consider, because we will be more interested in the what we call diffusivity terms right. I am not going to derive it is a very Reynolds you know An a average this things you will have to look at this equation take carry out this see, but I am just write and then each governing equations and then look at it what it would be, but I am just writing the final expression just to say that, how it will be different and it will be similar in format of the whatever we have derived for the shear stress and then heat flux and the mass flux kind of things.

So, turbulent diffusivity for momentum and also the thermal and also the mass diffusivity for e for mass momentum and energy is given by tau t is equal to nothing, but here rho v t and V x average by dy right. Keep in mind that this v t is what we call turbulent viscosity.

Similarly I can write down as rho C P alpha t I can write down d actually this is better d by dy, similarly a spaces I am saying turbulent would be rho d t keep it mind that this is your thermal diffusivity thermal turbulent. And keep in mind that this thermal turbulent diffusivity or turbulent viscosity or this is turbulent mass diffusivity; they are properties of the flow you will have to connect that right. And these we will we not considering, but let us look at how we can really describe this properties you know like how we can describe these things using various term terms.

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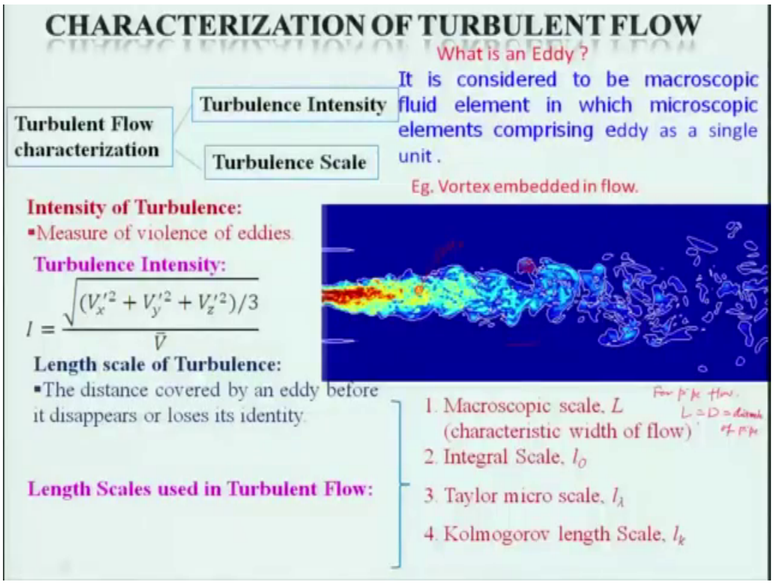

So, if you look at turbulent flow can be characterized by 2 quantities; one is turbulent intensity right and another is the turbulent scale right.

If you look at here this is basically a jet which is ejected from here and it is the turbulent in nature and these are all loops right and there will be a also there will be a rotation of fluid here and some elements of the fluid will be intervene and it will be rotating right will be the vertices. And those vertices will be having some identity right certain identity; that means, that the microscopically they will be rotating, but they will be together in macroscopically right, that we call it basically as eddies.

So, an eddy is base considered to be microscopic fluid elements in which, microscopic element comprising of eddies as a single units; that means, there will be some small eddies which will be rotating as a unit right for example, if you look at there will be various (Refer Time: 23:10) in the (Refer Time: 23:11) right.

Let us say some group is talking about yoga somebody is talking about bhakti right they are having also having some kind of thing they will be rotating they are moving around it, but they will be having similar in nature. So, that we call it as a eddies are you getting so; that means, some fluid elements will be moving let us say here I am now if I consider let us say in this bulb right I can consider as a this one right, they will be moving rotating and will be intermingling intervening, but they will be in a group which will be doing and that is known as a eddy and the as I told the vertex embedded in (Refer Time: 23:59) this is basically a vertex right which is embedded in the flow vertex means which will be rotating right.

And the intensity of the turbulence is basically a measure of violence of eddies. So, how fast it is moving. So, that energy is transferred right. So, that is known as turbulence intensity and turbulence intensity will be dependent on what basically fluctuating quantities. And if I say that V x dash you know fluctuating quantities along the x direction and v dash y in the y direction then and v z dash in the z direction, but it is fluctuating with the respect to time, then all this quote together divide by average it will be known as intensity it can be also put in terms of percentage right turbulent intensity 10 percent, 5 percent, 20 percent you know.

If you go for a wind tunnel generally low turbulence means a it is a better right in left, but you can create some turbulence to study what is happening to the turbulence label right. So, turbulence intensity is also looked at that way by which we can characterize. And there is a length scale of turbulence right, which is can be defined as distance covered by eddy before it disappears or loses it is identity, but what is happening let us say some fluid is moving here. And then as it moves it will be merged with this tops that would not be there right, if it is going with respect to time let us say it is moving with respect to these when it moves then it loses it is time.

So, that is the length scale what will (Refer Time: 25:51) how much distance, it will be lost it is identity distance covered by an eddy before it disappears or loses it is identity; that means, in between it will be keeping it is identity right. So, that distance known as the length scale.

Length scale will be what you call divided into basically 4 1 is microscopic length scale, which is the characteristics with of a flow let us say if it is a pipe flow, what it to be the microscopic scale for pipe flow for 5 flow what would be l will be basically d diameter of pipe right? And there is a integral scale l not and there is a Taylor micro scale and Kolmogorov length scale keep in mind that this is of course, mechanical that we use this mic microscopic scale for laminar flow, we always low bd by mu to find out Reynolds number, but in turbulence flow you will be using different scales to find out different kind of you know Reynolds number.

And keep in mind that these scales will be changed that, because eddies size will be changing and the time the distance it will be moving before it losing the it is identity also will change. So, therefore, the scale will be changing.

And keep it in mind there is a cascading effect; that means, larger scale eddies becomes smaller and smaller and smaller the lowest one will be Kolmogorov length scale which is the dissipation, because it will be dissipated after that this is a it is a very smaller scale is the Kolmogorov micro scale right.

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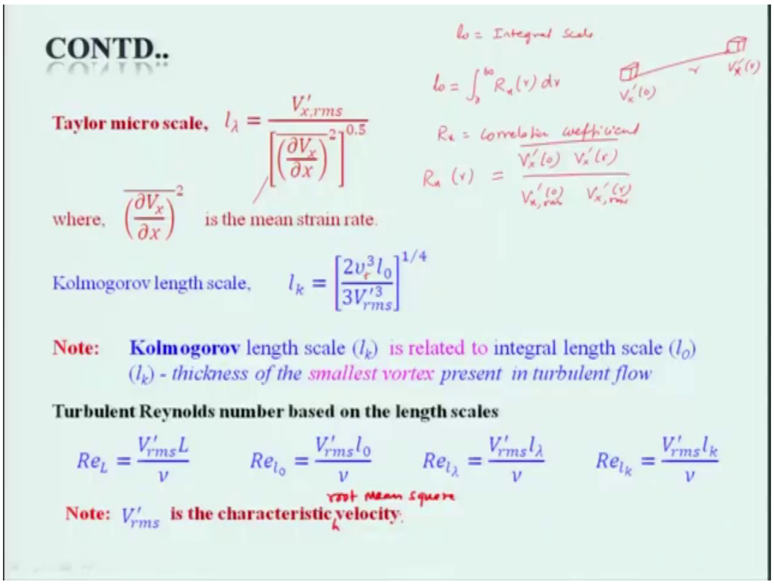

So, let us look at what you call the integral scale right l naught as I told l naught is the integral scale. And this basically represents the distance between 2 points in a flow where correlation between the fluctuating velocities between 2 locations are seized; that means, there would not be any correlation between; for example, if I say there is a fluid element you know having some kind of the what you call velocity fluctuations right. And then it is having some distance you know there is another between, which it is having let us say distance r right. So, this will be moving let us say V x this is at 0 right at 0 and this will be V x dash V x dash at r; that means, there will be some correlation between the 2.

And that distance will be telling you the integral scale. So, L no not that is the integral scale I can write down 0 to infinity R x r dr right and R x is the correlation coefficient right. And as I told this is basically function of what we call function of the distance right, between which the velocity fluctuation will be losing it is identity. So, I can define this R x r is basically V x dash at the time is ze r is equal to 0 and V x dash at r is average over the both the thing divided by V x rms dash 0 and V x rms dash r.

So, this is basically the correlation coefficient which you need to look at it to define the length integral scale. Similar I am like to know in another way we can talk about the Taylor micro scale l dash which is nothing, but V x dash rms divided by dou V x by dou x average of that into square is known as the mean strain rate this is basically mean strain rate right.

And divided by that that will be giving you the Taylor micro scale and the Kolmogorov scale is to nu cube l not divided by 3 V rms cube power to the 1 by 4 and this is by order of magnitude analysis people have come up. And this is related to basically integral length scale this is l 0 and also the V rms and this nu is basically the turbulent what we call viscosity right you can say this is t.

And lk as I told is the smallest vertex that could be present in the turbulent flow. After that what will happen it will be dissipated right this will loose it is identity all together; that means, all this things energy which will be carrying by this vertex will be lost are you getting these are all packets of what energy, which will be carried carrying by the this the vertex and which we call eddy.

Now, based on this you can define various kinds of Reynolds number based on this scales. So, that is turbulent Reynolds based on the length scale and this is your rel and this is your micro scales right. This what you call this basically micro scales microscopic scales and V rms l divided by nu and this is what you call generally we call Reynolds number in a laminar flow kind of things, but in turbulent flow depending on the situation which will be using certain cases this is Reynolds number based on the integral scale. Only you know difference is what you are using l 0 right and of course, here you using v dash rms right re l lamda is nothing, but v dash rms l lambda divided by nu and lek is nothing, but v dash rms lk by nu.

So, keep in mind that V rms is the characteristics velocity in the turbulent flow what we consider and that is the root mean square velocity this is characteristics root mean square velocity root mean square velocity right.

So, with these you know brief introduction about turbulent flow. I will stop over here in the next lecture we will be discussing about basically about the combustion. So, keep in mind that we will have to also look at this some of these terminologies whenever we will go for turbulent premix frame.

Thank you very much.