Fundamentals of Combustion

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Lecture - 49

Turbulent Flames – Part 1

Characteristics of turbulence

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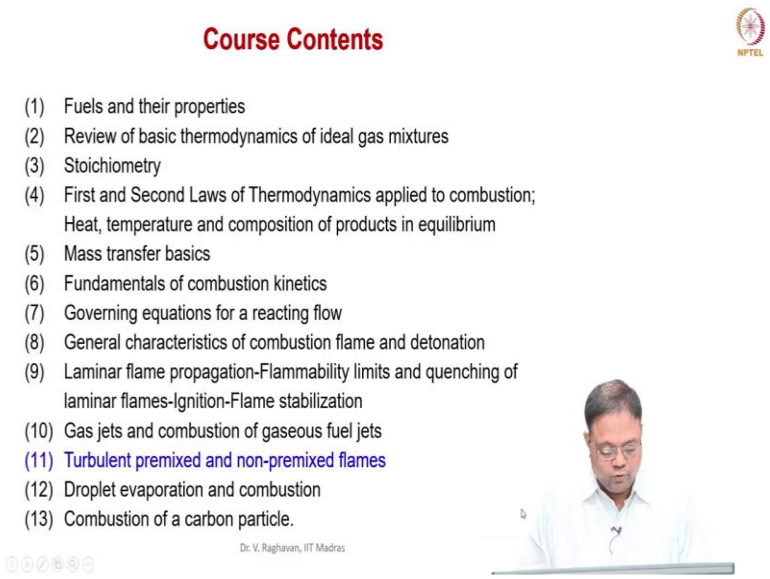

So next topic is turbulent premixed and non-premixed flame, so Turbulent Flames.

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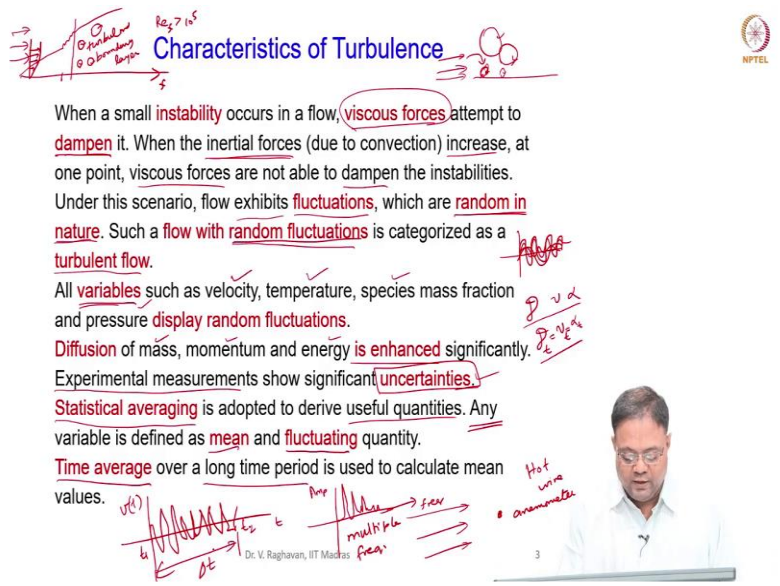

So, let us first quickly go through some important features or characteristics of turbulence. So, let us consider a wall, the wall will have some small roughness or something like that. So, it will be exaggerated like that. So, some roughness is there. Due to a flow which is flowing pass this roughness, a small eddy will be generated.

So, this is a sort of small fluctuation which is created in the flow; but when the flow Reynolds number is low what happens is the viscous forces are able to dampen the fluctuations or instability what we call. So, when there is a small instability, viscous forces will attempt to dampen it and it will be successful also in dampening it. So, the flow will remain without any major fluctuations; there may a be steady vortex shedding or something like that, but any unsteady or chaotic fluctuations will not be there in this.

So, this particular small vortex which is created due to some instability will take some energy from the main flow and grow in size. So, what happens is, the convective or the inertial forces increase and this feeds more energy to the vortexes, so the vortexes grow and so on. Then the viscous forces will not be able to dampen the vortex or instabilities. So, in such a case what happens is, the flow will exhibit fluctuations and these fluctuations are not steady or a regular fluctuation, it will be random in nature.

So, random fluctuations are observed in the flow. So, if there is a flow which has random fluctuations, we call that as a turbulent flow. So, there is a disorder and there is no structured flow pattern etcetera observed and the flow has several fluctuations. These fluctuations have different frequencies; see if there is a fluctuation like a sine wave, then we can definitely say it has a particular frequency.

But if the fluctuation has several sine waves imposed over, super imposed over each other and it has multiple frequencies; then such a fluctuation is a random fluctuation and such random fluctuations are exhibited by the turbulence flows. Now, due to the fluctuations what happens is, the quantities whatever variables what we have like velocity; then temperature and in the reactive flow, we have species mass faction, pressure etcetera will display the same type of random fluctuations.

So, this will be there, lot of eddies; eddies will be there of different sizes which is present in the flow. These eddies will actually make the diffusion, molecular diffusion and of mass, momentum and energy to be enhanced significantly.

For example, 500 times or 600 times it will be exaggerated, like the diffusion will be enhanced. So, thorough mixing will happen basically. In fact actually what we have is the binary diffusivity, mass diffusivity, then the momentum diffusivity or the thermal diffusivity; in the laminar flow they are actually fluid properties.

So, based upon the particular fluid, we will have the values of D and ν which is the momentum diffusion and the α, thermal diffusivity etcetera fixed basically. But, if you have a turbulent flow; we have the diffusivities, which we say the turbulent diffusivity.

So, D_t, ν_t and α_t etcetera and we can see that they will be equal. So, that means there is no difference between D, ν and α which we see in the laminar flow. For example, the values of D, ν and α etcetera in laminar flow are fluid properties based upon the temperatures etcetera they will be different.

So, they need not be equal. But once the turbulent flow occurs; then the diffusivities D_t, ν_t, α_t etcetera are enhanced several times and they will be of the same order. Now, another characteristic of turbulent flow is it has uncertainties which is very high.

When you make experimental measurements, so, there is a turbulent flow, I put a probe to measure this; say it maybe for example, anemometer, say a hot wire anemometer, which measures the turbulent flow as a function of time.

For example, velocity field as a function of time we can measure at a particular location. When I do so, I get velocity field which is not repeated again. I will not get the same field. So, there will be the issues in repeatability of the data and the uncertainties will be very high. So, experimentally if you try to determine, you do accurate measurements for several times repeated, then the uncertainties actually are very high. So, this is due to the randomness of the fluctuations, which is the inherent property of the turbulent flow.

So, what we normally do is, we do what is called statistical averaging. So, we will try to do a mean; then you can do lot of like deviations and other things. So, statistical averaging is the one which will give you some quantities which are meaningful and that will be used to quantify the turbulence.

So, for example, we take the fluctuation quantity, make RMS value, root mean square value and mean value etcetera. So, any variable like velocity, pressure, temperature, species mass fraction etcetera will have a mean value; because we do the statistical averaging, what we do is time averaging, then we get the mean value, time averaged value is called mean value and the instantaneous value is called fluctuating value.

So, a time average actually is done over a long period of time. So, as I told you lot of oscillations are present. So, when you take a time average for a particular time, you will get one mean. So, if you take longer time and do the time averaging, you get another mean value. So, the mean value what you take should not vary with the time period. So, if you take a sufficiently longer time period and do the time average, then you get a mean value which will not change with the time period basically.

So, the time average has to be done for a long time period and this basically will give you a mean value which will not change, which will not be a function of a time period basically. So, the turbulence is a very chaotic behavior of a fluid flow in which the viscous forces are not able to dampen the fluctuations or the instability driven features of the flow are not dampened by the viscous forces.

This is because the inertial forces, the convective force, the convective strength is very high in this and the viscous force are not able to counter the relation for this and the instabilities grow. So, once the small instability grows by taking energy from the main flow which is having higher inertia, then they grow in size and the instabilities actually grow as the turbulent flow proceeds.

So, we know that the there is a boundary layer. So, there is a flow which is coming from left to right here and you have a laminar boundary layer for some time. From some distance you have a laminar boundary layer; then after that there is a transition to turbulence, then there is turbulent boundary layer basically. So, this will be the turbulent boundary layer here.

So, as the Reynolds number increases; see for example, I tried to calculate what is Reynolds number as a function of x, this is the x direction. And if this is greater than say 10^5 for example, then I say the turbulent flow occurs. So, again you can see that in the turbulent flow, lot of eddies will be there; eddies have different sizes, which will exchange the energy from the main flow and dissipate it to the lowest timescale and so on.

So, this presence of eddies here. So, here you can see that the flow is laminar. So, if we try to draw a profile, you can see that the profile is basically a laminar. So, it is laminate means, it is a very regular structured good flow field will be there in this. But here you can see that the flow field is very oscillatory, because of presence of eddies and the eddies actually grow in size, break and so on, so that that there will be fluctuations.

These chaotic fluctuations results, these are chaotic in the sense they are very random and have multiple frequencies. It is not just like a single well behaved sine wave or say cos wave and so on. It is like waves of several frequencies and amplitudes super imposed and such a chaotic behavior will be there.

So, when you try to measure the quantity using the hot anemometer here; you can see the fluctuations will be there, as a function of time you record the fluctuation and velocity for example, and try to do a fast Fourier transform of that, you will get the multiple frequencies.

So, for example, the curve, this is the time domain. So, I say velocity as a function of time and this time instance its oscillation will be very chaotic. So, you get the oscillation something like that and now you try to put this, instead of time you have the frequency, frequency and amplitude.

So, if you try to do in the frequency amplitude domain, you will see multiple frequencies here, so multiple frequencies. So, if you take sine wave, it will be only one frequency and the corresponding amplitude. Here you can see multiple frequencies. So, the presence of multiple frequency oscillations is the main characteristic; so that random oscillations, multiple frequency oscillations are the characteristics of the turbulent flow.

So, if there are oscillations of multiple frequencies; every variable like velocity, temperature, species mass fraction, pressure everything, in several occasions even the reaction rate will undergo such a random fluctuation.

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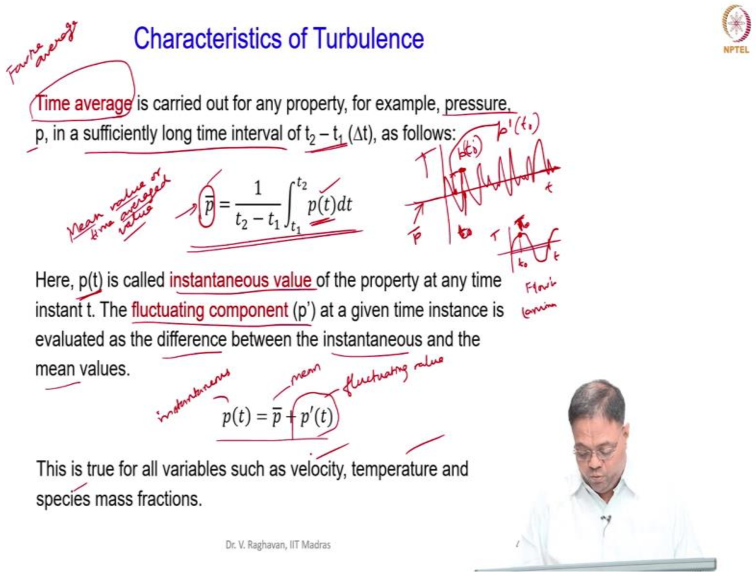

So, we talked about time average. So, you have a time period here; see for example, this will be the time period here in this, say t_p, time period. So, I take a sufficient time period. So, this may be t_1 and this may be t_2. So, $t_2 - t_1 = t_p$ or I will say Δt for example; Δt is a time period here and $t_2 - t_1 = \Delta t$ and I take this long time period. So, $t_2 - t_1$ is very long.

So, when I take this and try to take a time average; so I do the time averaging of this. I have taken pressure here, the mean value. So, this is the mean value or I say time averaged value. So, $\bar{p}$, I put $\bar{p}$ as the mean value or time averaged value which is nothing but $1/\Delta t$. So, Δt is $t_2 - t_1$.

So, 1/Δt integral of t_1 to t_2, p(t), which I actually measure. I put a pressure transducer say, for example, in IC engines I put a pressure transducer and I try to record the pressure as a function of time. So, that is this.

$$\overline{p} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} p(t)dt$$

So, for example, here the pressure versus time it may have some random fluctuations. At any time instant. So, this will be the pressure at a particular time say t_0 and this is called t_0, this time is I say t_0. At a particular time t_0, what is the corresponding pressure? So, that I put here and try to integrate this. When I do this, I get the time average.

So, as I told you, this would be sufficiently longer time interval. For example, if I do the experiment for say 20 minutes and record this data say for 15 minutes. If you take a time average for say one minute and say two minute, five minutes, ten minutes etcetera; you will see that once you do the time averaging taking at least five minutes into account, the mean value will not vary. So, that is called sufficient time period.

So, if you take 1 minute, two minute time period averaging, 3 minute etcetera; you can see that the mean which is obtained from one minute period will be different than that obtained from two minute period and so on. But if you take 5 minutes and say 10 minutes or 15 minutes etcetera; it may not vary.

So, sufficiently longer time interval corresponds to a time interval which will capture all the frequencies which is there in the oscillations. If you do this, then you get a proper mean value. So, it is very important to do this.

So, time averaging which is done with sufficiently longer time interval will give you a mean value which will not vary. So, you can do experiment several times but for example, at a particular location, this is the pressure versus time oscillations curve I get. Now, if I do it for second time, I will not be able to get this; see for example, this maybe at t_0, I get the value of $p(t_0)$, which is this peak.

Next time at the same location if I do the experiment at the same time t_0; I may see that the pressure will not be at peak, it may be at the lowest or it may be 0 also. So, because of these random oscillations, I can get any value and I cannot compare the instantaneous value at all. It is impossible to compare the instantaneous values.

So, what is instantaneous value? If you take this particular measurement at any particular time period the value of the quantity is called instantaneous value. So, for example, p(t) is called the instantaneous value, that is the property at any time instant t.

Now, let us say fluctuating quantity is $\overline{p}$. So, again that is also a function of time; you can see what is a fluctuating quantity?

So, this line if represents the mean value because there are quantities here above and below that and if this is the mean value, then the instantaneous value is nothing but the value of this. So, this is called instantaneous value p' at the particular time t_0

$$p(t) = \overline{p} + p'(t)$$

So, that p' will vary, p instantaneous value will vary and also correspondingly the fluctuations will also vary; mean we have kept it constant, by taking the time average using a larger or a sufficiently longer time interval.

So, the fluctuating quantity p' at a given time instant is evaluated as a difference between the instantaneous and the mean values. So, p(t) will be equal to $\overline{p}$, that is the mean value and the fluctuating value. So, this is instantaneous.

So, unlike pressure or other components like velocity components, temperature and species mass fractions, even reaction rates etcetera undergo such fluctuations. So, there are two types of averaging; one is called time averaging, another is called Favre averaging. For most incompressible flows, we will use the time average; Favre average we will not use, that is density weighted average.

So, normally we use time average for the incompressible flows. That is what we are going to see. So, now we can see that it is not easy to reproduce the instantaneous value. So, I measure a velocity or temperature or anything, even temperature can be; so instead of velocity pressure, it can be temperature here.

So, temperature also undergo this, at a particular point at a particular time instant; when I do the repetitive experiment with the same initial conditions, boundary conditions etcetera, if flow is laminar you can reproduce that.

If the flow is laminar; then you can see that I get a value at a particular time say t_0 which is T_0 for example If I do the experiment with the same initial condition and boundary condition, I will surely get the closer value to this.

So, that means, repeatability will be there in the experiments. So, experimental uncertainties will be very low for laminar flows. However, for turbulent flow uncertainties will be very high; because in one instant I can get p as a maximum value in the oscillatory field, but in the next time when I do the experiment, Same position and same time instant I will get a minimum value also for the p. So, that such a large uncertainty will be present in the turbulent flow.

So, the only meaningful value here is the $\bar{p}$ or the mean value which I am taking. I am ensuring that the value will be meaningful, because I take sufficiently longer time and average out. So, all the fluctuations positive and negative; see if this is a sine wave, I just only take one time period.

If I now time average, I get the average value which is very easy; I do not need to take very long, only the time period of this single oscillation I can take. But here several waves are present of different frequencies, amplitudes etcetera. So, if you take and we do not know the exact time period of these things.

So, you take sufficiently longer time, so that in all the super imposed waves; you will see that the maximum and minimums are cancelled and you get a zero. For example, there will be a mean value and values which are fluctuating above and below the mean will be cancelled out, so that sufficiently longer time interval is taken.

So, that is the meaningful value I have. Now, the instantaneous values or the fluctuating values etcetera does not have any meaning; because we cannot reproduce it. But anyway, this analysis we need to do. And how we are going to use this fluctuating component and try to get some logic for the turbulent flow is the question now.

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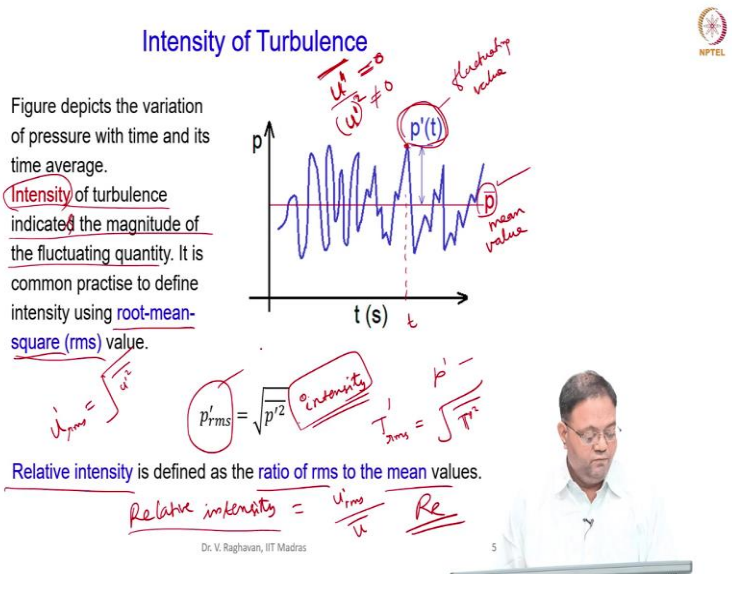

So, as I told you this is the typical oscillation. I have given here the p value shown in red line here and the instantaneous value at any time period here. So, this is for this time say t, I get the p'(t), this will be the value here. So, that will be measured with reference to the mean value here, this is the fluctuating component, this is the mean value.

Now, the fluctuating component p'(t) is actually used to represent the intensity of turbulence; intensity is the strength, the strength of turbulence or intensity of turbulence is indicated by the magnitude of fluctuating quantity. The intensity of turbulence indicates the magnitude of the fluctuating quantity.

Now, what we try to use; we do not just use p′ alone for the intensity, some function of p' is used for representing intensity. So, what is that function, I use the root mean square value of the fluctuating quantity. So, root mean square value of the fluctuating quantity I use. So, give this representing intensity. So, this is the intensity now. So, what is root mean square value?

$$p'_{rms} = \sqrt{\overline{p'^2}}$$

So, p', I square it, then I take time average of it and take the square root of that. So, that is the root mean square value.

So, root of mean of square of fluctuating quantity. It maybe temperature also. So, I say temperature r m s will be equal to root of mean of temperature oscillations square of the temperature fluctuating values. So, this will be the value I use.

So, we can also use the velocities. For example, velocity r m s will be equal to root of mean of $(u')^2$, ok. So, this will be the intensity; if this root mean square value is higher, the intensity is higher, if it is low then the intensity is low. So, that is the way you quantify the turbulence intensity. Intensity is the first one which we use to quantify the turbulence. So, this is very important, ok.

Now, we can also say what is called relative intensity which is nothing, but the ratio of the root mean square value here and the mean value, that is relative intensity will be equal to say for example, here for the r m s value of the velocity divided by the $\bar{u}$. So, that will be relative intensity. So, the ratio of the r m s to the mean values, that is the relative intensity; this intensity is the one which is very important for us.

So, the mean value will not represent the turbulent, because that is the mean. So, that will be like an average flow field, what we represent by using the mean values. However, the turbulence is quantified by the fluctuating quantity and if you take the root mean square value of that the fluctuating quantity, you get this.

So, you can also see that if you do a time averaging of $\bar{u}$, you can ask why? Why you are taking root of the mean square value; square value why we are making? Because if you take a time average of just the turbulent fluctuation, time average will be equal to 0 because the fluctuations cancel out.

But if you take this $(u')^2$ and take a mean value, it is not equal to 0. So, that is the reason why we take the square value, square value of the fluctuation and take the time average of that to get the mean value and take the root of that. I want the strength of the fluctuation only.

So, I first square it; because if I just take the fluctuating quantity and take the time average, it will become zero, that is why we are trying to take in the mean. So, long time period and try to take the average, so that the fluctuations in the positive and negative sides of the mean value cancel out. So, I get the mean value $\bar{u}$; so that means that, the time averaging of the fluctuating quantity will be equal to zero.

So, in order to get the influence of turbulence, I need some quantification of the fluctuating quantity. So, what I do is, I take the first square of the fluctuating quantity. So, $(u')^2$; now positive and negative will be same. I squared it so that it will be positive; u' can be positive or negative with respect to the mean, but $(u')^2$ basically will be positive.

Now, I have time average of that quantity $(u')^2$ and take a root of that to get the intensity. So, the intensity in terms of r m s will be a positive quantity. So, that is what we are trying to extract. If it is low, where the fluctuations are very low, then the root mean square also will be low.

So, that means the intensity of the turbulence is low. The flow is not as turbulent as what we expect at higher Reynolds numbers. So, Reynolds number is the main non-dimensional number which will quantify the turbulence in a forced convective environment.

So, the main point here is first of all you need to understand the relationship between the mean and the fluctuating quantity. How to define the turbulent intensity which is nothing but the r m s square of the fluctuating quantity.

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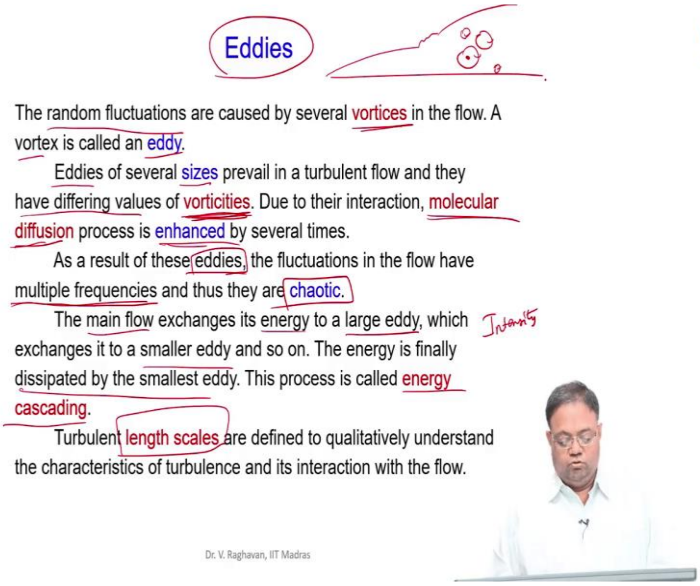

So, as I told you, we will now see some eddies. So, as I told you in a turbulent field, you can see this is turbulent field, several eddies are present of smaller and bigger size. This will not remain as the same size; for example, the smaller eddy will take energy from the main flow, grow to a larger eddy and the larger eddy dissipate energy to the smaller eddies and shrink in size and so on.

So, for example, at the particular point if you have an eddy of this size in the next time instance there will be a smaller eddy and at another time instance, there will be no eddy at all. So, eddies of different sizes are there present in the flow.

So, these random fluctuations are caused by the growth and the diminution of these eddies. So, the random fluctuations caused by several eddies are nothing but vortices and the vortex is called eddy. So, a vortex, a particular vortex is called eddy and the vorticity is the strength of the eddy.

So, eddies of different sizes, that is several vortices are present. And they have different values of magnitudes, that is the vorticity; the vorticity is the magnitude or we quantify a vortex with its vorticity strength.

So, vorticity, several values of vorticities will be there. So, based upon its size, it will have different vorticities and you can see that they will grow in size or diminish in size etcetera based upon the energy which is transferred from the main flow to the eddy or from the bigger eddy to a lower eddy and so on. Or it may also lose, the particular eddy can also lose the energy to the main flow or dissipate to the walls and main flow and so on.

So, vorticities, several vorticities, vortexes of several vorticities are present in the flow. Due to the interaction, the molecular diffusion is enhanced by several times that is what. So, for example, it is like stirring this particular field, if you take some water and put some salt in it and leave it; by molecular diffusion it will take several minutes or hours to fully dissolve this salt.

But on the other hand, you just put a spoon and stir it; immediately you can see that the vortex which is created within the liquid layer, that will immediately dissolve the salt in the water. So, similarly the molecular diffusion is the very slow process based upon the concentration gradient, thermal gradient etcetera it occurs but if there are vortices, several vortices in the field, then the diffusion is enhanced by several times.

So, the molecular diffusion is enhanced by several times due to the presence of these vortices or the eddies. Now, as I told you earlier, when several eddies are there; they grow and shrink in different rates and then due to the energy transfers between them and the other eddies and the main flow etcetera.

So, what happens is the fluctuations are also very random and they have different frequencies, multiple frequency fluctuations are present and therefore they are called chaotic. So, it is a chaotic behaviour Why chaotic?

Because as I told you; once I put the probe in one place and start the experiments with the same conditions, without any change, while the same experiment can be exactly repeatable for a laminar flow. When the flow has become turbulent, I get different results which I will not even anticipate.

So, such a chaotic behaviour is displayed because of the multiple frequency oscillations which are exhibited due to the presence of eddies of several sizes and strength.

Now, as I pointed out, the main flow will give the energy to the eddy; the main flow has some energy that will be given to the eddy and eddy grows in size and dissipates the energy to their lower sized eddies. And finally, the lowest size eddy will dissipate it; the lower size eddy will dissipate it into the main flow or the wall and so on.

So, the main flow exchanges its energy with a large eddy which exchanges, energy basically we can say that it is the flow strength. So, that is given to the larger eddy. Now, this the larger eddy exchanges with a smaller eddy and so on.

The smallest eddy which is present that will actually dissipate the energy, dissipate the energy completely because it cannot transfer to any other eddy so it will dissipate the energy. So, this process of transfer of energy from main flow to the lowest sized eddy is called energy cascading.

So, energy cascading is a process by which the turbulent flow sustains and increases the molecular diffusivity by several times and create chaotic fluctuating behaviour in the flow. Now, intensity we have seen already, the turbulence intensity.

Now, what we will see is the length scale of turbulence, this is very important; because see I have told you several size eddies are there. So, what is the smallest scale which is going to dissipate, smallest eddy size? What is the largest eddy size which can be formed here?

So, the sizes of the eddies will contribute to several turbulent scales; it is not like one particular scale. For example, in laminar flow, we have one characteristic dimension which we can take as a scale; but in turbulent flow, lot of scales are present.