Fundamentals of Combustion

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Lecture – 52

Turbulent Flames – Part 4

Turbulent premixed flames and flame regimes

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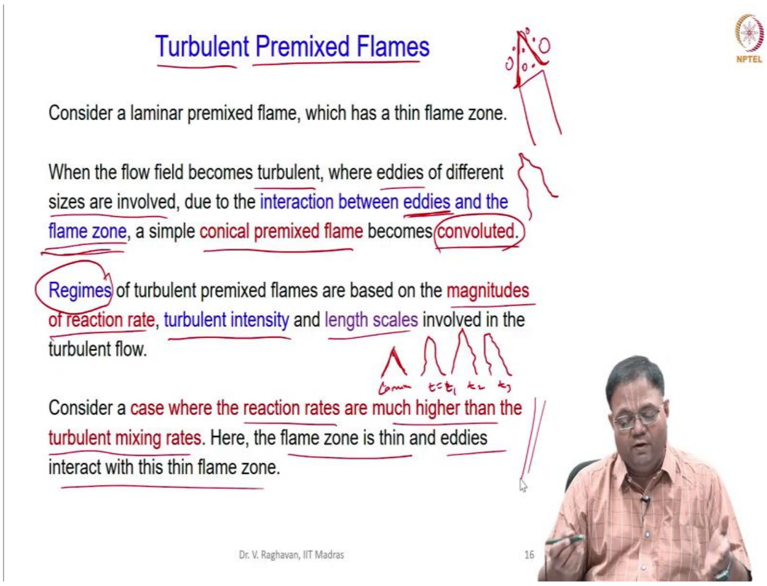

So, now we go to see about the characteristics of flames. So, let us first see the characteristics of the turbulent premixed flames. Consider a laminar premixed flame which has a thin flame zone.

So, the flame zone is considered thin because it is having a thickness of say 1.2 mm – 1.5 mm something like that. So, let us just draw a flame like this, a conical flame, at the end of Bunsen burner which will be very thin in this. So, it is the flame what we get in the laminar regime. So, this is the flame, we are going to get.

So, it is very well behaved and thin flame and if you take photography as a function of time, there will be not much variation in this shape and the flame is intact. We are talking about the stable flame basically. However, when the flow becomes turbulent, eddies of different sizes are involved.

We have seen that is the characteristics. So, eddies of different sizes are involved and because of the interaction between the eddies, so eddies will be there of different sizes everywhere in this.

So, because of the interaction between the eddies and the flame zone, a conical flame which like this becomes convoluted, that is complex. So, you can see that the eddies act on this and you can see some oscillations in the flame zone.

So, a flame which is conical in shape like this, acted upon by the eddies will be like this. So, with time this is going to change. In one time instant, it will be like this; in another time instant it will be like this; another time instant, it will vary. So, there will be fluctuations on this.

So, what we are assuming is this a very thin reaction zone, eddy size is not smaller than this. So, in this case, now the surface is distorted like this. So, the conical premixed flame becomes convoluted and this is laminar. So, this t = 0 is the onset of turbulent. So, t = 0, I will say t_1, t_2 and t_3. At different time instant, you will see different flame shapes and the surface is not smooth enough and there is no conical shape at all in this.

So, this is what we are going to get when there is an interaction between the eddies in the turbulent flow which are of several length scales and the flame zone itself. So, that is this. So, the regimes of turbulent. Now, only this can happen or anything else can happen that will be dependent upon several things. For example, if we are talking about the thin flame, that means, the reaction rate is very fast. So, you know that the thickness of the flame is inversely proportional to the laminar flame speed.

So, if the reaction rate is very fast, then the laminar flame speed is expected to be higher. So, the flame thickness is very thin. It is very low. So, when you talk about thin flames, the size of the lowest eddy, a smallest eddy that is the Kolmogorov scale can be higher than this flame thickness. In that case, the flame will not be affected by the eddy coming into the reaction zone. So, several factors affect this.

So, magnitude of the reaction rate that is very important. Then, the magnitude of the turbulent intensity and the length scales, these are the things which will affect the flame. So, when the flame is going to be affected by this, you can see that the eddy size, the reaction zone thickness if its slightly increased, eddy can penetrate that and so on. So, lot of things will be there. So, we get different regimes of turbulent premixed flames, different regimes we get. So, what are they?

Now, first we will consider for the same thing, we will try to extend and see where the conical flame is established over a Bunsen burner, we will take and here the reaction rates are assumed to be much higher than the turbulent mixing rates. So, that the flame zone is very thin and the eddy interact with the flame zone, without going inside the flame zone that is what this regime is. We will anyway come back and name this regime later.

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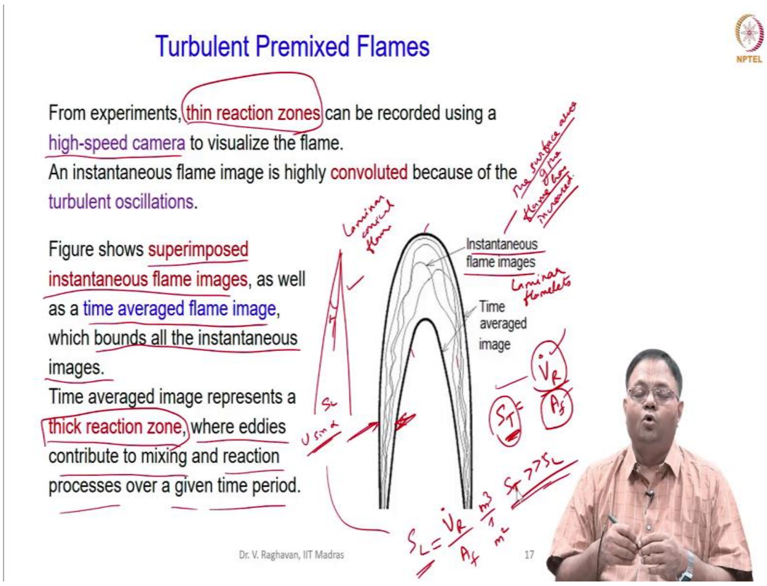

So, in this case, what happens we will see this. So, the figure shows the convolution of the laminar flame, that is the initial conical flame basically. Now, due to the eddy interaction it becomes convoluted and we will get this at one time instant. So, instantaneous flame images are given here at one time instant. You get a flame which is convoluted like this, acted upon by the eddies.

Similarly, different time instants, we will see and you can see that this boundary here, this boundary and this boundary will be the boundary which will include all the flame oscillations. That means, the flame will be extending only within these boundaries. So, this is a thick zone. So, this is time averaged thing.

At a particular time instant, you get the reaction zone which is thin and when you take the instantaneous flame photograph continuously, you get several instantaneous flame images and when these flame images are time averaged, you get this thick flame.

So, this thick flame is nothing but the time averaged flame image and that bounds all the instantaneous images. So, we start with a thin reaction zone which is laminar and try to increase the velocities of the mixture.

So, after a particular range, when the diameter of the burner and the velocity increase, the Reynolds number exceeds the value and the turbulent flame establishes. Try to use a high-speed camera because there are low frequency fluctuations, we need to capture that.

So, for example, we can go for say 1000 flames per second something like that. In order to capture the variations. So, high frequency fluctuations, we can capture and we get instantaneous flame images. Several of them and if we try to complete a cycle, then we can see that after a particular cycle is completed, again the flame will start oscillating within this and this. So, the minimum flame extent will be this part and the maximum flame extent will be this. And within this, the flame will be oscillating. When you take an average, you will see this will be the flame shape of that.

So, superimposed instantaneous flame images will contribute to a time averaged flame image, so that will bound all the instantaneous images. The time average represents the thick reaction zone. Why this has become thick?

It has become thick because of the eddy interaction. So, that means, when I say this is the time averaged image, I say that the reaction zone will be anywhere in this regime. So, in this region, what I have plotted in these dark boundaries. The flame can be anywhere in the regime, so that is what.

So, that represents a thick reaction zone, where eddies contribute to the mixing and the reaction progress over a given period of time. Now, what happens? This is the laminar flame, laminar conical flame. Now, there is a particular flame velocity for this. I know U into sinα will give the S_L. So, S_L can be found. That is the laminar flame speed.

But in this case, what happens you can see the instantaneous image, the surface area of the flame has increased. Now, coming back to the laminar case, I can say S_L. It is nothing but the volumetric flow rate of the reactant divided by the surface area of the flame. So, here also we can see that the surface area in this turbulent case of the flame has increased significantly. So, a conical surface has become like this. So, it has actually become wavy and enlarged and so on.

So, effectively the surface area of the flame has increased several times. So, here the turbulent flame speed will be equal to the volumetric flow rate of the reactant divided by the surface area of the flame. Now, we can see that the S_T will be much greater than S_L. So, the affect of the turbulence is to increase the laminar burning speed; that means, you can see that the flame can now consume more reactants. So, that is what the consequence of the turbulence here.

So, when you have a conical flame which is well behaved, you have a given surface area and the flame when it interacts with the eddies of several sizes, you get different flame shapes and they are not conical anymore.

But when you measure the surface area, that is much higher than the surface area of the cone what we got in the laminar regime. But you can see easily that when you calculate the flame speed by using this, we can see that this S_T is seem to be much higher than S_L.

So, when you calculate the surface area, volumetric flow rate, this is m^3/s divided by the m^2. So, this will be the S_L. So, this is small and we can also do it by the Usinα, the half cone angle.

But if you take the turbulent burning velocity, you can see the surface area is increased by this and the volumetric flow rate is also higher, much higher to cause the turbulent flow. So, this turbulent burning speed S_T is much greater than S_L, you see even though the surface area is higher because the volumetric flow rate is much higher now.

So, this means that the flame can now consume more reactants. So, that is what this means. We have correlations for S_T; S_T by S_L ratio because we have a lot of correlations for this based upon the regime. So, the summary here is we can see that the turbulence causes a thin flame zone, taking the thin flame zone the turbulent causes interaction outside the flame zone.

The eddies cannot penetrate the flame zone and we can see that the conical flame is now convoluted to different shapes with increased surface area and when you take instantaneous time, you will see that variations are there in the flame shape with respect to time. When you take a time average, it will represent a thick flame zone in which at any time instant, you will have a flame within this particular zone. So, this thick flame zone will have eddy interactions basically. So, there will be eddy inside this and outside this also. So, these instantaneous flame zones are called flamelets; Laminar flamelets. Now, when we talk about the surface area, the surface area of the laminar flame is much smaller than the convoluted flame which is actually very larger, the surface area is larger. So, now you can calculate the laminar flame speed like volumetric flow rate of the reactant divided by the area of the flame that will be basically higher for this turbulent case. Because the volumetric flow rate what we use is higher, to increase the Reynolds number. So, this is much higher and even though the flame area is increased, you can see that the S_T will be much greater than S_L giving an idea that this turbulent reaction zone will consume more reactants.

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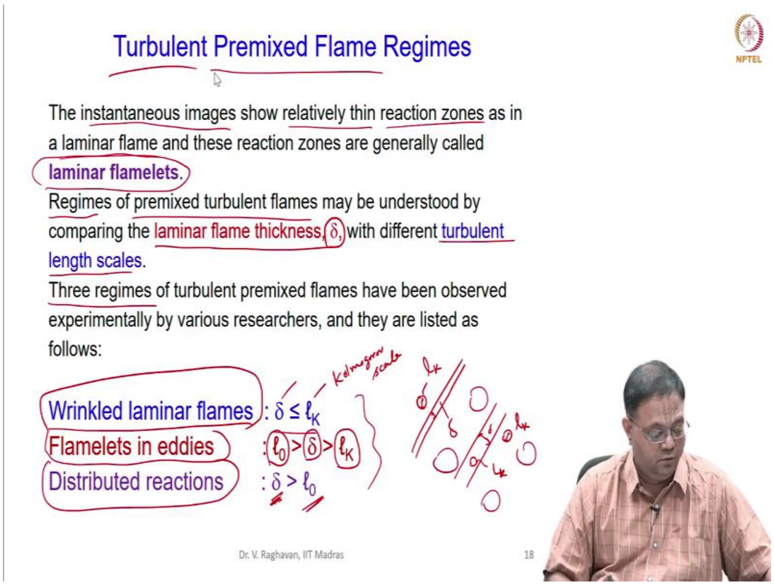

So, the instantaneous flame as I told you the instantaneous images what we have shown is relatively thin and it represents the laminar flame basically. Now, till that point this is extremely thin reaction zone which is having a length scale lesser than the smallest length scales of turbulence. So, the eddies cannot penetrate to the reaction zone.

So, this thin flame reaction zones can be called laminar flamelets. So, that we have to understand, laminar flamelets. So, these are the laminar flamelets or the reaction zones which are not affected by the eddies which is penetrated inside. So, only outside the laminar flamelets eddy can be prevailing. So, the laminar flames are thin reaction zones, where there is no influence of eddies basically; but based upon the size of the reaction zone, we have several regimes.

So, we will come up on that now. The regimes of the premixed turbulent flames can be understood by comparing the laminar flame thickness δ with the turbulent length scales. So, that is the simplest things we will do. See for example, the regimes are presented here. So, we will actually see three regimes, basically lot was observed by the several researchers.

The first regime is called Wrinkled laminar flames in which the laminar flame thickness is less than the smallest length scale. This is the Kolmogorov scale. So, now you can see that when the flame thickness, the extremely fast reaction take place and the flame thickness is very small which is less than the smallest eddy size what we have. So, that means that if this is the flame zone, then eddies are larger than this. So, the eddy lengths are larger, this is the l_k and this is the δ.

Now, $\delta \leq l_k$, so that means the eddy cannot go into this, penetrate into this, and because of this the flame zone is extremely fast. Because eddy length scale is larger than that, it cannot penetrate that.

So, in this case, eddy can only act outside the surface of the flame. So, that will form what is called the Wrinkled laminar flames, that is what we see here. Basically, the eddies act upon this flame zone conical flame zone, make it convoluted like this and this changes with time and we get a thick flame zone finally. Now, in the second regime, we have flamelets in eddies.

Now, what happens is the Kolmogorov scale is now smaller than the laminar flame thickness. Now, you have a slightly thicker δ here and Kolmogorov scale is smaller now l_k; l_k is smaller. So, this eddy can be inside. So, this is the l_k. So, this can go inside. Now, the smallest eddy can penetrate into the flame; but this integral scale, turbulence integral macroscale cannot penetrate. That means, there are lot of bigger eddies which still remain outside, the smallest eddy can now penetrate.

So, this is the regime where $l_0 > \delta > l_k$. That will contribute to what is called Flamelet in eddies. Let us see that later how it will look like. Then, the third is the distributed reaction zone. Now, you can see that $\delta > l_0$, the integral scale; So, these are the regimes which will tell us whether the turbulent eddies will penetrate into the reaction zone or not.

So, in the first case, there is no penetration of the eddies inside the extremely thin reaction zone and only the surface convolution happens for the flames; laminar flames. Anyway, we can see that there is an increase in the burning speed, rate of consumption of the reactants and so on. Second is the flamelets in eddies. Here, the problem is part of smaller range of eddies can penetrate into the reaction, but there are again larger eddies which cannot penetrate.

But if we go to distributed reaction zone, the flame thickness is higher than the integral scale itself. So, the l_λ will be somewhere in between this. So, the Taylor's micro scale. Based upon the comparison of the laminar flame thickness δ and the turbulent length scales like l_k and l_0, we have three regimes for the premixed flames in the turbulent regime; three separate regimes we have. So, we will go to see how they are going to be like what are the characteristics they have.

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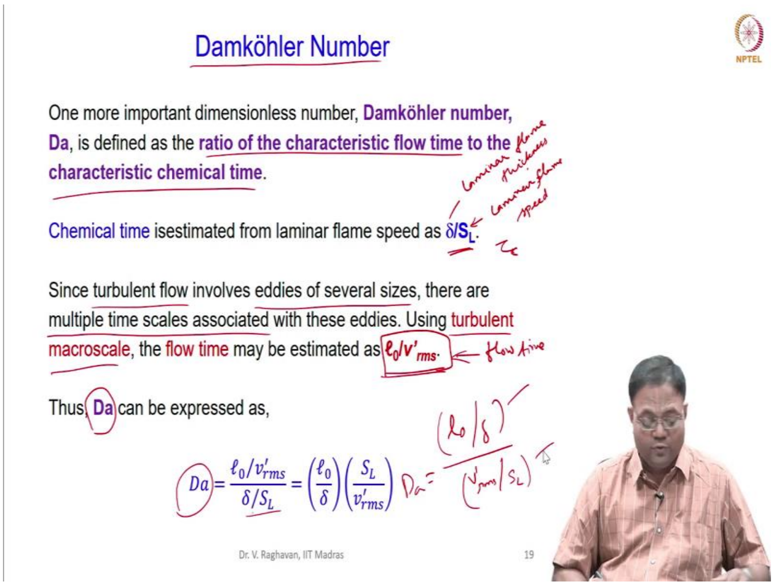

So, before that we will also introduce the Damkohler number which we know is very important characteristic non-dimensional number for us. We know that it is the ratio of the characteristic flow time to the characteristic chemical time.

So, that we know already. Now, chemical time in this scenario can be defined based on what the flame thickness is. This is laminar flame thickness and this is the laminar flame speed. So, this ratio will be the τ_c, chemical time. Now, how will you calculate the flow time? Since turbulent flow involves eddies of several sizes.

So, for example, based upon one length scale, you will have one time scale, characteristic flow time. So, multiple time scales are associated. So, the turbulent macro scale or the integral scale, let us use that to calculate the flow time and the velocity will be the rms value. So, l_0/v'_{rms}, this is the rms value of the fluctuation. If we take this as the flow time, then the Damkohler number can be put as the ratio of the flow time by the chemical time that is $(l_0/v'_{rms})/(\delta/S_L)$. So, this is the flow time and this is the chemical time. So, we can write like this.

But we can also write the Damkohler number as l_0 that is the ratio of this which we have already seen, the ratio of the turbulent length scale to the laminar flame thickness divided by. So, here we have v'_{rms}/S_L. You can see this turbulent length scale divided by the laminar flame thickness divided by the turbulent intensity divided by the laminar flame speed. So, this is also Damkohler number. So, both ways you can write this. So, based upon the value of the Damkohler number, we can define the regimes.

So, in the previous slide, based upon the comparison between the laminar flame thickness and the length scales, the regimes are different. Now, the same thing can be done with the value of the Damkohler number also.

We can see Damkohler number is nothing but the flow time which is the integral scale by the turbulent intensity divided by the laminar flame thickness divided by the chemical time. The laminar flame thickness divided by the laminar flame speed. So, this can be written as a ratio of the length scales and the velocity scales.

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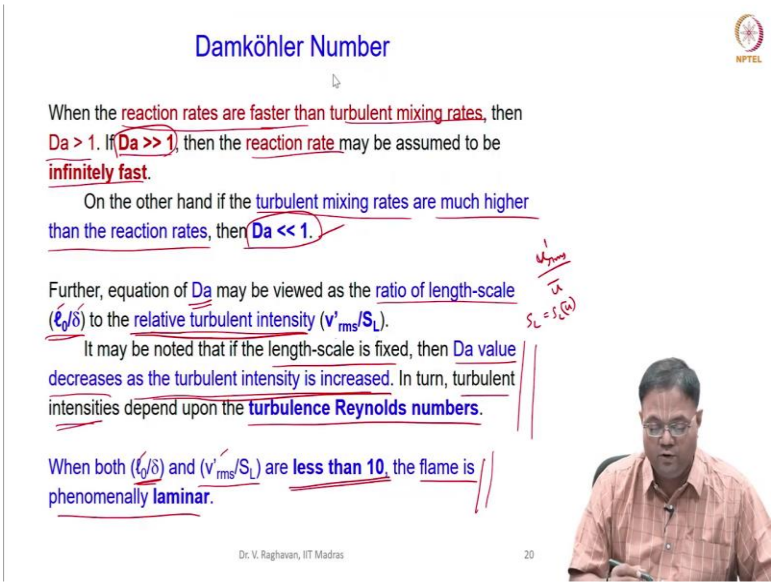

Now, based upon that we will try to understand the consequences. So, let us first say the reaction is infinitely fast. So, Damkohler number will be much greater than 1. So, reaction rates are faster than the turbulent mixing rates. So, when I say reaction rate, please understand, it is called a volumetric reaction contributed by the mechanism what we have. So, it may be the single step mechanism or it may be a chemical mechanism with the chain reactions elementary reactions and so on.

But when the set of reactions what we use are faster than the turbulent mixing rates, then in this case Damkohler number will be greater than 1. Now, when the reaction rate is assumed to be infinitely fast, very reactive species and the flame speed is very high, the reaction zone is extremely thin. Now, we have the Damkohler number >> 1. In the extreme cases, other opposite cases, the turbulent mixing rates are much higher than the reaction rate, then Damkohler number will be much smaller than 1.

So, this we can easily understand by the equations what we have written. Similarly, what I have told is same thing Damkohler number can be written as the ratio of the length scale of the ratio of the length scale of the turbulent and the laminar flame thickness as to the relative turbulent intensity. So, v'_{rms}/S_L is called relative turbulent intensity. Normally, relative turbulent intensity can be written as v'_{rms} or $\bar{u}_{rms}$ divided by $\bar{u}$, mean velocity.

Now, since $\bar{u}$ and S_L are connected, S_L is a function of $\bar{u}$, I can say this v'_{rms}/S_L has the relative turbulent intensity. So, we can also define like this. So, basically, we can draw maps in this coordinate and try to see where the turbulent premixed flame regime will lie, that we are going to do it eventually. Now, if the length scale is fixed then the Damkohler number decreases as the turbulent intensity is increased. This intensity is increased that will decrease because this is the ratio. So, $(l_0/\delta)/(v'_{rms}/S_L)$.

So, when you fix the length scale, when the turbulent intensity increases, then the Damkohler number will decrease. So, that will contribute to this regime, where the turbulent mixing rates will overtake the reaction rates. Now, turbulent intensities, how they will increase? They depend on the turbulence Reynolds number. As the Reynolds number increases, then the turbulent intensity will increase.

So, when we set a problem, then the length scales are almost set. So, basically, we are talking about the l_0. So, that will also be almost the same. So, once you have a chamber, everything is defined, then the length scales are pretty much fixed. So, when you increase the Reynolds number, the turbulence Reynolds number basically, you increase the turbulent intensity.

So, we move from the reaction rate control to the turbulent mixing control regime. So, that is what you have to understand. We will see more on this. Now, what is laminar regime? See everything is basically turbulent, even then there is some length scale which may be smaller etcetera, there may be some small oscillations present in the field etcetera. So, based upon this, when we have this length scale ratio l_0/δ or the relative turbulent intensity $v'_{rms}/S_L < 10$, then the flame will behave as a laminar flame, phenomenally as a laminar flame.

So, this is also one of the important things which we should understand. So, these are the things. So, once you define this Damkohler number like this, we can understand several regimes based upon the values. We are trying to attempt, where we will compare the l_0 and δ and v'_{rms} and S_L and try to come up with the regimes.

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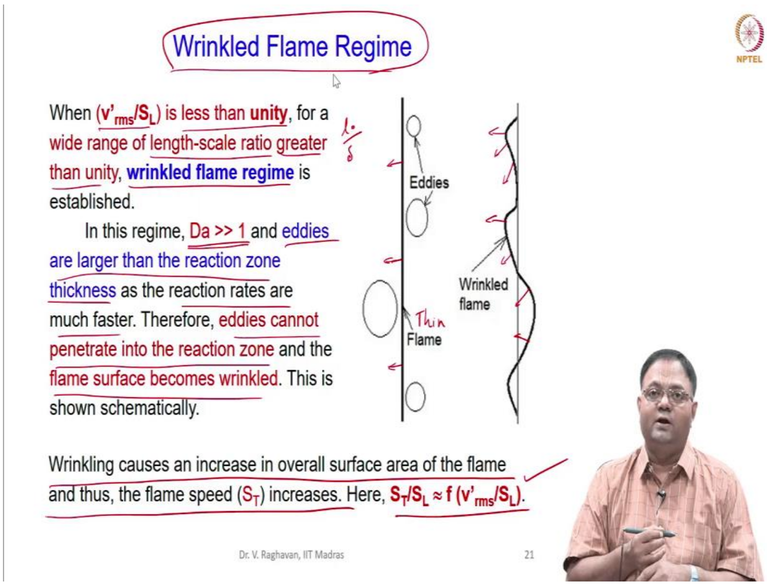

So, let us go into the three regimes in slight detail. So, first one is the wrinkled flame regime. Now, v'_{rms}/S_L is; so, in wrinkled flame regime S_L is very high. We are talking about high reaction rates. So, high values of S_L. So, what happens when high values of S_L are prevailed? The flame thickness will be extremely thin; so, thin flame. So, I am saying about this thin flame and the S_L being high, so, this ratio is less than 1.

Now, once you fix this intensity, relative intensity, then for a wide range of length scale ratio which is greater than 1. This is the $l_0/\delta > 1$, we will say because already you can see that δ is smaller. So, this is actually greater than 1. So, for a range of these values of this ratio, you get what is called the wrinkled flame regime.

Basically, because the smallest eddy cannot penetrate the flame, they act upon this and the flame surface area is now increasing as you can see, this will be surface area now, this into say the in-depth whatever be the width that may be taken as the surface area. But here, you can see that the flame is convoluted because of the action of these eddies.

So, this eddy acts and pushes the flame like this and so, the wrinkling of the surface takes place and the surface area is increased. So, now the reactants are consumed at a faster rate in this particular thing. So, you can see that here the burning velocity will be normal to this surface; but here you can see that the burning velocity changes the direction etcetera like this. So, they are normal to the surface, where the surface itself is now convoluted. So, you can see at the surface due to the increased surface area; more reactants are consumed.

So, volumetric flow rate which is taken is higher, so the flame speed increases. So, in this regime obviously we have already seen that the Damkohler number will be much >>

1, the eddies are larger than the reaction zone thickness and the reaction rates are much faster. So, it will be the same thing what we have seen. So, now, eddy cannot penetrate to the reaction zone, flame surface becomes wrinkled only.

So, the consequence is the increase of surface area of the flames, not any change in the reaction zone, still the reaction is controlled by the reaction rate the mechanism what we have. The eddies cannot control the reaction rates because they are slower. So, wrinkling causes an increase in the overall surface area of the flame as I told you and thus, the turbulent flame speed S_T increases.

So, normally, we can see that the ratio of the turbulent flame speed S_T divided by the laminar flame speed S_L will be a function of the relative turbulence; as this increases, this will also increases. So, when we fix the length scale, when the turbulent intensity increases, the flame speed will increase. So, lot of correlations are available based upon this function.

So, lot of correlations we can write. In the wrinkled flame regime, which is the regime where Damkohler number >> 1. Here also we have seen this; infinitely fast chemical kinetics, Damkohler number >> 1.

So, that regime will not have the eddies to penetrate into reaction zone and the reaction zones are still controlled by the chemical mechanism and the action of the eddies is to increase the surface area of the flame in order to make it consume more reactants. So, that is the first regime. Second regime is called flamelets in eddies.

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