Fundamentals of Combustion (Part 2)
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Lecture – 57
Introduction to Turbulent Premixed Flame

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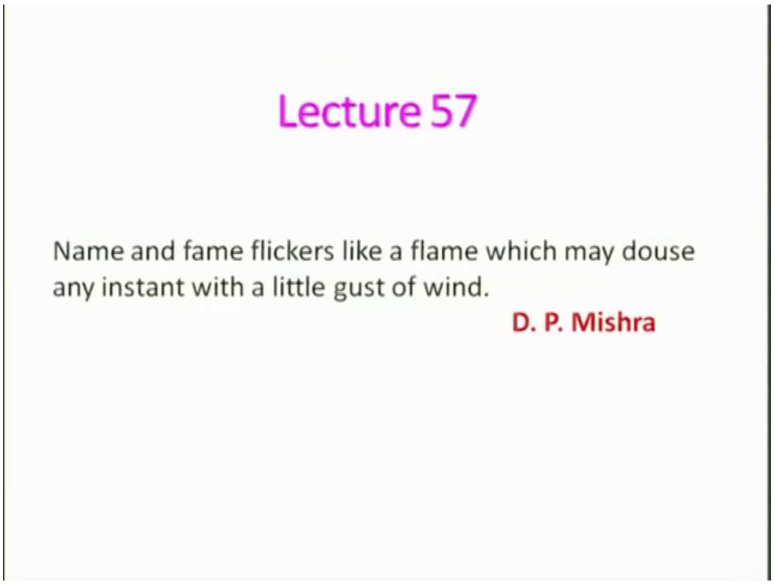

Let us start this lecture with a thought process. Name and fame flickers like a flame which may douse any instant with a little gust of wind. So, in the last lecture if we see that we basically looked at the ignition energy, types of ignition system one can think of and then later on we found out a simplified relationship for the minimum ignition energy. And we have looked at like it will be dependent on the pressure, initial temperature and then equivalence ratio type of well air, mixtures kind of things. But now I will be giving some evidence how it is changing particularly from taking some experimental data's right.

If you look at as I told that in the last lecture, we analyzed basically the minimum ignition energy on a quiescent atmosphere. There is no velocity, but in real situation for example, gas turbine engine spark ignition engine. Even in your LPG stove is not quiescent it will be moving right some velocity will be there. So, that we will have to look at it, and we are looking at effect of low velocity on ignition energy.

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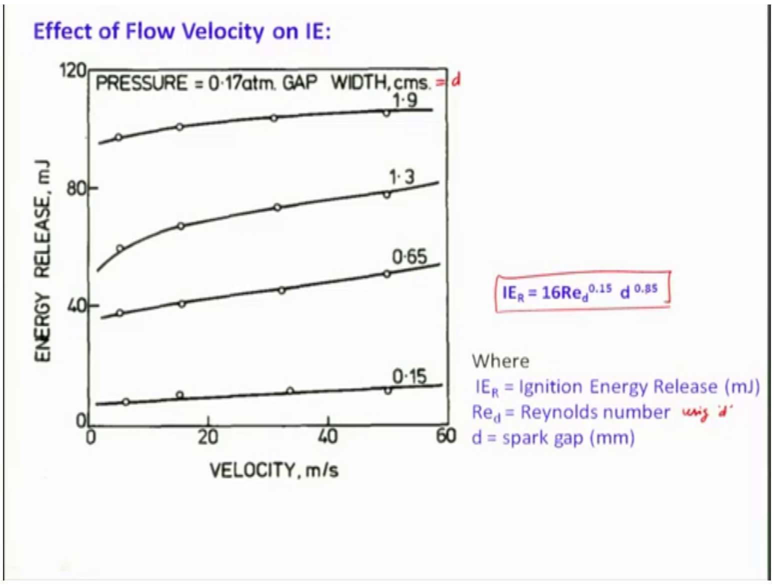

And this is the energy is not really related to minimum energy, it is about the energy which will be released whenever you apply some gap width between the spark electrode and certain pressure you will be giving right.

So, this is being shown here, that is the energy released versus the velocity. You can see that for all the cases whatever the spark gap width is there, that is basically is increasing with the velocity which is expected because some of the heat will be taken out. So, therefore, the heat release which will be affected by that. And when of course, the gap is increasing then it is basically energy requirement will be higher because the you will have to give some amount of energy the voltage will be higher and then you will have to give more amount of energy in the volume.

So, if you take this datas and then couch in the form of some empirical relationship we will get IR 16 R e d 0.15 d is the 0.85 this width is basically nothing but d. And keep in mind that these R in IR is the ignition energy release in millijoules, Re is the Reynolds number based on using d as the length scale right, and d is the spark gap.

And this is the semi empirical result which will be utilized only for the range it is being experimented, it cannot be generalized that you should keep in mind.

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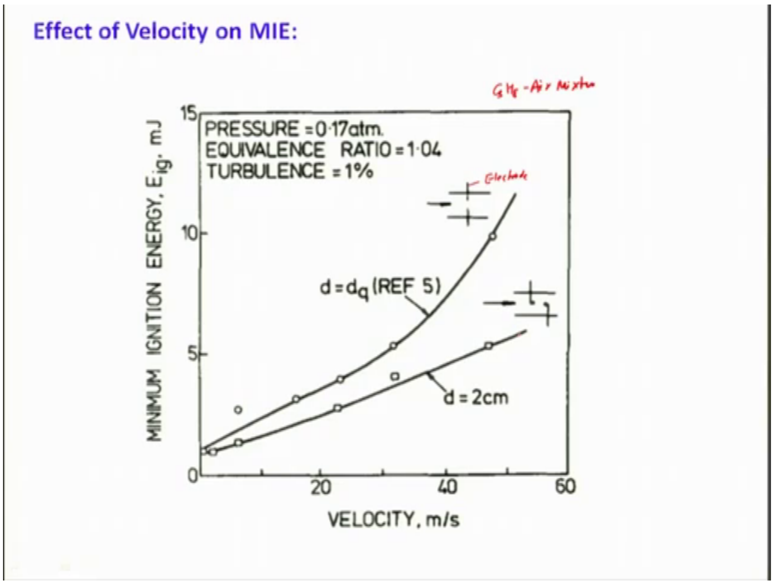

Let us look at the effect of velocity on the minimum ignition energy right. Here the situation is like that turbulence is 1 percent very low turbulence. And equivalence ratio 1.0 and this is basically C 3 H 8 air mixture right. And pressure is 0.1 atmosphere and that depends on the how this electrode these are basically electrode right. And flow is this way like electrode are being arranged it is what type of electrode right. And this is a line itself like a alone if the flow this is different.

So, therefore, in these case the ignition energy minimum ignition energy is higher right, as compared to the d is equal to 2 centimeter right both are same, but it is having. And however, you can note by our main point is that minimum ignition energy increases with the velocity right? It increases with the velocity that indicates what we had seen earlier. But that is not minimum ignition that is the energy will be released whenever you apply certain amount of voltage and current right.

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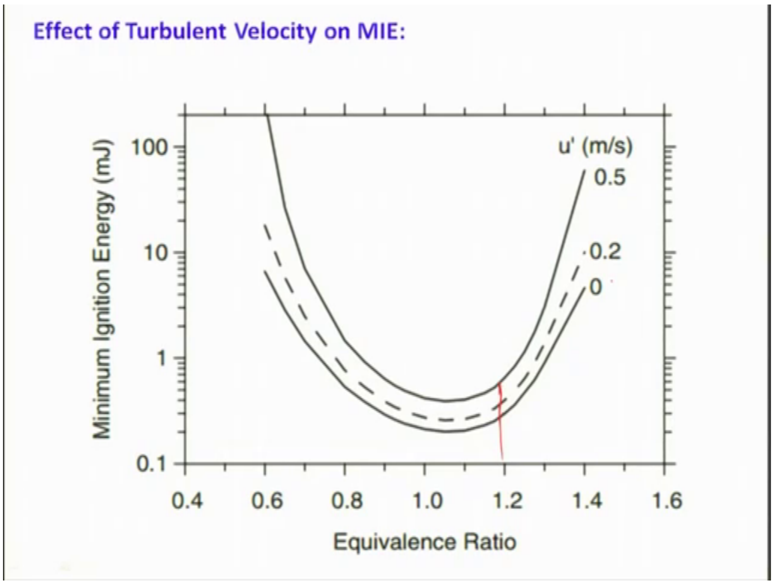

And let us look at the effect of turbulent velocity on minimum ignition energy. And this is the, is not experimental some kind of a semi empirical relationship that I have taken. And u dash is the turbulent fluctuating velocities it is something 0, 0.2, and 0.5 meter per second. And this is very quite low turbulence level, and you can see even though low turbulence level the minimum ignition energy for any particular equivalence ratio if you look at there is a increase; in the minimum ignition energy where the u dash goes on increasing from 0 to 1. And this is 0 means there is no turbulence at all right kind of things.

So, you can see that it is basically minimum ignition energy is affected by the turbulence level. It is affected by the velocity, affected by the initial temperature, pressure, and fuel air mixture and it is ratio type of fuel layer mixture and it is ratio means fuel air ratio right. So, these are the things what we have discussed till now about ignition energy. And now, we will be moving into the turbulent flame. So, till now we have discussed about basically laminar flames or the laminar pre mixed flame to be more particular and because of fact that this is very fundamental. Although the laminar flames are really used in application, can you tell me where we use laminar flame in application wise?

Student: LPG burner.

LPG burner you can consider to be laminar, but actually it is a jet so, generally there will be some turbulent flows, but you can consider that as a laminar approximately.

Otherwise other places like it will be basically turbulent being imparted in the combustors because of fact that they want to release the heat at a very higher rate right. So, therefore, it is being used of course, nowadays people are talking about micro combustors, where the laminar flame will be there right and this is of course, application is not that very predominant or not being used that much, but; however, it will be there. But we discussed too much on the laminar premium because that is fundamental to even turbulent flame.

So, therefore, it is and in practical application like your gas turbine application, spark ignition engine, furnace and other burners right; industrial burners, the turbulence is being utilized intentionally right; to enhance the flame stability and also the release the heat release at a higher rate.

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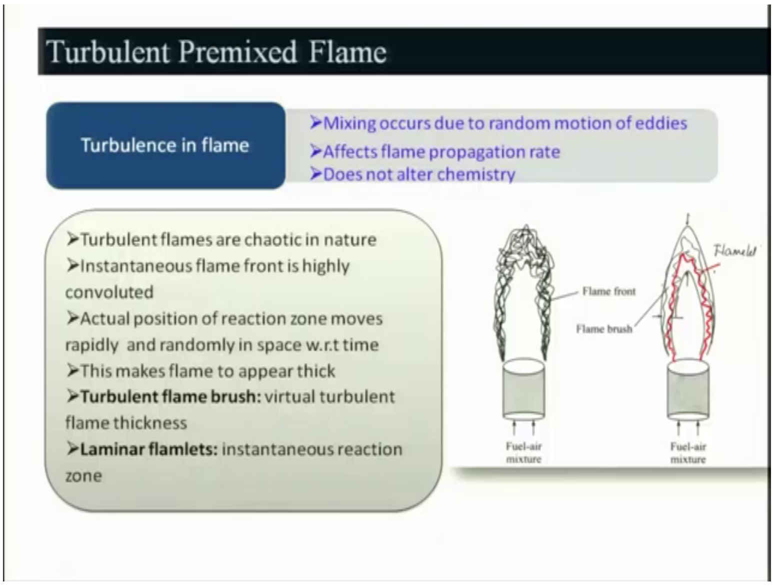

So, if you look at the turbulence basically what happens when you use the turbulence; you will be having certain Eddies and then that helps in mixing the things and there will be fluctuating velocities, which will be there. So, mixing occurs due to the random motion of Eddies which we had discussed the Eddies earlier right. And as a result the mixing will be good and it will be affecting the flame surface right, and as a result the flame will be very convoluted kind of things.

And, it affects the flame propagation rate that is a very important right? But; however, it is being talked about that it does not affect the chemical kinetics, but; however, in recent time there is a contest in these people some people are saying that it does affect the chemistry under certain regime right it is not a universal statement what people have believed, but this is the recent one which is not a part of your textbook kind of thing will say all debatable.

So, that is we can you know keep in mind. And as I told that turbulent flames are a random or the chaotic in nature right because of what? Because of Eddies; and Eddies will be various kinds large, Eddies, small Eddies, medium scale is we have talked about various scales; like integral scale, like Kolmogorov scale, Taylor micro scales all kinds of scales we have had already discussed so those scales will be different.

So, therefore, the vortex sizes will be different and it will be very violent against nature. So, as a result what will happen that; instantaneous flame front is highly corrugated or the convoluted, unlike the flame in case of laminar flame you might have seen I have shown you some picture very very smooth very slick. But here it is not. So, it will be very much corrugated kind of surface you will get like for example, if you take any one line this will be corrugated. For example, if I draw that here it is not the way I am drawing it will very zigzag kind of thing, this is a corrugated right. So, this flame is not as smooth as this looks to be right. So, this is the features because of Eddies it will be violent it will be trying to make this flame surface to the (Refer Time: 10:23) right? And this flame surface will be changing its position with respect to time rapidly and randomly right.

It will be very fast right and also so as a result what will happen; when you take a image of the flame turbulent premix flame particularly Bunsen flame what we are talking about now. You will find that it looks to be a very thick flame right and why? Because of fact that this all these thing, this we call it basically flamelet right. And this is at any instant of time, but when you take image you will be taking certain time. You know like when you take this image in the high speed photograph then you will get a some corrugated set right. Otherwise in general camera you will not get or in your naked eyes you will not see you say you will look to be smooth no that is not smooth.

So, this is we call it as basically a flame brush because if I consider this, you know all these images you are looking at one stone. So, there might be several of them right. And this inner one and outer one, what you will be seeing right in the flame that we call a virtual turbulent flame thickness. The actual flame will be very thin, but you are getting this thickness for example, thickness here it will be like that higher array and this is virtual. Because of you cannot see it you know naked eyes except very high speed you know imaging we can see that.

So, but Laminar flame let us as I told it is a instantaneous reaction zone; laminar flamelet as I told one of them let us say red color I have shown any one of them right will be instantaneous reaction zone. So, now when you talk about basically turbulent flame there will be various regimes right. And now it can be broadly divided into 4 categories right? That does not mean only 4 categories, there will be several varieties also in between right.

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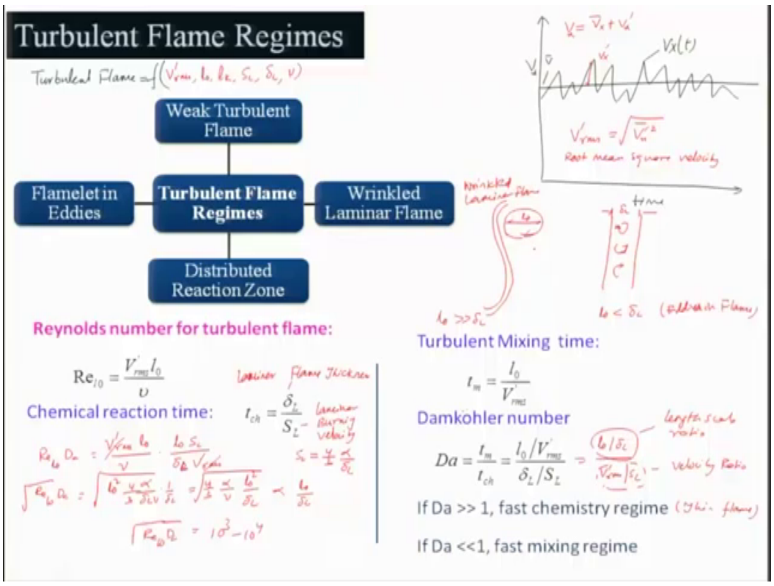

So, this turbulence one will be weak turbulent flame, other is will be wrinkled laminar flame; that means, it will be wrinkling the flame surface, but it is laminar in nature right, and flamelet in Eddies, and distributed reaction zone. Now question arises we have talked about it, but how we are going to basically divided into 4 categories.

If you look at, like a we have already looked at that; I mean what are the variables, when you talk about turbulent flame what are the variables which affect the turbulent flame right; any idea? Of course, you can think of various length scales right. Also velocities when you talk about velocities right it will be the fluctuating quantities that will be effecting right, yes or no? For example, if I say that fluid is having a fluid is turbulent right or the velocity is turbulent, I can talk about time here and this is your velocities here. I can write some velocity fluctuation right and this is nothing but your V X. I can say if it is this X with respect to time right, I am talking about one dimensional like flame. Now, there will be some average velocity right if I take this with respect to time I will be more interested to look at what is the average right.

This is my average velocity V right. So, if you look at, this is V is equal to or V X is equal to VX average plus V dash. Now these V dash is changing with respect to time, but which will be affecting the flame is it V average or V X or V dash. It will be V dash which will be affecting the flame surface because that is the fluctuation. If you look at this is basically you what is this V, X or this is VX dash. What is the VX dash I can talk about, this is the VX dash right. And it is time then how well consider right, what I will have to do I will have to define a rms velocity, V dash rms will be basically root over V dash square X; I can say because I am talking about X or right. Are you getting?

I have this root mean square this is root mean square velocity fluctuating right the component. So, that will; that means, this will be function basically turbulent flame will be function of V dash rms. Then, what are the length scale we are talked about one is integral scale or Taylor micro scale.

Another will be talking about coal mother of scale LK, beside this it will be function of what? It will be of course, the laminar burning velocity it will be also dependent on the flame laminar, flame thickness. And it will be also dependent on the properties like a kinematic viscosity right, nu is the kinematic viscosity. Because these are whatever the laminar will be considering and also will be considering the turbulence whatever. So now, when you talk about that this basically you will be looking at the Reynolds number for turbulent flame. And that is nothing but your re based on the integral scale or the Taylor micro scale integral scale and Taylor micro scale l naught is equal to V dash rms l naught right into nu. And this if you look at then that is the Reynolds number because it will be very difficult to consider all those thing, but you can put into a non dimensional forms to understand what is happening.

So, chemical reaction time I can define as delta L by SL. We have already looked at that you know because that is nothing but your time in which the chemical reaction this is the l n delta L is basically flame thickness right. Flame the means flame thickness of what it is a laminar flame thickness right and SL is the laminar burning velocity right, this is laminar burning velocity. So, we will be also defining another time scale that is turbulence mixing time right. And that is nothing but your t m is equal to l naught divided by V dash rms right; root mean square velocity fluctuating velocities right.

And that will be talking about like how much this Eddies will be taking time to get mixed kind of things like with the V rms other thing. And we can also define another non dimensional number considering the chemical reaction time and turbulent mixing time that we call it as a Damkohler number right.

Damkohler number is basically t m divided by t c h and which is I have already using this chemical reaction time nothing but delta L by SL. And this is l naught divided by V rms dash right. And I can write down this as basically l naught by delta L divided by the V rms by SL. And this is if you look at this is basically length scale ratio. And this is the term one can look at is the, how far the root mean square velocity is different than the burning velocity. This is you can say that velocity ratio right. Now, we are now what we are defining we are basically talking about the Reynolds number and Damkohler number, like you know from these variables. And we can look at what really happening because can we combine this Reynolds number and Damkohler number together and see what we are getting.

If I say this is re l naught into D a is nothing but your rms l naught by nu into, I can say this is l naught right l naught S L by delta naught V dash rms right. So, this V rms will cancel it out and we can get is basically l naught. And l naught SL, you know l naught square is coming. Now we know this is not delta this will be l. We can also express in terms of the SL in terms of flame length thickness we know that SL right, SL is equal to basically 4 by 3 alpha by SL right no sorry, SL is equal to 4 by alpha by delta L right; yes, or no?

So, now we can write down this as basically Re l naught D a is nothing but your l naught square right and l naught square in SL I am putting it these values. So, this is 4 by 3 alpha by delta L into 1 by delta L right. So, yes or no right. So, this is basically I can say 4 by 3 there is a nu.

Student: Nu.

Will be coming, nu will be in down right. So, you can say alpha by nu right and there is a l naught square by delta L square. So, if I take a root over that then it is source that is proportional to l naught by delta L right. That means, what it indicates if this is a very high values root over Re l naught, D a naught if it is a very high values let us say something 10 power to the 3 to 10 power 3 4 right; what happens? Right it will be very high means what like l naught will be much higher than the flame thickness. The Eddies will be very large right and that will be affecting basically the flame safe right. For example, if I say this is my flame right and this is the Eddies which will be there which is having a distance of l naught.

So, it will be corrugating the flame, but it will not be affecting the chemical reaction. So, this is known as wrinkled laminar flame right wrinkled laminar flame. In this case what I am saying the length scale is much greater than the delta L. There might be a situation where length scale right is very very less it is a order of or it is length scale is less than the delta L. Then what will happen there might be a flame here the Eddies will be, these are Eddies right, which will be smaller than the flame thickness this is basically delta l right. So, this is known as small scale and I think. So, that will be affecting the mix of flame thickness right in the flame inside it will be affecting because of it may affect also the chemistry, because a mixing will be very higher here right.

So, this is the another thing which is called flame Eddies in flame right Eddies in flame right. So, now we will have to I think I missed one point, let us look at that there is a Damkohler number when it is higher right. So, if Damkohler number is greater than 1 very, very higher values what it indicates; that means, this is length scale is very, very higher and then the chemical reaction time. That means chemical reaction time is much smaller right than the mixing time. Means the chemistry will be very fast right, it will be instantaneously as soon as it will mixed it will reacting will reaction will be taking place.

So, you would Damkohler number is very, very small than 1 then; that means, the mixing is faster the length scale ratio is much higher as compared to the velocity ratio; or in other words the mixing time is much very, very small as compared to the chemical time right. So, that is the Damkohler number less than one fast mixing regime right and this is if you look at the first chemistry this will be thin flame.

Flame will be very thin right as compared to what? As compared to the size of Eddies which will be affecting the flame. And based on this what happened is basically about the people have divided the various regime, and that is diagram which is being talked about to divide these flames and as I told that of turbulent flame right.

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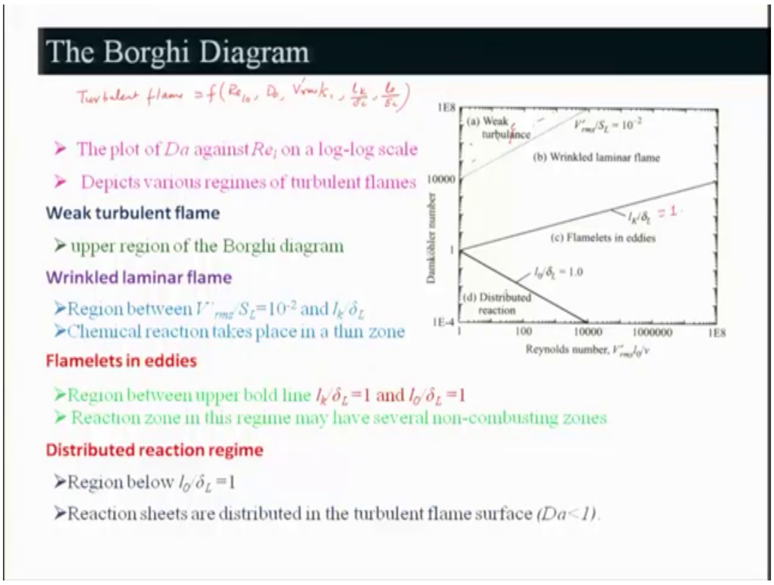

Flame is basically function of what I have already told let me summarize it l naught that is the Reynolds number based on the integral scale. Damkohler number right then I can talk about V rms by SL right. And I will talk about a another scale which we had not considered, but we will talk about is a Kolmogorov scale right, that is LK by delta L. And there is of course, we have already considered integral scale by the delta L plane thickness.

So, these are the variables which based on which we can have this diagram where we will delineate the various regimes of the flame. And the plot is basically Damkohler number against the Reynolds number on a log plot, which I have shown here right. And depicts various regimes of turbulent planes if you look at that the weak turbulence will be occurring here, where Damkohler number is very high right, but whereas, the Reynolds number is small this is the region right these are the regions where we are talking about weak turbulence right. And this is the upper region of Borghi diagram and this region where V rms SL is the around 10 power to minus 2 and LK by this thing is equal to 1 right. In this region is basically wrinkled laminar flame where the Damkohler number is moderate, but Reynolds number is very high regime like it from high to low.

And in these regime from L K by, in this wrinkled laminar flame chemical reaction takes place in a thin reaction zone right the kinetics is very, very fast right the size of the Eddies will be larger.

But this zone is the flamelet in Eddies, which will be basically L K by delta L is equal to 1 to l naught divided by delta L is equal to and these regime it explain. And reactions zone is this regime may have several non-combustion zones right mean; there will be some holes in the combine in the reaction zone, because that will be quenching the flame locally and some places it will be there. So, reaction zone will not be there, so and right and there is a very important one the distributor reaction zone where which will be taking place at the low Reynolds number and low Damkohler number. And this is the regime below the l naught by delta L and distribute a reaction zone but this is not practically achieved right.

Reaction sheet are distributed in the turbulent flame surface and but however, people are thinking if they could devise a you know combustors or they burner in this regime that will be very good. Because it can have a higher heat release and also the people are expecting that the emissions will be reduced. So, but this is not that easy to really establish in practical situations. With this I will stop over, we will be discussing about in the next lecture about various aspects of the you know turbulent flames.

Thank you very much.