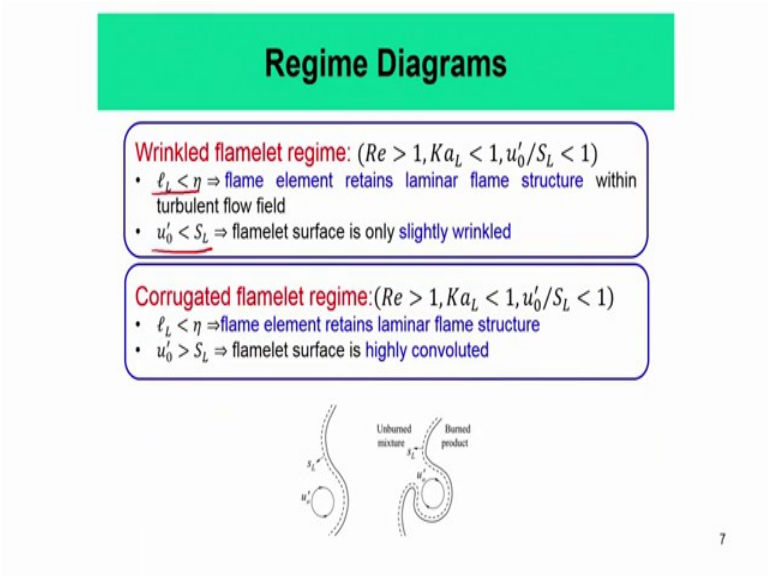
# Combustion in Air Breathing Aero Engines

Dr. Swetaprovo Chaudhuri
Department of Aerospace Engineering
Indian Institute of Science, Bangalore

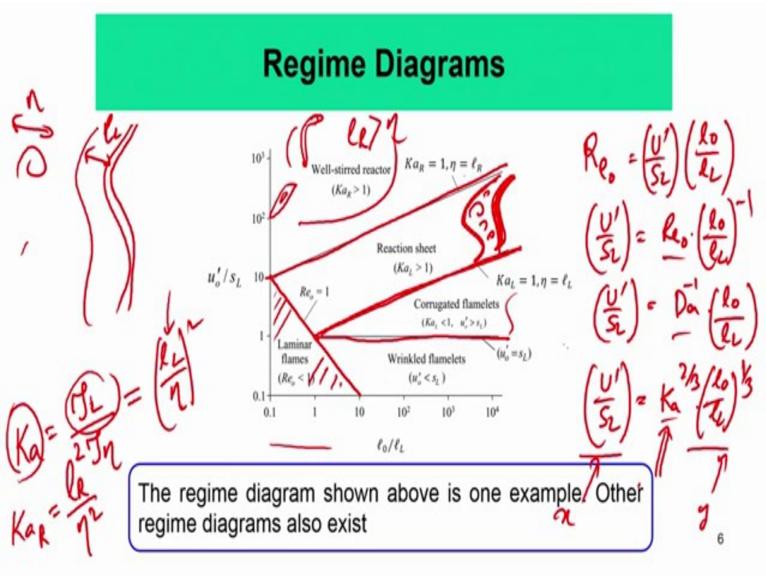
## Lecture - 43
## Turbulent Premixed Flames II

(Refer Slide Time: 00:14)




So, just to summarize what we have done and to formally tell them that in the wrinkled flame regime; we have got essentially the Reynolds number to be greater than 1 and the Karlovitz number to be less than 1 and u prime is by S L is less than 1. So, of course, you are this means that you are your flame thickness is less than the Kolmogorov of length scale and the flame elementary retains the laminar flame structure within the turbulent flame speed and since u prime is S L is less than 1 that flamelet surface is only slightly wrinkled. And in the corrugated flame regime of course, you have Reynolds numbers to be greater than 1 and Karlovitz number is still flame Karlovitz number is still less than 1.

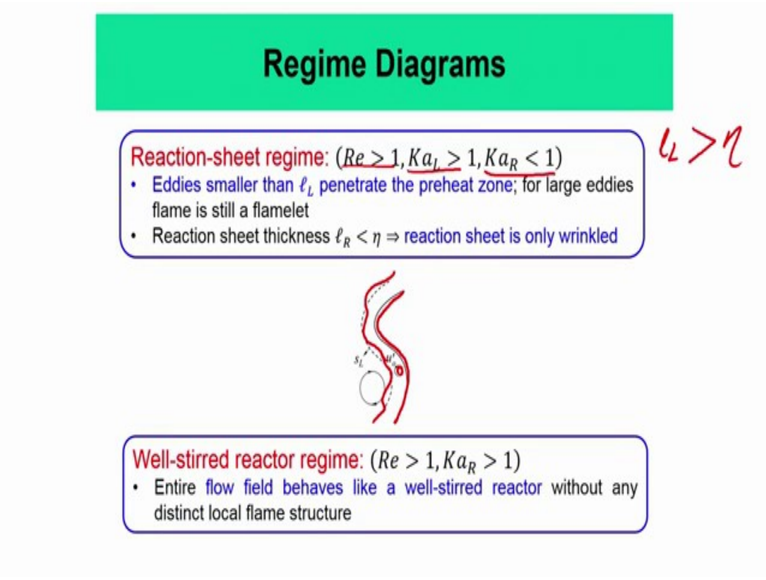
(Refer Slide Time: 00:55)




But and your u prime by S L is actually is as you see here in the corrugated flamelet regime; u prime by S L is greater than 1. So, this is a type of is corrected. So, your u prime by S L is greater than 1. So, you are still the or since your l L that is the flame thickness the preheat zone thickness is less than the Kolmogorov of length scale. The flamelet structure is retained that is a laminar flame in the flame elementary retains the laminar flame structure and your u prime by S L is essentially greater than 1. So, the flamelet structure is highly convoluted. So, you can see here over to just to give you an example here you see an eddy which is essentially rolling it.

And you see here it is essentially for stretching it and then forming a fold and this kind of structures are found in this corrugated flamelets regime, but in the reaction sheet limit in the reaction sheet regime.

(Refer Slide Time: 01:41)



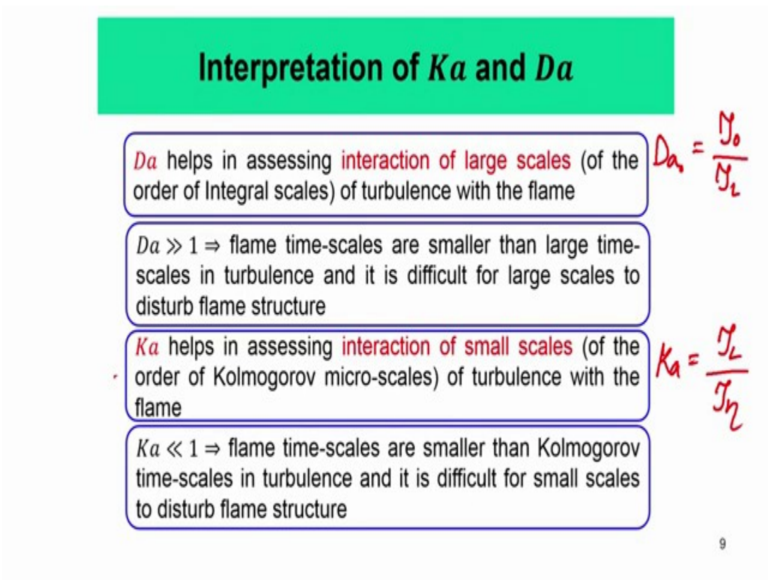

When the Reynolds numbers is greater than 1 and the Karlovitz number is the; flame Karlovitz number is actually greater than 1; here also it should be greater than 1 in the reaction sheet limit when the flame Karlovitz number is actually greater than 1. So, this has to be greater than 1 and this flame Karlovitz number has to be greater than 1. So, when the Reynolds number is this; in the reaction sheet regime when the Reynolds number is greater than 1 and the flame Karlovitz number is greater than 1.

But of course, the reaction Karlovitz number is tell less than 1. So, this means that Karlovitz number greater than 1 as I have said means that your l L is essentially greater than your eta and your tau l is greater than tau eta. So, it means that essentially the eddies smaller than l L which are essentially, but still greater than eta can penetrate the preheat zone for large eddies inside a for large eddies flame is the flame is a still a flamelet. So, whereas, a large eddies means that eddies which are greater than l; the flames still behaves the problematic manner and the reaction sheet thickness of course, this l R is less than eta. So, the reaction sheet zone only wrinkled. So, the reaction sheet is like this it is it does not change structure whereas, this eddy has penetrated inside this and this thing can change a structure like this.

So, the preheat zones structure is changed whereas, the reaction zone structure is retained. So, this is called a reaction sheet limit and this is very very much of practical interest in terms of gas turbine engines in terms of like S; I engines in after burners etcetera a lot of those flames are essentially belong to the reaction sheet limit now well stirred reactor regime that is typically not experimentally not has not been well studied it tells us that the Reynolds number greater than 1 and Karlovitz number reaction Karlovitz number greater than 1 and the entire flow behaves like a well stirred reactor without any distinct local flame structure of course, as you said that these are like looser boundaries to identify the flames.

And even in this limitation is that that you see here we assume that the Kolmogorov of length scales have are chemical enough to effectively change the structure. Now the Kolmogorov of length scales are essentially these eddies are just prior to dissipation. So, the Kolmogorov of eddies are just are very short lived and that because they will be immediately dissipated. So, whether the carry enough kinetic energy to as on distort the flame structure that needs to be export. So, anyways, these are just some guidelines about what kind of flames to expect in what situations and based on these one can formulate different kind of models and apply different kind of turbulent closure models or reaction closure models.

(Refer Slide Time: 04:34)




So, one thing just one few comments about the interpretation of the Karlovitz number and the Damkohler number; so, the Damkohler number helps in assessing the interaction of large scales of turbulence with the flame. So, large scales is of course, of the rough into of the order of the order of the integral length scale because Damkohler number; the flame Damkohler number is essentially given by your tau integral divided by tau flame or tau l. Now where as the Karlovitz number and of course, the Damkohler greater than 1 means that the flames time scales are smaller than the large times is in turbulence and it is difficult for large scales to disturb the flame structure.

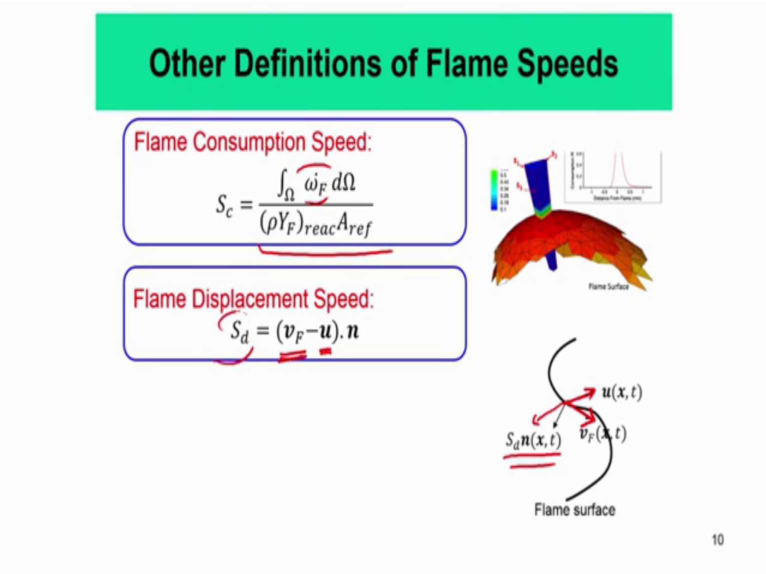
So, when Damkohler number is much greater than 1; your flame structure essentially retains the same property as that of a laminar flame when Damkohler number is less than 1. It means that your eddies of the integral length scales are even can disturb the flame structure. So, when the Damkohler number less than 1 essentially means that the flames turbulence interaction can become very strong and the interaction can span from them essentially the integral size eddies down to the smallest scales in turbulence. Whereas, the Karlovitz number; it is interesting; it helps in assessing the interaction of small scales of the of turbulence with the flame because the Karlovitz number is essentially.

If you remember the Karlovitz number is essentially the flame time scale divided by the Kolmogorov of time scale. So, it is essentially assesses the interaction of small scales of turbulence with a flame and this helps in telling us that how much mixing it can do in inside the flame structure mixing of like a fresh reactants with the intermediates of the intermediates to the products one. So, and all these sort of things; it can tell. Now in the Karlovitz number much less than 1 means the flames time scales are smaller than the Kolmogorov of scales and turbulence and is difficult for the small scales to disturb the flame structure.

So, these are the 2 limiting conditions that the Damkohler number much greater than 1 and Karlovitz number much less than 1 essentially means something that the laminar flamelet structure. The exact laminar structure or the near bent laminar flame structure will be preserved whereas, Damkohler number much less than 1 and Karlovitz number much greater than 1. This means that that essentially you are in a state where turbulence is very strong and it can disturb the flame structure at different levels and when it disturbs the flame structure, the associated properties like diffusivity can inside the flame; one has to be considered that is that is a turbulent diffusivity has to be considered.

And can certain cases override molecular diffusivity. So, this needs to be understood, but of course, molecular diffusivity has been shown by recent research that molecular diffusivity is still very important at all conditions; when it comes to flames essentially because at smallest scales molecular diffusion again becomes very important when the large gradients are produced now few definitions of flame speeds of course, as you see that.

(Refer Slide Time: 07:34)

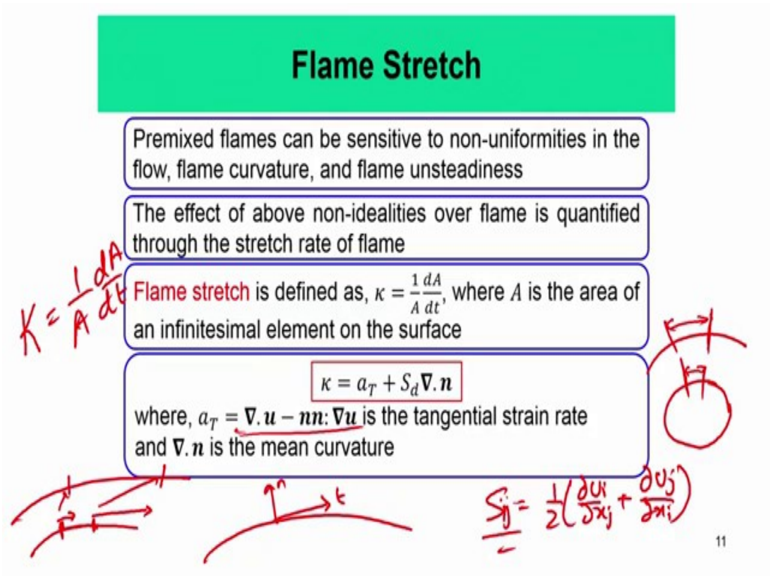



The laminar flames; the definition that we have obtained; this laminar flame speed expression that we obtain that was valid for planner laminar flame speed, but still that is gives you a very clear idea about how the flame should behave on what factors it depends and now.

But for doing analysis in turbulent flows, we need to have different kind of definitions from which suppose you have a turbulent flame solution d n as data set. So, and from that how will excite the flame consumption the different flame speed. So, one is a flame consumption speed which is given by the; if you integrate over the entire volume the fuel consumption rate and normalize that by rho times Y F of the reactants divide by a reference area that gives you the local flame consumption flame speed and then also; there is a definition of displacement flame speed and which is defined essentially the way the flame is; the flame speed is defined that it is the local.

And it can be defined at any point that is it is a velocity of the flame surface with respect to the local flow field in the direction normal to the flame surface itself. So, V F is the velocity of the flame surface. These are on an absolute in the laboratory reference frames. So, this is V F is the velocity of the flame surface and u is the velocity of the local fluid. So, this is the velocity of the flame surface that flame surfaces; this is the flame surface. It is moving in with a velocity V F and this local velocity is u. So, then the resultant velocity of course, is greater minus u and the resultant velocity of these 2 things of V F n minus u is essentially given by S d times n.

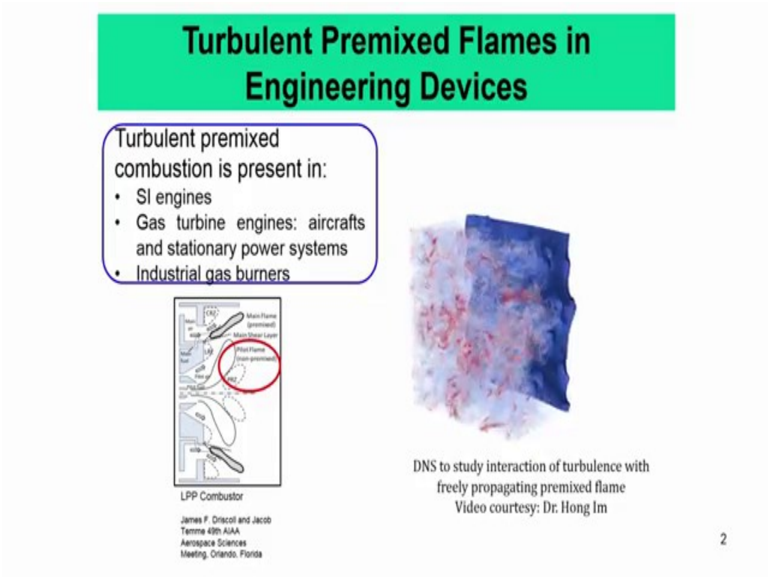
(Refer Slide Time: 09:27)




So, then you multiply with the normal vector you get S d. So, from this also you can get; if you can track the flame surface. Now here we need to introduce before we go into it; before we go into the other details about how to be model this things, how do we modeled a turbulent of flames in turbulent flows; one important concept for laminar premixed flame that we need to introduce here is essentially call the concept of a flame stretch. It is essentially the rate of change of area with of the flame surface area with time per unit originals area.

So, this is important because as you see that you if you go back to the previous if you go back to the previous video that we shown that we had shown that you see that initially this surface area was planner.

(Refer Slide Time: 10:04)




And initially it was planner and, but this is planner and then in the same cross sectional area then it becomes convoluted it becomes distorted. So, of course, you can understand this at a later time the surface area of this convoluted surface is much greater than the initial planner surface area. So, of course, then the surface area is increasing then the surface area is increasing because of the stretching action of turbulence. So, this in premixed flames and even to some extent in non premixed flames; the stretch flame stretch is a very important concept. It is the rate at which is the rate of change of area per unit original area and premixed flame as you know can be less sensitive to non uniformities of the flow.

And flame curvature and flame unsteadiness and the effect of the all these things; that is why does the flame area change the flame area actually changed because of these things that is the non uniformities of the flow, it change of changes due to flame curvature, it change due to flame unsteadiness and all of this effect of this non idealities over a flame can be quantified through the stretch rate of a flame. So, actually it is the 1 by is actually the you will see that; the stretch is essentially 1 by a d a d t, but this change in the area is affected through this things like the like the non uniformity of the flow and curvature and flame unsteadiness.

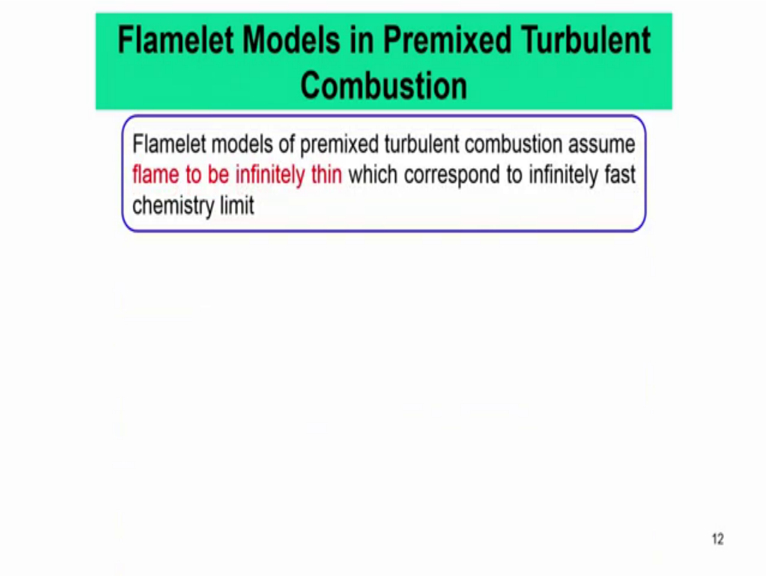
So, as you see here that the flame stretch is defined as one by a d a d t where a is the area of an infinitesimal element on the surface now and these is quantified of course, and derive it, but you can take a look into postal laws book for the derivation of this thing, where this flame stretch defined by kappa is actually defined as the sum of 2 quantities that is it is the sum of the tangential straining rate on the flame surface which is given by this quantity and it is essentially the strain rate when you project it on the tangent to the flame surface area. So, tangent can obtained from the flow strain you know S I j is equal to d u i half of d u i d x j plus d u j d x i.

And when you project this along the flame surface area; so, what I want to say is that the strain rating of fluid is essential S I j s half of d u i d x j plus d u j d x i and then if you have a flame surface like this. So, if this is a normal and this is the tangent; tangent can be in any arbitrary direction on the surface so, but suppose we choose a particular direction of a tangent. So, the tangential flames are a flame stretch on that is given by when you project S I j onto along the tangent and that is given by this quantity and so, this is important because when you have flow on uniformities actually what it means is the tangential strain that is what it means is that. So, if you have a velocity on the flame at this point.

Which is this and at this point which is small. So, of course, this point of the flame will move much further than this point. So, essentially at after some time then this surface will look like this. So, this point has maybe has moved here and this point have moved here. So, as you see that this leads to growth of the surface area whereas, if all points on the flame tangent on the flame tangent; if they move with the same velocity is then there is no flame stretch. So, the flow non uniformities flow; non uniformities along the tangent is what create this tangential strain rate its very intuitive that you are basically on a surface if you have if you have different if you push the different parts of a surface differently then of course, if we this can lead to this can lead to extension or contraction of the surface.

And that is what is quantified by the tangential flame is quantified by the tangential strained rate alright and the other thing is that when you have curvature suppose you have. Similarly you have like a flame which is a spherical flame which expands. So, of course, after expansion you will see that this point has gone here this point is gone here. So, of course, this thing has even if there is no fluid non uniformity. So, you see that because of the curvature this part of the flame segment of has become like bigger and as a result of that this is essentially causing stretch also. So, stretch essentially increases the surface area it can decrease the flame surface area also.

(Refer Slide Time: 14:42)




But if the flame stretch is positive, it will decrease; increase the surface area of the flame stretch is negative. It will reduce the surface area and this is essentially as you see is quantified by 2 things. This tangential surface area tangential strain rate and the tangential strain rate and the flame speed times the curvature. So, these are the 2 things.

So, we will take a break and in the next class we will basically come back into discussion about the different models for turbulent combustion.

Thank you.