Combustion in Air Breathing Aero Engines
Dr. Swetaprovo Chaudhuri
Department of Aerospace Engineering
Indian Institute of Science, Bangalore

Lecture – 39
Turbulent Non-Premixed Flames I

So, friends we will come back to this course. So, for we have discussed turbulent combustion, essentially we have discussed the beginning from at the beginning of this part of the course on turbulent combustion, we have discuss essentially the physics of turbulence. The modeling turbulence how you can basically use the Reynolds averaged Navier-Stokes equations to get an idea about the mean flow field. And how this when you average these equations, this problem the closure problem emerges. And then in the last class you have seen that how using this a different eddy viscosity hypothesis we can essentially have this kind of closures.

We have the eddy viscosity closures by using the mean strain rates we can use them to close the Reynolds averaged Navier-Stokes equation. And we have also seen how for reactive scalars how problems emerges in terms of closure of the reaction rate the mean reaction rate or the reaction rate in terms of the mean temperature or the scalar transport, so there are problems. So, when we have discussed as some simplified models engine generalize simplified models like the eddy break up model the eddy dissipation concept eddy dissipation model different things. How those can be used to model turbulent combustion, but those are very like very preliminary and rudimentary models and actually the field of turbulent combustion has progressed for beyond that. So, in this course so we will give you glimpse of the modern developments in turbulent combustion and we will start that by using turbulent non-premix combustion.

So, we have seen that that in the beginning of the course, we have essentially distinguished combustion in terms of non-premix flames and premix flames. Non-premix flames are those in which the fuel and air are separated as it enters into the combustion as it enters into the combustor. So, we have done actually the analysis of one-dimensional laminar flame or the one-dimensional chamber flame, where the fuel and air basically were separated by two sides; one on the left one on the right and the flame was form somewhere in the middle. And then we did analysis of that and we obtain linear profiles of temperature of a mass fraction etcetera. And then we did droplet combustion also. Now, but here in this class we will take up turbulent non premix combustion.

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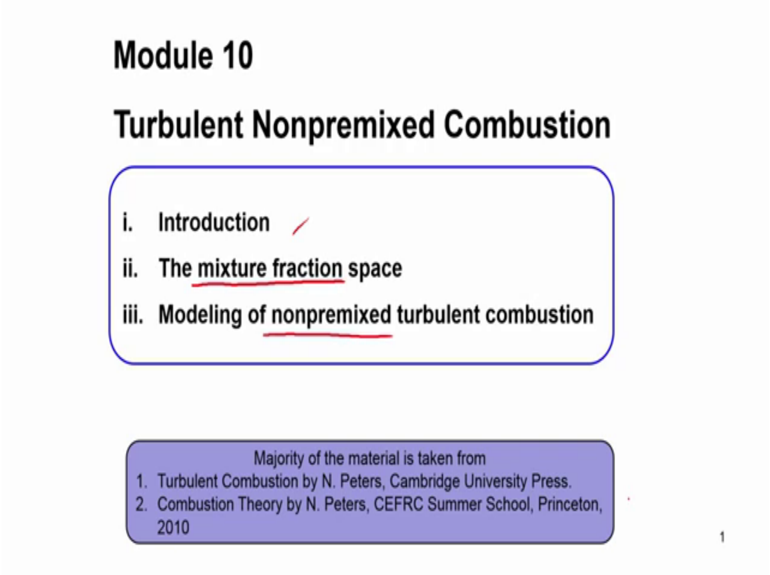

Module 10

Turbulent Nonpremixed Combustion

i. Introduction
ii. The mixture fraction space
iii. Modeling of nonpremixed turbulent combustion

Majority of the material is taken from
1. Turbulent Combustion by N. Peters, Cambridge University Press.
2. Combustion Theory by N. Peters, CEFRC Summer School, Princeton, 2010

And this is divided into essentially this three parts. We will go with the introduction. We will say where you can essentially encounter turbulent non-premixed combustion. We will then this introduce a very important concept call the mixture fraction. This we have not introduce, but this we can use in laminar flames also. But essentially the importance of these and the beauty of this concept of mixture fractions becomes evident in turbulent nonpremixed combustion. And then we will use those ideas of mixture fractions to essentially do this analysis or modeling rather modeling of turbulent nonpremixed combustion.

On the majority of the material in this course is taken from these two books mainly. Turbulent Combustion book by Norbert Peters published by Cambridge University Press; and this Combustion Theory by Norbert Peters from the CEFRC - Combustion Energy Frontier Research Center Summer School, Princeton, this lectures will developed in 2010. And this is I believe is available online free of cost in the CEFRC website. So, these are both the references that we will follow for this part of turbulent combustion turbulent nonpremixed combustion and later in the next class turbulent premixed combustion, the next model turbulent premixed combustion. So, in this model, we will focus on turbulent nonpremixed combustion.

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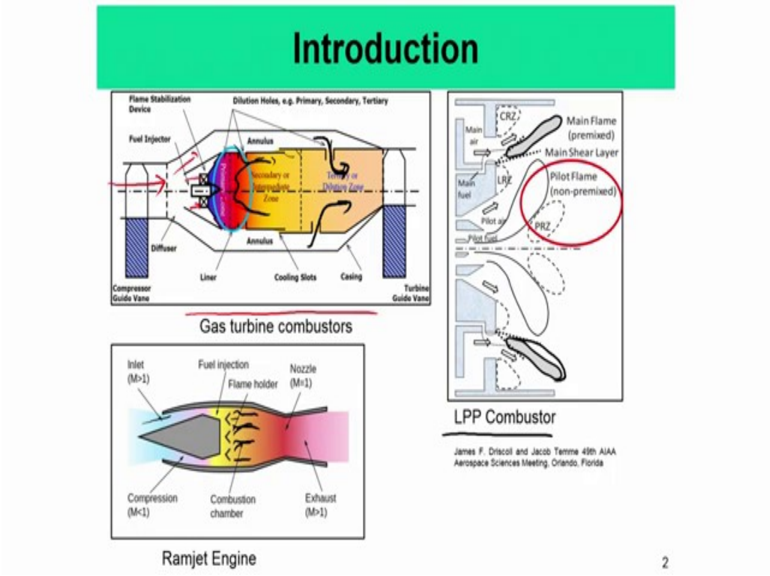

Introduction

Gas turbine combustors

LPP Combustor

James F. Driscoll and Jacob Temme 49th AIAA Aerospace Sciences Meeting, Orlando, Florida

Ramjet Engine

Now, why we will study that as you see this course is on combustion in aero breathing aero engines and of course, gas turbine engine and ramjet engines are two very important parts. And as such in the gas turbine engines the most of the aero gas turbine engines utilize historically have utilized turbulent nonpremixed combustion. So, essentially this you see is the essentially the gas turbine combustor. So, after the flow enters from the left to the right, so the compressor guide vanes it passes through a diffuser section, this part whether pressure is lightly recovered and then it passes through this set of solar.

So, when we will going to the main when discussing when we will going to discussion about the gas turbine combustor, this details of this combustor and this architecture will become more clear. But essentially here you have essentially you will see that the fuel is injected in a liquid sheet through this central injector, and then this liquid evaporates then this liquid essentially liquid should essentially breaks up, and then in this should droplets are formed and large droplets are formed. Then in this large droplet breaks into small droplets and then this small droplets evaporate and this droplets are essentially of (Refer Time: 05:05) jet fuels. So, essentially this liquid evaporates and then it a basically forms nearby cloud of this mixture of this fuel essentially which then mixes with the air and sometimes the point at which that mixes with the air, the mixes is not very efficient and essentially the flame that you have is a nonpremixed flame.

So, in gas turbine aero gas turbine engines typically flames are have been historically has been nonpremixed flames except with some reason developments mutual discuss now which will discuss little later. And you see here you have the primary zone essentially the main combustion will be essentially will be here. So, here we have the flame like this after coming out of this injector or the flame will be is something stabilize along here. And this is essentially a nonpremixed flame or partially premixed flame. Though it can have premixed segment also, but predominantly this type of classical gas turbine combustors utilize non premixed flames.

So, from understanding gas turbine combustion or for I mean in an IC engine, if you want to understand diesel combustion then these nonpremixed flames are typical examples of the kind of combustion that happens in this typical engines of nonpremixed of this gas turbines. So, of course, there are thing as also like this cooling holes which essentially cools down the hot gases, so that the turbine temperature can be controlled we can have a limited turbine entry temperature.

And in ramjet engine is also you see here you as a. So, the intake as a flow comes in it is essentially through the shock strains its essentially supersonic intake. And then it were becomes to the subsonic through this formation of this series of shocks. And by the (Refer Time: 06:56) into the combustor these are essentially subsonic flow. And you have a flames stabilized in this flame holders and this fuel is injected right upstream of this flame holders. And the typically you get a different amount of non premixes in this flow and the flame that you get is essentially are nonpremixed flame also.

So, ramjet engines and gas turbine engines are good examples of nonpremixed flames. Now, there are some regions also were you get premixed flames, but the on the large fraction of the flame also nonpremixed flame. So, as you know in nonpremixed flames mixing is very important. So, yes we will see that how we can essentially model mixing in nonpremixed flames. As you remember if in the when we did the analysis of the one d nonpremixed flames we essentially assumed with the chemistry infinitely fast and essentially the flame parameters were essentially mixing controlled. And here also we will see that how while modeling turbulent nonpremixed flames, this hypothesis of the flame in time scale being essentially controlled by the mixing that the mixing being direct limiting a step that hypothesis is ensure whole (Refer Time: 08:13) also.

On the right hand side, you have an examples of lean premixed pre vaporized combustor. These are the very modern combustion which are used in a modern gas turbine engines like the taps two nano non premixed solar combustor at the which power is essentially the Boeing 787 as you know. And here also you see that the yes that it has this is the main premixed flame branches on the two sides, but it has also a pilot flame which is essentially non premixed flame. So, this as you again see that this nonpremixed flame is also present even in the very modern gas turbine combustors now as we have if you remember we discuss that there are disadvantages of nonpremixed flames because you essentially cannot control the temperature.

The temperature is always essentially the Stoichiometric adiabatic flame temperature unless you have like something like this cooling halls here as you have seen here downstream. But an other than that this temperature is high, it is a locally at the flame location the it is a temperature is adiabatic Stoichiometric adiabatic flame temperature. And this is result of that all the pollutants are also being formed suit, nocks etcetera. So, that is the main disadvantage, but I will see later at that non premixed flames are much more robust than premixed flames because here you do not have a velocity scale like something a flames feed. So, essentially it can be stabilized in fast flows also as long as there is mixing. So, once again this fact that the nonpremixed flames this essentially and mixing control phenomena has an advantage that it is much more robust and it does not response to the flow oscillations as much as a premixed flame does so that is one big advantage. So, non premixed flames has been very, very in a prevalent in all this aero gas turbine engines.

Now, in a ramjet engine flame is to a large degree nonpremixed though there are frame premixed segments also. So, one thing you must understand this in the actual gas turbine engines that flames are also though they can be like a predominantly nonpremixed serial like flow of a segments, there are like regions which are premixed for partially premixed also. So, it is a mix of these two, but I mean combustion modeling historically has progressed in the way that it models non premixed flames and the premixed flames separately because of their distinct its properties. So, to understand though how to model essentially of flame in a combustor which is predominately nonpremixed, we will go into this course and when go into these detailed analysis and see how to essentially one of the approaches by which non premixed flames in this type of engines in this type of combustors can be model it.

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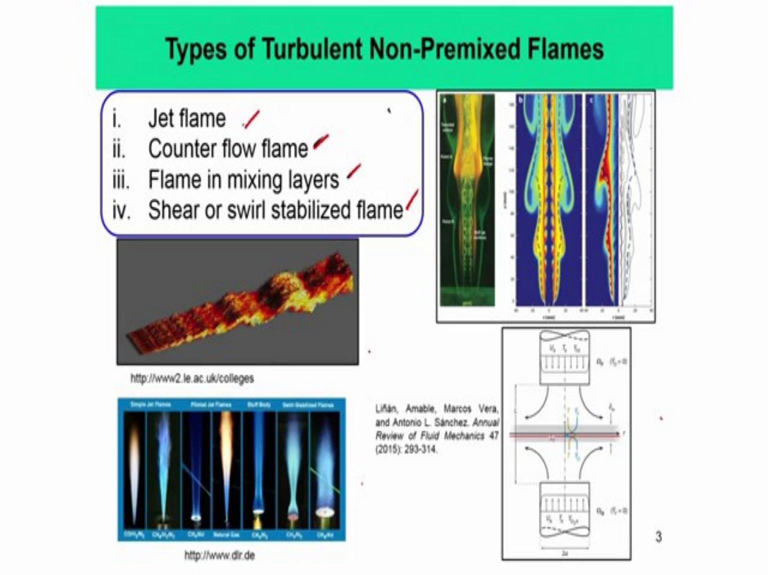

Types of Turbulent Non-Premixed Flames

i. Jet flame
ii. Counter flow flame
iii. Flame in mixing layers
iv. Shear or swirl stabilized flame

http://www2.le.ac.uk/colleges

http://www.dlr.de

Liñán, Amable, Marcos Vera, and Antonio L. Sánchez. *Annual Review of Fluid Mechanics* 47 (2015): 293-314.

So, in a lab what you encounter what you of course to make models you cannot use directly go to a gas turbine combustor. So, what you do is that what people have done is that they have basically done detailed measurements in this kind of simple non premixed flames which like can be like a jet flame counter flow flame flames in mixing layers shear or swirl stabilized flames. So, these are the typical flames, people have studied in laboratory. So, the idea is that you develop detailed diagnostics using base in the different kind of optical methods, people have done detailed measurements of the flow, temperature, species and etcetera of and these this different kind of flames. And then they have used different modeling approaches with which they have validated them experimental data.

So, then the idea is that these tool set on develops for modeling the simple flames. Once they are robust regress and we have develop sufficient confidence in them then these can be utilized towards essentially the modeling the actual nonpremixed flames that happens in a real gas turbine engine or a real ramjet engine or a real scramjet engine so that is the approach. So, people have really done this kinds of flames in the lab. So, we will see the this is the examples of different kinds of a counter flow flame jet flame etcetera. And there are flames in essentially mixing layers. So, jet flames, counter flow flames, flames in mixing layers and these the typical this pictures come from the turbulent nonpremixed flame, work shop work shop were essentially people have done a different kind of flames is simple jet flames, pailator jet flames, (Refer Time: 12:34) jet flames, flames stabilized may block body and also stabilized flames. And using all these they have done detailed measurement in them and then you have use people have use them for validating the different numerical simulations.

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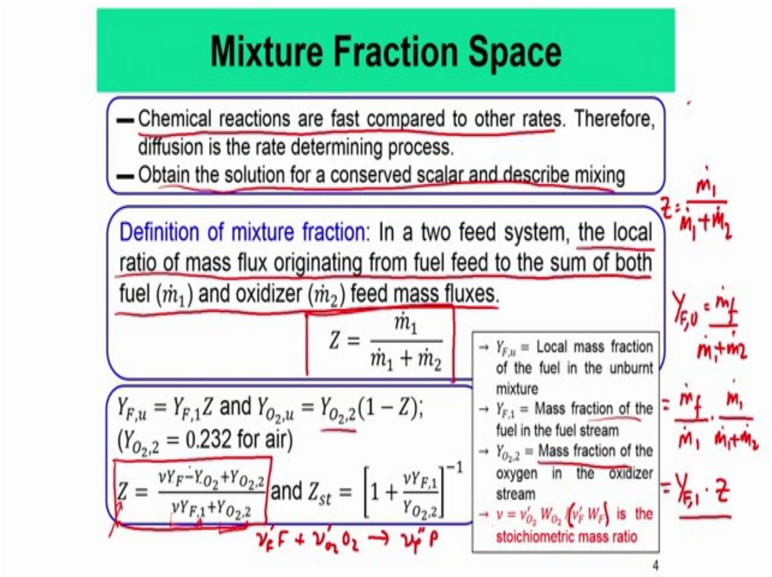

Mixture Fraction Space

- Chemical reactions are fast compared to other rates. Therefore, diffusion is the rate determining process.
- Obtain the solution for a conserved scalar and describe mixing

Definition of mixture fraction: In a two feed system, the local ratio of mass flux originating from fuel feed to the sum of both fuel ($\dot{m}_1$) and oxidizer ($\dot{m}_2$) feed mass fluxes.

$$\boxed{Z = \frac{\dot{m}_1}{\dot{m}_1 + \dot{m}_2}}$$

$Y_{F,u} = Y_{F,1} Z$ and $Y_{O_2,u} = Y_{O_2,2}(1 - Z)$;
($Y_{O_2,2} = 0.232$ for air)

$$\boxed{Z = \frac{\nu Y_F - Y_{O_2} + Y_{O_2,2}}{\nu Y_{F,1} + Y_{O_2,2}}} \text{ and } Z_{st} = \left[1 + \frac{\nu Y_{F,1}}{Y_{O_2,2}}\right]^{-1}$$

$$\nu'_F F + \nu'_{O_2} O_2 \rightarrow \nu''_F P$$

→ $Y_{F,u}$ = Local mass fraction of the fuel in the unburnt mixture
→ $Y_{F,1}$ = Mass fraction of the fuel in the fuel stream
→ $Y_{O_2,2}$ = Mass fraction of the oxygen in the oxidizer stream
→ $\nu = \nu'_{O_2} W_{O_2} / (\nu'_F W_F)$ is the stoichiometric mass ratio

$$Z = \frac{\dot{m}_1}{\dot{m}_1 + \dot{m}_2}$$

$$Y_{F,0} = \frac{\dot{m}_f}{\dot{m}_1 + \dot{m}_2} = \frac{\dot{m}_f}{\dot{m}_1} \cdot \frac{\dot{m}_1}{\dot{m}_1 + \dot{m}_2} = Y_{F,1} \cdot Z$$

So, from here on we proceed onto essentially the turbulent non premixing modeling. First we will do the essentially introduce this mixture fractions concept of this mixture fraction space in a laminar nonpremixed flame. So, we will do a little bit of go back little bit into this laminar flame or we will this generalize it essentially, but will go back to this once again to this apply this mixture fraction ideas to the 1 D non premixed chamber flame that we discussed. So, we will see how the mixture fractions concept can be applied in those kind of simple configurations and then utilizing them, we will proceed to essentially see how the mixture fraction helps a lot when you go for a modeling turbulent nonpremixed flames.

So, what does a mixture fraction why does it come. So, as you see that in a nonpremixed flames the basic idea is that there is very basic underlying embedding idea. The embedding idea is that the chemical reactions are much faster compare to other rates. Chemical reactions are much fast or faster compare to other rates. Therefore, diffusion in even diffusion it means a diffusion of both heat as well as species. So, species as well as thermal diffusion is essentially the rate determining process. It is a rate controlling process and it is a rate of diffusion that governs how much their combustion rate will be. So, we have to essentially the idea is that let we need to find out the suitable concepts scalar.

As you remembered the concept scalar is one in which does not have a source term so which there is no source or sink term so that one is a conserved scalar. So, we need to obtain first we need to define in a conserved scalar and obtained that a solution of that conserved scalar and so that we can use that to describing this mixing which is the determining process so that is the idea. So, to in search of that conserve scalar, we going to define this mixture fraction.

So, what is this mixture fraction? The mixture fraction is defined in a in this manner that if you have a two feed system what is a two feed system suppose you essentially have a suppose you have a nozzle like this. At the center of the nozzle this is an axis symmetric nozzle. So, you have a fuel and on the sides you have another annular nozzle annular cylinder through which air is coming out so that is a two feed system. So, that two feed system means essentially is basically you have a feed of you have feed line of fuel we have one feed line of air and of course, this fuel and the air are not mixing.

So, then the mixture fraction definition is that in such a two feed system the local ratio of mass flux originating from fuel feed to the sum of both fuel and oxidizer feed mass fluxes is defined as a mixture fraction. So, you see that the it is the local ratio of mass flux originating from the fuel feed to the sum of both the fuel and oxidizer mass fluxes. So, suppose the fuel mass flux is m 1 we will use a symbol subscript one for the fuel feed and we will use a substitute two for the airs feed. So, the mass flux from the feed line is m 1, and the mass flux from the oxidizer line is m 2. So, sorry this is m 2. You see, but that is m 1 this need not be pure fuel, it can cause in it can contain inert also. So, this is a fuel feed where you have to have a well defined mass fraction for the fuel, it need not be always one.

Similarly, here the oxygen mass fraction need not be one. If it is air or any other things we have also there can be oxygen and the nitrogen can be present in different proportion. So, but we call this is the oxidizer feed line and this is the fuel feed line. The fuel feed line is designated by one and the oxidizer designated by two. So, the mixture fraction z is essentially the ratio of m one dot divided by the total m dot that is m 1 dot plus m 2 dot. So, I will just write it down z the local mixture fraction is defined there is m 1 dot divided by m 1 dot plus m 2 dot. So, this is the mixture fraction.

So, now, this can be taken up in more details that the Y F, u that is the unburnt fuel mass fraction then is essentially Y F, 1 that is a fuel mass fraction in the stream one times z why is it. So, this is because what is Y F, u, Y F, u is essentially m dot of f divided by m 1 dot plus m 2 dot and that is equal to m dot of f divided by m 1 dot times m 1 dot by m 1 dot plus m 2 dot. So, m dot f minus by m 1 that is what is the mass fuel mass flux that is going on inside through the feed line one that is Y F, u, Y F, 1 is essentially times this is z. So, that is why Y F, u that is unburnt fuel mass fraction that is going in is essentially Y F, 1 times z . So, the total unburnt fuel mass fraction that is entering into this combustor is essentially given by Y F, 1 times z.

Similarly, the oxidizer the oxygen mass fraction that is entering into the combustor is essentially Y o 2 dash 2 that is the oxidizer mass fraction in the second line in the oxidizer stream times 1 minus z. And then combining this one can obtain a generalized definition of mixture fraction in terms of the mass fraction of the fuel and the oxidizer and this is given by the Z, a mixture fraction at any point in space inside the combustor is given by nu I will come. What nu is times Y F minus Y o 2 that is a local mass fraction of fuel times minus the local nu times a local mass fraction fuel minus a local mass fraction of Y o 2 plus the mass fraction of the oxygen in the air stream or the oxidizer stream that is coming in divided by nu times Y F, 1 that is a fuel mass fraction in the fuel stream plus the oxidizer mass fraction in the oxidizer stream.

But this you just what this out why it is so, but this you will I promise you that this will turn out to be very, very useful concept. So, even if its seems little bit acquired at the beginning just you get a custom to this notations and what it exactly means and it will become your friend very soon.

So, now as you see that here at the definitions are Y F, u is essentially the local mass fraction of the fuel in the unburnt mixture, unburnt fuel mass fraction Y F 1 is a mass fraction of the fuel in the fuel stream. These two are not necessarily same because Y F, u is essentially is in the unburnt mixture this is a mass fraction. Similarly, Y o 2 is the mass fraction of the oxygen the oxidizer stream. And nu, nu is very interesting is the Stoichiometric mass ratio you will saw this was this previously also this essentially nu o two dash times W o two dash this is the Stoichiometric coefficient of oxygen times the molecular weight of oxygen divided by the Stoichiometric coefficient of fuel times the mass fraction of fuel. So, however, these defined these has like nu f dashed times fuel plus nu o 2 dashed times o 2 goes to nu p double dash product. So, these are the Stoichiometric coefficient, so please keep this in mind.

So, nu dash is essentially the Stoichiometric mass ratio. So, the actual definition of Z is this, but it any point inside the combustor the Z can be obtain from this. If you know the mass if you know the Y F and Y o 2, we can know this, but then this is not very useful then we are just a algebra combination of Y F and Y o 2 what we essentially go to a what we want to essentially do is that we essentially want to find out an equation of Z and then find out the Y F and Y o 2 in terms of z that then belongs to useful.

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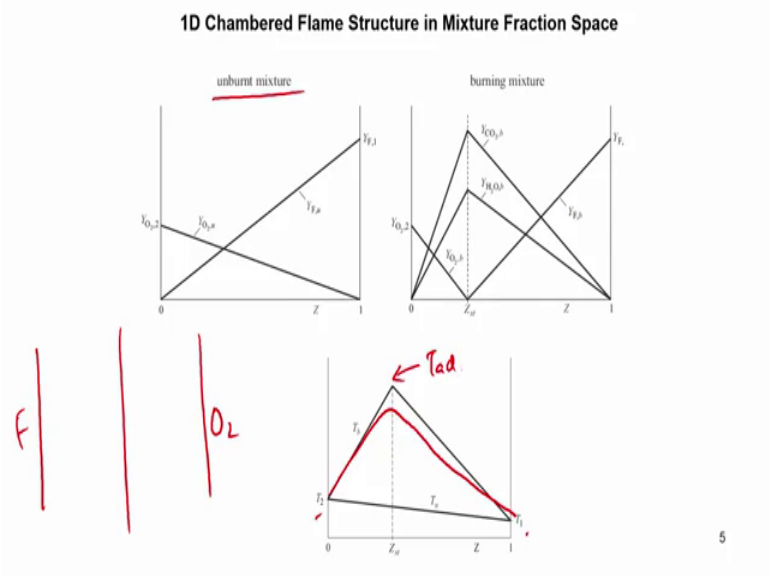

1D Chambered Flame Structure in Mixture Fraction Space

So, if you remember that chambered flame solution I mean this is a very generic solution is essentially can be call the equilibrium solution also. So, if you remember that chambered flame solution it was like a one side, you have fuel using out one side you have oxidizer using out. And then if you do the solution and projects the solutions in the mixture fractions space, so then you will see that if you it is there is no flame if you have if you do not ignited then the solution you will get this is initially like this straight lines through once again. Because it is essentially a linear it will turn out to be linear differential equations partial or ODE depending on the whether we have time and not. If it is a steady, it will turn out to be essentially an ordinary differential equation as we have seen before.

And then for burning mixture you will have a of course, product formation. So, and you will have oxidizer going down up to the Z st and Y F going up from Z st to going to zero at Z st and here you will have the solution of T 2 that is if this is the T 2 and this is T 1. So, this you will have the solution like this. So, it is essentially very we will just have to write this thing in the you have to solve it and then you just write it in terms of z if you just solve for z we will get this things. So, it is very, very simple. But the you see that this just like in we had the idea that this gives you that just like we saw the 1D chambered flame space the laminar 1D chambered flame space, you can essentially have a solution in the mixture fraction space also and it is equally representative.

So, of course, you have the maximum temperature at the Z st which is the Stoichiometric mixture fraction value. So, what is the Stoichiometric mixture fraction value that is if you put the Stoichiometric numbers here the mixture fraction that you get. So, for Z st here you will get this two essentially go out and then you will essentially will be left with this and we will have that Z st is equal to essentially this thing. So, this is the so essentially this is the thing you get, and you can basically have this kind of simple laminar solutions in terms of (Refer Time: 23:55) Z also. We just take a look and you just do this soft this i will not go into this again because we already did the solution of a one d chambered flame. So, this you just one more step where you convert those solutions into the mixture fraction space.

But then this is important because the solutions you see that it gives you an idea that you can using this mixture fraction you can essentially go from the physical space in terms of x to the mixture fraction space which is in terms of Z. So, you know if all flames essentially have obtain this then the life would have been simple. So, these you know exactly you have essentially analytical results for this, this 1D chambered flame and you can write all flames to be essentially in terms of this, but of course, that is in a true because you will see that Y this temperature can essentially deviate to temperatures like this from the adiabatic flame temperature. And of course, this is the T adiabatic flame temperature for the given mixture.

So, now what we want to do is that now that because of the fact that we have establish that the mixture fraction is a very important concept and we can essentially write the temperature or species or any reactive species as such as a function of Z, this gives you this idea. That this that this possible that when you when you essentially have the solutions in terms of the mixture fraction space and that mixture fraction is a concept scalar. So, the then the idea is that. So, let us do some modelling in terms of z and first things to essentially find out how Z this mixture fraction is transport at inner turbulent flow.

So, for that we need to essentially develop this kind of averaged equations this Fabre average equations for the z and the transport equations of z. And then what we will try to do is that we will try to use these solutions this solutions to essentially project this kind of temperature etcetera along the mixture fraction use this solutions to essentially define local flame lets at a different points in the flow in terms of the mean Z and the Z variants of Z. So, that is what we will try to do ok.

So, the idea is that that since these from these pictures from these pictures of the one d flame we find that mixture fraction is a very revealing, it essentially acts like an independent variable in this in in the frame work of this 1D chambered flame. So, you can write things like y, mass fraction, temperature, etcetera in terms of the mixture fraction. So, those can be express is a function of the mixture fraction.

Now, of course, the thing is that so essentially if we are told that at a point if you have which is a burning, you have essentially mixture fraction of say this value. So, then you know the temperature at that point is this you know at a point and this is add as this values. So, then we know that the temperature the mixture you know that the temperature at that point is adiabatic flame temperature. So, these gives you a map of this different reactive scalars as a function of the mixture fraction value.

So, the idea is that to first we have to know that in a given combustor at a particular point is space what is my mixture fraction value. To know what is that mixture fraction value, you need to essentially solve a transport equation of Z like in a combustor you know want to know what is particular point, you add particular point what is the velocity. So, to know what is the velocity, we essentially need to solve for the continuity and the momentum equation and may be other equations also if we need to if that is a coupled with density.

So, similarly just to know what is that point to know in the combustor what is my mixture fraction because if I know my mixture fraction then and if this, this solution if i assume this solution holds the simple solutions holds in that at each points in the flow. Then just by knowing what is the value of mixture fraction, I can find out what is a temperature. So, first we have to know what is the value of mixture fraction of course, we can or within or not interesting in the instantaneous value of mixture fraction rather we are interested in the average value of mixture fraction. And for that we need to first find out and transport equation that gives that gives us the average value of the mixture fraction and the and its variance at a particular point in flow. So, we need to first define a governing equation that we will tell us essentially what is the how to find out the mixture fraction is transported.