

Combustion in Air Breathing Aero Engines
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Lecture - 18
Laminar Non-Premixed Flames I

Welcome back. Today we are going to talk about Laminar Non-Premixed Flames. Laminar non-premixed flames happen when the fuel and the oxidiser are not mixed a priori. So, that is a very natural situation because even in nature or in engines when you send a fuel stream inside a combustor it takes some time to mix and if the reactions are fast you will have a flame of course, in a very narrow region which separates the fuel from the oxidiser and those are basically called non-premixed flames.

So, non-premixed flames are common in a common in terms of aero engines and they have certain advantages, but they have certain disadvantages also the advantage is that as we will see that they are very robust in the sense that their position their stabilization is much much robust that is they will be formed only where the fuel and the oxidiser will be at stoichiometric locations or on the other hand because of this stoichiometry that is where the fuel and the oxidiser are present in purely stoichiometric conditions there or the problem is that the temperature is also will be very high we will show this by analysis and also as a result of which it has it produces much more emissions.

So, the temperature in non-premixed flame is difficult to control and, but it is quite robust in terms of flame stability and. So, we will see, but the most important thing is that here in the non-premixed flames we do not have to mix the fuel and the oxidiser a priori. So, if you have an actual engine like in an aero gas turbine engine where you have where you send a fuel spray through the injector. So, the fuel spray will basically first atomise that will display the cylindrical spray will break up into small droplets and then these droplets will evaporate and then this will this evaporate at fuel will actually mix and then will mix and then the mix with the oxidiser the other stream will meet with oxidiser and these positions where they will meet a flame can be formed.

In this lecture actually we will see how a droplet actually evaporates and burns and how a non-premixed flame is essentially formed around the droplet.

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Module 4

Laminar Non-premixed Flames

- i. Canonical structure
- ii. Gasification of condensed fuels
& Stefan flow
- iii. Droplet combustion

Majority of the material is taken from
i. Combustion Physics by C. K. Law, Cambridge University Press.

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In a sense that this work; this topic today of non-premixed flames and as you will see that we will talk about the canonical structure of the non-premixed flames we will see this canonical structure that is a basic structure of a non-premixed flames. And this gasification of condensed fuels and Stefan flow and droplet combustion all these problems are of very high importance in terms of an air breathing aero engine alright, but you can always ask as I keep reminding that of course.

The situation in an actual engine is much more complex because in gas turbine combustor, the Reynolds number, the (Refer Time: 03:22) Reynolds number is very high because as a pressure is high the density is high and the and the Reynolds number is very high and the combustion happens in a very strongly turbulent state, but then what we will show later that this even the combustion happens in a strongly turbulent state. The fuel and the fuel air still there is the fuel air actually mixing is actually promoted by turbulence, but still we can think of if you take the entire flame we can find out segments of the flame in which this laminar structure this laminar flame structure will be preserved.

So, to understand the unit flame that is if fundamental building block of a big completed turbulent flame structure you need to first know how does a laminar flame structure looks like. So, that is the importance of today's study that to understand something complex you need to understand the fundamentals first right now to understand its basic

structure first. So, today's lecture is actually we will be dealing with that. So, we will dealing with the fundamentals of laminar non-premixed flames that is essentially will deal with laminar non-premixed flames, but we will see that here what we will study we will go a long way in on understanding of what happens in a gas turbine engine and which will come later.

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Problems/Phenomena Studied

1. The chambered flame
2. Condensed fuel vaporization/condensation
3. Droplet vaporization & combustion

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So, in previous class you have seen that before going into what kind of problems we will study in previous class we have done the governing equations and the constituent relations and also the coupling function formulations. So, we will take those help they take help of those governing equations in the coupling function formulations and using those we will study these following problems and phenomena that is we will study he chambered flame it is basically a very ideal non-premixed flame it is an example of a ideal laminar non-premixed flame in which there is no flow there is no convection.

Of course, last class we have seen that even if there is flow you can always find a very find a small region near the flame at the flame where you can think that the flow is negligible or the or the convective terms are negligible because they are of first order and on only the flame can be destroyed between a competition between your diffusion and reaction. Of course, one can do the idealisation, but in this topic in this chambered flame we will assume that there is no flame as such and only there will be species diffusing of

course, you remember that by flow we mean the flow bulk velocity u when you say diffusion we mean the diffusion velocity that is capital V i right.

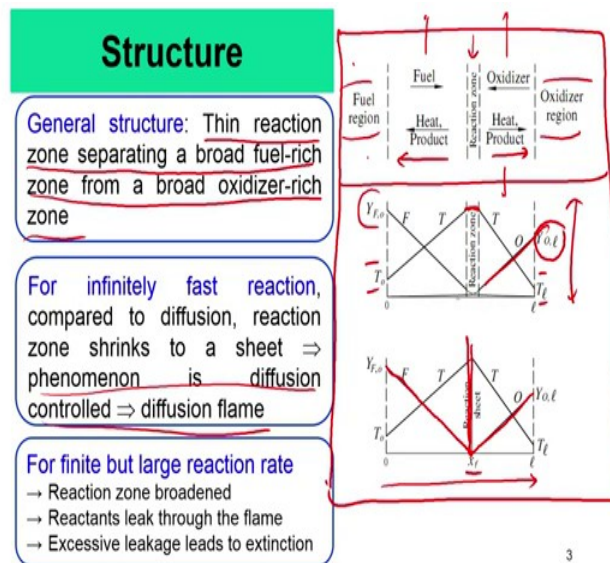
So, here in this chambered flame we will only have diffusion in the sense that only species will be diffusing from 2 sides and will meet at the flame and then products will be diffusing out of the flame and also heat will be diffusing out of the flame. So, that is the definition of that is the description of a chambered flame we will come in to that then we will consider this condense fuel vaporisation and condensation. If you take a beaker or if you take a vessel which is half filled with water say and then we will continuously blow wind on the top of this vessel. So, as to remove any fuel any liquid vapour accumulation the vapour of the liquid accumulation and then we will see how does we can describe that of course there is a as you will see later that this will be essentially a quicker cell to this study.

So, we will then one after we have done this study of condenses fuel vaporisation and condensation we will move on to droplet vaporisation and condensation. So that is as you know that as I told you that droplet vaporisation and condensation is a problem of the amount importance for understanding any your within engines, because as we have seen previously that the most important fact of that combustion is indispensable in air breathing engines is because of the fact that liquid fuels have extremely high energy density and that is why you can basically you can in a small amount of mass you can carry a lot of energy actually.

So, how do you get energy how do you convert the chemical energy to thermal energy the chemical energy stored in the liquid fuel to thermal energy of course, in reactions in this case is does not happen in the liquid phase. So, first you have to basically convert the droplets or the liquid into essentially into fuel vapour and then in the fuel vapour and the oxidiser can mix and you can have a flame and you can generate heat and then you can do the accelerate that heat at flow and then can generate thrust or you can use a turbine to generate the required power to drive the combustor.

So, that is why this topic of this fuel vapour fuel vaporisation and condensation is so very important, so we will go into these three topics today and first the topic is this one that is the first we will talk about the chambered flame; what is the chambered flame first we have to basically understand its structure.

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So, this is the structure of the chambered flame at different levels of complexity. So, here what is happening is that let us consider first let us consider a focus on this part that is in the top part all right that is this part.

So, what is happening here is this; suppose on the left hand side you have a fuel region pure fuel how can you have that you practically you can have a porous plug essentially? So, on that you can have a fuel region and which contains purely fuel. And on the then you have some consider some space some air in between and then you have essentially an oxidiser region. And now basically suppose you this fuel will because here there is no fuel on and here there is no oxidiser the fuel essentially will diffuse from this fuel region and will go towards the towards the oxidiser region and this oxidiser will go towards the fuel region, but of course this is just for diffusion and non wide bulk motion right.

Now, if you have a flame inside the situation will change because. So, if you have a flame inside that is this is a flame the situation will change because now you basically have fuel will be consumed at the flame region and you will also have oxidiser consumed in the flame region and on the this on and in return the this flamy region or the reaction zone will basically give heat out on both these 2 sides heat will conduct or diffuse on these 2 sides and it will also the products will also diffuse on these 2 sides. So, if the in reality this region where this happens in reality what this where the where this reaction happens that is the finite thickness.

But the, but at the same time, this region is very small because we have seen that because of the large activation energy the reaction zone is always very thin all right. So, of course, it will, but it will still definitely have some thickness.

Now, if it has some thickness what will happen is that will have a structure similar to this where the temperature will increase T_0 . Let us give the definition now let us say that the fuel mass concentration pure fuel mass fraction that is the mass fraction of fuel in this fuel region is essentially $Y_{F,0}$ now please keep this; this nomenclature in mind because we will use this throughout this class. So, on the left hand side you have this fuel mass concentration fuel mass fraction of $Y_{F,0}$. Now why is it not equal to 1 because you can also have some inert in the fuel the fuel can be a mix of like say hydrogen mixed with nitrogen.

So, then the amount of the mass fraction of fuel mass fraction of hydrogen is essentially is given by $Y_{F,0}$ whereas, $1 - Y_{F,0}$ is a mass fraction of nitrogen like that similarly on the right hand side you have basically the; you have the fuel we have the oxidiser and the mass fraction of the oxidiser that is a pure mass fraction of oxygen is essentially $Y_{O,1}$ of course, this can have an air. So, basically my $1 - Y_{O,1}$ is equal to the mass fraction of nitrogen alright.

Now, let us say the left hand side temperature is T_0 and the right hand side temperature T_1 T_0 is not equal to T_1 because the fuel region and the oxidiser region need not be at the same temperature alright now say let us say now you have a flame. So, if you have a flame then the temperature of this, this is the region where the flame is. So, then the temperature will have a shower curve. And then the fuel, of course the fuel mass fraction will decrease and then it will decrease, but if there is a finite reaction zone this will not be immediately it will not be 0 and there will be some reactant some fuel leakage through this reaction zone. And then, similarly this oxidiser will decrease and then it will also slightly can leak through the reaction zone.

But, now we will not consider this description we will just consider a simplified description where we will say that basically we are taking a zoomed out view where the reaction zone will not consider any thickness of the reaction zone will consider the reaction zone to be essentially a sheet that is the activation energy. So, large and the

reaction rate is so fast that the entire reaction is concentrated in a thin sheet of infinitesimally small thickness.

And as a result there is no reaction zone only a reaction sheet and in that case of course, your T_0 and T_1 will have a sharp boundary within; of course, it is the temperature is discontinuous, but it will be discontinuous in the derivatives and then if the reaction of course, if the reaction this reaction sheet is an approximation of a of a infinite reaction rate. And then what we will say is that- in the in this reaction sheet limit will when you say infinite reaction rate we mean that the reaction rates are very very fast compared to other processes in the in the system essentially like diffusion.

So, essentially this problem will be diffusion controlled because the reaction time scales are very very small and of course, when the reaction rates are very fast then everything is consumed such then there is no leakage you see there is no leakage here and then Y_F becomes 0 right after at x_F which is the flame location. So, in this 1 dimensional picture this is the this x_F is a flame location of course, you can see that now it is clear why this is a 1 dimensional problem because these regions are essentially are infinite in these 2 directions in both these up and down directions.

So, this problem is essentially 1 dimensional and then the temperature increases up to the flame then it decreases from the flame location to the to the right hand side and then of course, you have this oxidiser also goes to 0 at x_F and there is no oxidiser leakage from the from x_F . So, that is an important point that we need to basically consider.

So, beyond x_F there is no fuel on the right hand side and before x_F there is no oxidiser on the left hand side. So, essentially the general structure as you see is the flame in this you know we call this essentially a non-premixed flame we get people also call this diffusion flame in the because you see in at this is this problem is we will see that it is diffusion controlled, because the reaction zones are reaction rates are much much faster than the diffusion process. So, then the diffusion becomes the rate limiting step and such for there the problem becomes diffusion controlled and people call this flame diffusion flame, but that is slightly bit slightly misleading because that implies that premixed flames n premixed flames diffusion process is not important which is of course, not true in premixed flames also diffusion is important in diffusion n non-premixed flames and diffusion flames are also diffusion process is very important in all flames diffusion is

very very important and as a result of this we will call this instead of diffusion flames we will call this non-premixed flames.

So, because you see that the reason is simply because the fuel and oxidiser they do not meet and they are no premixed a priori. So, they only meet at they only get mixed at the reaction sheet of the reaction zone. So, this zone structure is essentially I am coming back this zone structure is essentially a thin reaction zone separating a broad fuel rich zone from the broad oxidiser rich zone.

So, this much broad this is much broad this is very very thin, so that is why it is we call this nomenclature. Now as we have seen that for infinitely fast reaction compared to diffusion that is reaction; reaction rate itself need not be infinitely fast we must consider it to be infinitely fast compared to diffusion is much much faster than diffusion process, because as the diffusion is a slow process and the reaction zone shrinks to a sheet.

And we call this becomes a phenomena as diffusion control. We call this diffusion flame but we will call this non-premixed flame, because as we have said that both premixed flame and diffusion flames are non-premixed flames with a diffusion control sheet. And this is the thing where when we consider a finite, but large reaction rate that when the reaction with the zone becomes broadened then reactants leak to the flame and excessively leakage leads to extinction.

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Recall, from Coupling Function Formulation

Define stoichiometrically weighted mass fraction as,

$$\tilde{Y}_i = \frac{1}{\sigma_{i,n}} \left(\frac{Y_i}{Y_{n,B}} \right) \text{ where } \sigma_{i,n} = \frac{W_i(v_i'' - v_i')}{W_n(v_n'' - v_n')}$$

n=Unspecified reference species

B=Boundary location at which Y_n is known

Similarly, define stoichiometrically weighted, non-dimensional enthalpy

and temperature as, $\tilde{h}_s = \frac{h_s}{Y_{n,B} q_{c,n}}$ and $\tilde{T} = \frac{cpT}{Y_{n,B} q_{c,n}}$

where $q_{c,n} = \frac{\sum_{k=1}^N h_k^0 W_k (v_k'' - v_k')}{W_n(v_n'' - v_n')}$ is the chemical heat release

The species-enthalpy coupling function can be defined as,

$$\beta_i = \tilde{T} + \tilde{Y}_i$$

So, this is the reaction leakage phenomena that I was talking about of you see that this does not go to 0 here and this goes to 0 here all right. So, from you know we will just recall the coupling function formulations previously that we did in a in the previous class. So, we defined the stoichiometrically weighted mass fraction as this $1 - Y_i$ is equal to $1 - \frac{W_i}{W_n} \frac{Y_i}{Y_n}$ where Y_n is a reference species which is not defined yet it can we have to define it can be fuel oxidiser product etcetera b is the boundary location.

So, in this case the boundary $Y_n|_b$ can be essentially $Y_n|_f$ where n where we consider fuel to be the reference species and b boundary to be essentially the left hand side boundary I will come to this and also this W_i is the stoichiometric coefficient. And this is defined as the ratio of molecular weight times the difference of the stoichiometric coefficients divided by the molecule with the reference species times the difference of the stoichiometric coefficients.

And then we defined a stoichiometrically weighted non-dimensional enthalpy and temperature h_s^* and T^* . And these things are as you will see that essentially Δh_s and ΔT are essentially Δh_s^* and ΔT^* will be or h_s^* will be essentially equal to $T^* - T_0^*$ will be same essentially this will difference will be very close and. We will use it interchangeably and this scheme c_n that is defined here is the chemical heat release on that is normalised by this W_n times W the difference of the stoichiometric coefficients will come to this. And then we will see that here using this will come we can define a non-dimensional we can define a species enthalpy coupling function can be defined as $T^* + Y_i^*$.

Just to recall how we did this if you remember that when convection could I mean in the flame zone will consider that the convection to be could be ignored, because it was essentially a competition between diffusion and reaction and assuming that the process is steady state we arrive at this equation gradient of λ by c_p times gradient of sensible enthalpy is equal to heat release rate this came from your energy equation and gradient of ρD_i times gradient of Y_i is equal to minus W_i that is consumption or production rate of individual species that came also from your species equation. And these like distinct diffusivity formulation alright.

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$$\begin{aligned}
 & \nabla \left(\frac{\lambda}{c_p} \nabla h^s \right) = \sum_{i=1}^N h_i^s \omega_i \quad \left. \begin{array}{l} \\ \\ \end{array} \right\} \text{Distinct Diff. formulation.} \\
 & \nabla (\rho D_i \nabla Y_i) = -\omega_i \\
 & \text{1 step combustion reaction } \nu_F' F + \nu_O' O \rightarrow \nu_P'' P \\
 & \tilde{Y}_F = \frac{Y_F}{Y_{F,0}} \quad \tilde{Y}_O = \frac{Y_O}{\sigma_O Y_{F,0}} \quad \sigma_O = \frac{W_O (\nu_O'' - \nu_O')}{W_F (\nu_F'' - \nu_F')} \\
 & \tilde{h}_s = \frac{h^s}{Y_{F,0} q_c} \quad \tilde{T} = \frac{c_p T}{Y_{F,0} q_c} \quad \nabla^2 \tilde{h}_s = \left(\frac{c_p}{\lambda} \right) \omega_n \quad \omega_n = \frac{W_n (\nu_n'' - \nu_n')}{Y_{F,0}} \\
 & q_c = \frac{\sum_{k=1}^N h_k^s W_k (\nu_k'' - \nu_k')}{W_F (\nu_F'' - \nu_F')} \quad \nabla^2 \tilde{Y}_i = - \left(\frac{c_p}{\lambda} \right) \omega_n \quad n \neq F \\
 & \boxed{\nabla^2 \beta_i = 0 \quad \beta_i = \tilde{T} + \frac{\tilde{Y}_i}{Le_i}}
 \end{aligned}$$

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And then, if you consider a one step combustion reaction which is given by $\nu_F F$ plus $\nu_O O$ goes to that is fuel these has stoichiometric coefficients we already know this is the fuel this is oxidiser goes to product in one step then we can define \tilde{Y}_F is equal to Y_F by $Y_{F,0}$, whereas O is essentially our left hand side boundary and \tilde{Y}_O is equal to $Y_{Oxidiser}$ mass fraction of oxidiser divided by sigma over the oxidiser divided by Y_F at the boundary reference we have chosen n to be the reference species and h_s is equal to h^s sensible enthalpy by $Y_{F,0} q_c$ and \tilde{T} is equal to $c_p T$ divided by $Y_{F,0} q_c$. Whereas, q_c is chemical heat release is nothing but summation k is equal to 1 to capital n h_k enthalpy of formation specific enthalpy of formation molecular weight this thing divided by the reference species which is our fuel and then sigma i because you are here we have also defined sigma s sigma i is nothing but r sigma o is nothing but $W_O \nu_O'' - \nu_O'$ divided by $W_F \nu_F'' - \nu_F'$ all right and then of course, with this simplification.

We have already shown that we can arrive at this equations that is Laplacian of h_s tilde is equal to c_p by λ times W_n del square Y_i tilde by Lewis number of i -th species is equal to minus c_p by λ times W_m . Whereas, W_m is equal to capital W_n times $\nu_n'' - \nu_n'$ times $Y_{F,0}$ times this omega which is species independent reaction rate will just write it here because it is not visible.

And of course, if this is fuel or you can keep it actually as n whereas, n is equal to like fuel you can write it in terms of the fuel fine. Now, then of course, we see that if we add these 2 things if we add these 2 equations on the right hand side vanishes and we can write as this as $\Delta^2 \beta_i = 0$ where β_i is actually instead of enthalpy we can just write it in terms of T tilde that is because your what is your T tilde minus T_0 tilde is essentially your h_s tilde. So, that is why we can we can we can write this as in terms of your T tilde instead of h_s tilde and we can write β_i is essentially equal to Y_i tilde by Lewis number l_e . So, this derivation is involves much symbols, but is actually very straight forward.

So, I suggest you do this on your own and then everything will become very very clear so, but then the end advantage is that this whole complicated equation. You see the beauty is that the whole complicated equation just becomes a Laplace equation, where no with the with the right hand side equal to 0 and this is your coupling function β_i is equal to T tilde plus Y_i tilde by Lewis number l_e .