Turbulent Combustion: Theory and Modeling
Prof. Ashok De
Department of Aerospace Engineering
Indian Institute of Technology - Kanpur

Lecture-18
Laminar Premixed Flames (contd.) and Laminar Non - Premixed Flames

Welcome back let us continue to the discussion of the ignition analysis of premixed flame.

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So, we are doing some simplified ignition analysis and this we already discussed what we are wanted to look at minimum ignition energy. These are the application area.

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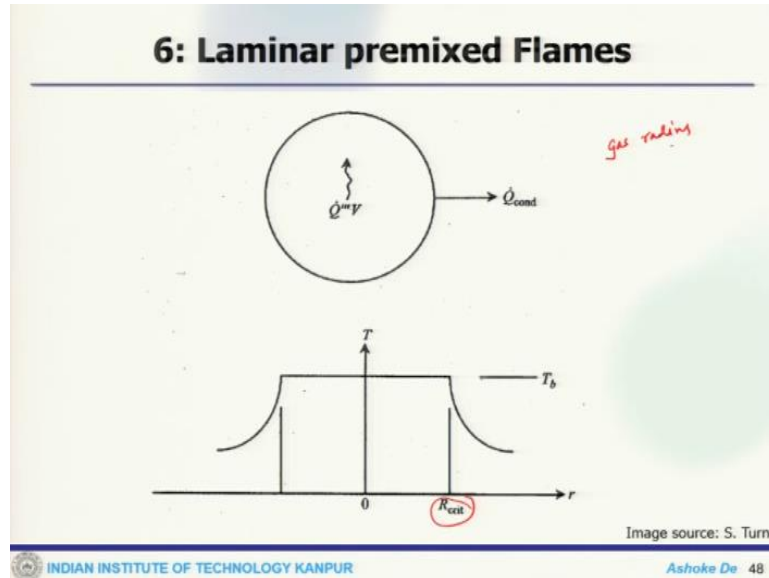And these are the analysis that how we are going to do basically we define in gas radius and then use the spark to find out that.

So, this is the radius that the gas volume radius and here we will put the spark and this is that critical radius and that would be the burning temperature because of the heat production.
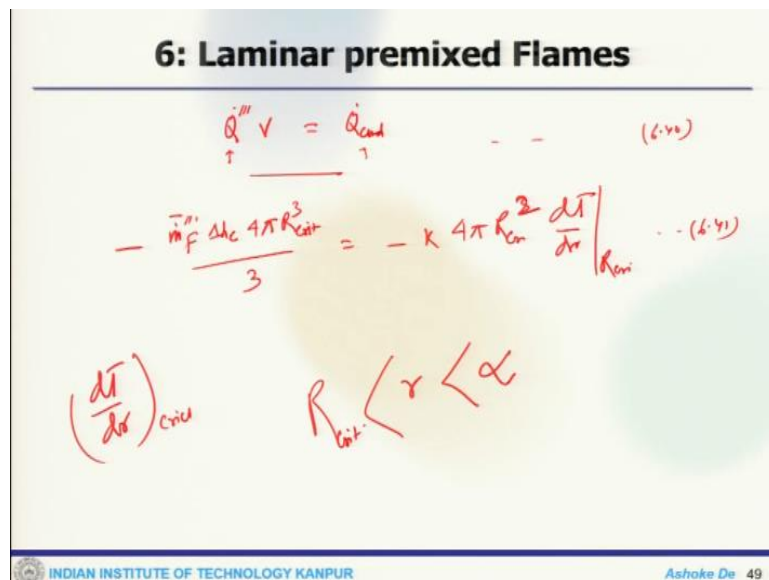
So, we can actually correlate the generation of the energy. And from the energy equation, the heat generation to the heat conduction can be correlated. So, that means, we are equating the heat generated due to reaction and the rate of heat loss to the cold gas by conduction. So, these

are the equation that you get then basically it is a total amount of energy, these we can replace by your previously obtained reaction rate:

$$-\frac{\overline{\dot{m}_F'''}\Delta h_c 4\pi R_{crit}^3}{3} = -\kappa 4\pi R_{crit}^2 \frac{dT}{dr}\Big|_{R_{crit}}$$

So, here $\left(\frac{dT}{dr}\Big|_{R_{crit}}\right)$ can be obtained from the temperature distribution and r will lie between infinity and R_{crit}.

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Then the temperature distribution, one can write these as:

$$\frac{dT}{dr}\Big|_{R_{crit}} = -\frac{(T_b - T_u)}{R_{crit}}$$

Now, we substitute this 6.42 in 6.41 we get so putting 6.42 into 6.41 will get:

$$R_{crit}^2 = \frac{3\kappa(T_b - T_u)}{-\overline{\dot{m}_F'''}\Delta h_c}$$

Now, we have already got some relationship in 6.20, the average reaction rate in terms of so, that is already gives my average reaction rate in terms of S_L and δ.

So, that thing we can use and also we have enthalpy of combustion as:

$$\Delta h_c = (v + 1)C_p(T_b - T_u)$$

So, 6.43 becomes R_{crit} becomes:

$$R_{crit} = \sqrt{6}\frac{\alpha}{S_L}$$

So, you get a critical radius and here alpha is $K/(\rho C_p)$. Now, if you replace these things with δ, one can rewrite this is equal to:

$$R_{crit} = \left(\sqrt{6}/2\right)\delta$$

That is another way to represent the whole thing. Now, one can note here that this factor $\left(\sqrt{6}/2\right)$ is just an order of magnitude and should not be taken as a pressure constant therefore, the critical radius is slightly a few times larger than the flame thickness

Now, we assuming the energy added by the spark, it is the critical volume of the burned gas temperature. So, we can estimate that the ignition energy is $M_{crit}C_p(T_b - T_u)$. That is the ignition and what about in critical that is nothing but $\rho_b 4\pi \, {R_{crit}^3}/{3}$. So, if you put this back, you can write this is somewhat:

$$E_{ign} = 61.6\rho_b C_p(T_b - T_u)\left(\frac{\alpha}{S_L}\right)^3$$

So, that is one way to express these things which will become a function of burn density and the temperature and the flame speed.

Now, one can eliminate this ρ_b from here by using the ideal gas law if we do that this, so using ideal gas law one can eliminate that ρ_b and you get:

$$E_{ign} = 61.6P\left(\frac{C_p}{R_b}\right)\left(\frac{T_b - T_u}{T_b}\right)\left(\frac{\alpha}{S_L}\right)^3$$

So that is what you get. So, this is my ignition these things.

Now we can get the pressure and temperature dependencies. So, from 6.47 we can assist the pressure dependency and ignition energy. So, what we get that α is proportional to:

$$\alpha \propto T_u \bar{T}^{0.75} \bar{P}^1$$

This is what you already obtained in 6.27 this correspond to 6.27 and also 6.29 has given us for n=2:

$$S_L \propto \bar{T}^{0.375} T_u T_b^{n/2} exp\left[-\frac{E_A}{2R_u T_b}\right] P^{\frac{n-2}{2}}$$

So, this is what we have already obtained in 6.29. So, these information we have and we want to use this or connect with this ignition energy equation.

And if we do that the combined effect of S_L is E_{ign} is proportional to the P^{-2}. So, this actually exists quite well with the experimental observation, this has been already proven fact now, if T_u is increased, then what happens to the impact ignition energy also decreases because ignition energy is proportional to T_u^{-x}. So, these are my 6.48 equation number. So, that is how it depends on pressure and temperature. Now, this is how one can do a simplified analysis for ignition energy and get that.

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Now move to the last important point of premixed flame is that flame stabilization. Why do we talk about flame stimulation? Because this is very specific and one of the important issues for premixed flame, because we have already seen how premixed flame is susceptible to some issues like extinction, flashback, liftoff and as we say, this is quite necessary to understand the flame stabilization to avoid flashback or liftoff because these are something which fits to the design of your reacting system.

Because one hand as we have seen earlier or kept on discussing these the premixed mixture or premixed reaction system has less impact on the emission and the pollution, but at the same time, this is quite challenging to have a controlled combustion in premixed system that reason is very simple because your fuel and air they are already mixed before they are getting into a combustion chamber or the reacting system. So, this is the major source of concern at once you have a premixed mixture, which is always sort of exposed to the reaction. So, any transparent from the other side it shows or in terms of radicals or anything that can ignite this mixture instantly and that is why one of the things that you have you see in your a saying in the auto

ignition because that says continues ignition of this mixture that will torch upon when we go a little bit and talk about the ignition.

Now in flashback flame actually enters and propagates through the burner upstream without quenching. So, this is what we have already seen that means this is my chamber and the flame actually goes there and sit there which will make damage to those system and lift off flame is not at us to the burner but stabilize at a distance from it. So, that means what happens this is my system, if this is the burner, it is supposed to stabilize here, but due to lift up it will stabilize like this.
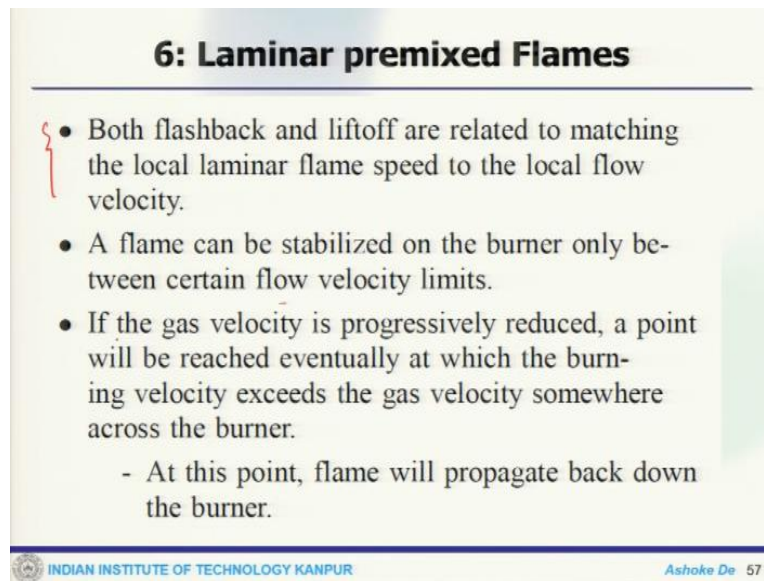
So, flame will be sitting somewhere else, which is also not good for the design purposes, because the heat will be generated and heating this portion of the chamber and all these lot of design issues. So, flashback has safety hazard, liftoff have negative incomplete burning, ignition problem, and control of the flame pollution. This would be some issues that would happen.

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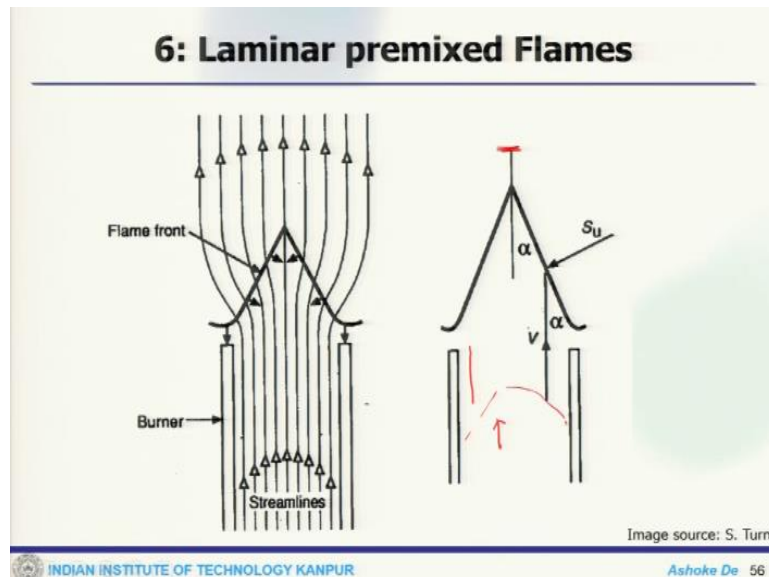
Now, one can see these are some schematic of a lab scale burner where that is a mixture comes through this and this is the flame front. So, this is the flow comes in, this is the burner and this is the flame front if it is theoretically nice organized flame structure it is supposed to be stabilized right there. But if it is lifted, the flame would be somewhere sitting here or if there is a flashback the flame would be somewhere sitting inside like this.

Now, more to it both of these phenomena the flashback and liftoff are related to matching the local flame speed to the local flow velocity. So, that is quite important when one wants to avoid this. So, that flame can only be stabilized on the banner for certain flow velocity limits that means this will be attached to this burner for certain condition if I push or if I inject with too high velocity, the flame would be pushed back.

So, for a defined or control limit, this flame would be only stabilized at the burner otherwise either it would be pushed back or it may come up. So, both of these situations are likelihood possibilities. So, third is that if the gas velocities progressively reduced, a point will be reached eventually at which the burning velocity exceeds the gas velocity somewhere across the burner and this is where the flashback occurs that means the upstream velocity exceeds the burning velocity will be occurring towards this site normal to the flame front.

Now, if this gas velocity is reduced and some point of time S_L becomes higher and then the flame would start propagating upstream. So, this would happen and that will lead to the flashback.

So, if you put some this is again and representative picture. So, this is a fuel oxygen ratio within the increasing site is the flow velocity. And there are different zone what you can see one is this small zone sitting there is the flashback. This is again a unwanted phenomenon. So, one has to design that operating conditions and the system says that flame does not happen this is fuel blowout that means it is completely blowout of the system which is also not undeserved system.

Then this is the stabilized plan what we mean by burner blindness to realize flame this area is something binary stabilizer lifted plan then there will be again a limit of blow out with the limited film see the limited flame has an issue that if you push these things too much light by the flame from pushes here slowly render it is lifted and then it can go out of the beyond the chamber. So, it will happen and the side is your extinction side because the flow will be completely extinct.

So, there are certain limits, which these things put you and your design should be constrained to these parameters. So that you have so, that is pretty much that we wanted to discuss about the laminate premixed flame and we continue now on our discussion in the non-premixed flames.

Now, once we do that, then slowly get into the turbulence and then turbulent non-premixed system because when you go to the turbulence system, all these understanding of flame speed, flame thickness, ignition flammability limit, blow up and all these would be required information one has to understand now, when you say non-premixed which clearly makes a difference between your premixed system and non-premixed system.

What happened in your premixed system the fuel and air they are premixed and then they are pushed to the combustion chamber and in a non-premixed system, if this is your combustion chamber, fuel air here they are injected separately and the mixing takes place due to molecular diffusion inside the chamber before the ignition takes place. So, it clearly a difference, but it gives you some flexibility.

But obviously, when you talk about these non-premixed flame, they are more or rather well known for producing lot of emission like emission gases, soot and all these they are also quite easy to handle or other they are stable, but you pay the price in other factors. So, it is and again all the time this is a process of optimization. So, one and premixed system gives you some advantages, but that also come with some concern non-premixed system can avoid those concern or can be free from those concern.

But it will give you some other issues to control. So, bottom line is that all the time it requires the optimization of the system and then how it can be used for the purpose.

Now, what do we know for a diffusion flame? The combustion occurs at the interface between the fuel gas and the oxygen gas. And the burning depends more on rate of diffusion of reactors than on the rate of chemical process in what so it is always in the interface where fuel and oxidizer they will interact that is where the reaction takes place. So, it is more difficult to give you a general statement of diffusion from largely because no simple miserable parameter analogous to the burning velocities in premixed can be defined.

So that burning velocity that we defined in the premixed flame that is actually not a parameter which you can define for diffusion and flame because the whole idea behind premixed and non-premixed they are different as soon as you go to non-premixed this definition of burning velocity does not exist, you cannot actually define it.

7: Laminar non-premixed Flames

- Used in certain applications (e.g., residential gas appliances).
    - mostly partially-premixed flames
- Used in fundamental flame research.
- Primary concern in design is the flame geometry.
- Parameters that control the flame shape,
    - Fuel flow rate
    - Fuel type
    - Other factors

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Now, application wise obviously the non-premixed flame explain the application would be more and it starting from your residential gas application. But do that slightly partially premixed claim you can have in a plenty of places where it is used and we have already seen that. So, it can be used in fundamental research. So, one of the concerns is that how you can control the flames you can control through fuel flow rate, you can control through fuel type, you can also control through other factors.

7: Laminar non-premixed Flames

Candle Flame.

Image source: S. Turns

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So, if you look at this example of this simple candle flame, which we have seen earlier also it is a very nice flame, but which we use in our daily life without knowing that actually burns under non-premixed mode. Now, here this is the solid candle which is a carbon and you have

air which is coming through and the solid carbon actually through paralyses it reaches a gaseous state this is your paralyses process and the reaction takes place.

So, there are different zone what you can actually distinguish. This is your main reaction zone and this is your laminar zone which you can see there, when the candle burns you can see a nice laminar zone. And this is some of the other reaction where you see some radicals see zone to zone there. Now, if you ever dared to put your finger deep through this candle flame, you will see the maximum heat the outer surface when you come close to the inner surface, you can see their minimum heat there.

So, that will not affect but obviously, I mean the other way to measure it that you can use some common couple which is not temperature measuring device. So, if you use a thermal couple and put it inside you can see the temperature variation there and that tells you in a different zone.

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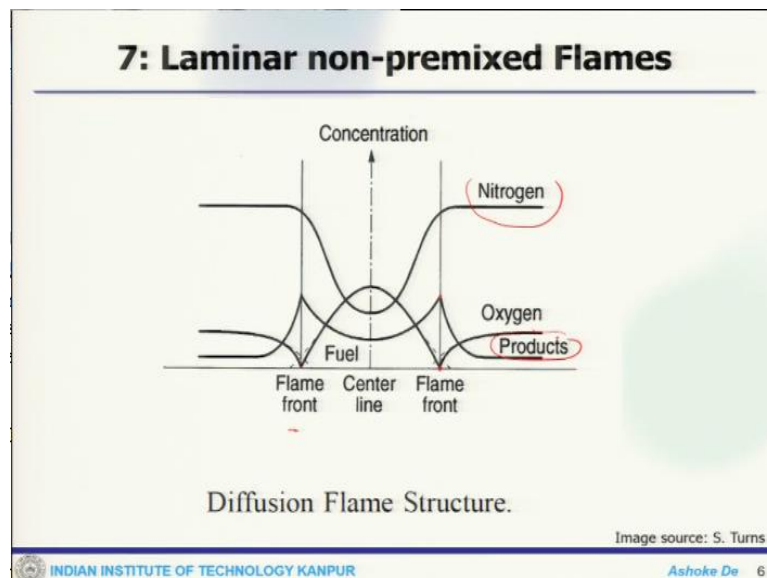
Now, this is a typical diffusion flame structures, this is my flame front, this is also important this is my fuel and this is the oxygen. So, fuel comes down also oxygen is completely consumed at this location. So, one can see that production is performing here. This is the product line oxygen will be completely consumed, film would be completely consumed and in between the center line fuel is varying, product is also varying and oxygen is also varying.

So, the nitrogen variation is also shown there. So typically, if you see this is what happens basically these are the areas what we kind of see these are the points because this is one media reaction, this is another area in the reaction you normally you get the product front of that.

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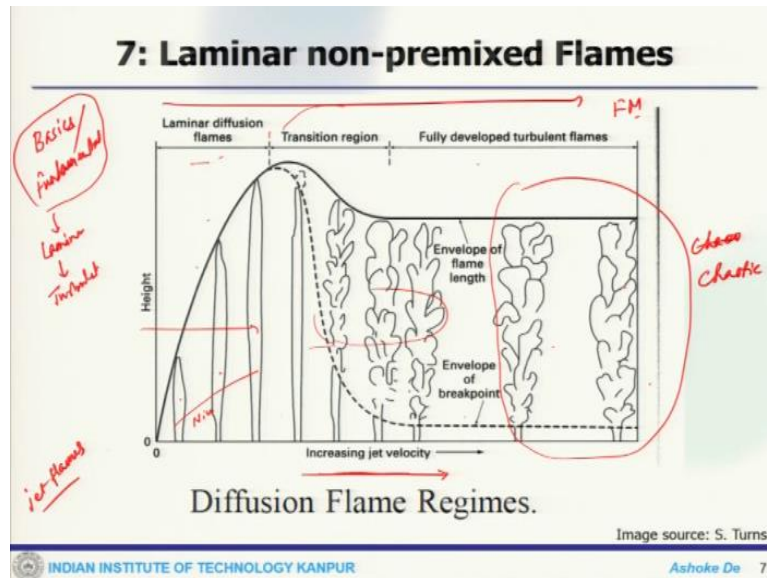
Now you can have different diffusion flame regime and this is based on the so this is the flame height along these. So first thing you can have laminar diffusion flame and you can see the laminar diffusion flame with the increasing good velocity that means for a simple jet flames, this is not for all this is for some jet flames you can see the height it is increasing, that is a laminar diffusion flame. Now, this is along with the increasing jet velocity.

So, that means, when you increase the jet velocity it reaches a certain point where beyond increasing the velocity you may have a different kind of flame which is not through the structure if you look these are nice looking structure. But beyond a certain point the structure gets into this kind of structure which are not nice looking structure. So, this is called that to this division is based on your fluid mechanics laminar very calm quiet sequence.

Some things are nicely balanced, you get to see a nice flame structure. You increase velocity to a beyond limit you get to see this transition zone where the flame structure become quite chaotic and there will be envelop of breakup point that will envelop of flame length and if you increase further you are completely in turbulent zone. So, that means it is a pure chaotic structure of the world and there is a nice analogy you can extract from this picture is exactly what we are doing.

We are first we started I mean before that if I put something these are the basics or fundamentals. So, this is where we discussed about all the commercial fundamentals basic thermodynamics kinetics, heat and mass transfer coupling of kinetics everything then we got to laminar system, then we want to go to turbulent system. This is exactly what you can correlate from this picture where starting there is a laminar nice looking structure.

This has certain properties what one has to understand and why the laminar goes into transition with the increase in velocity, then you see the flame structure is distorted but it is not completely chaotic. But when it becomes completely turbulent, it becomes completely chaotic. So, that is why we started here and slowly go there, because whenever we look at this turbulent system, you require the information of this laminar understanding and that is what we are doing. And we will stop here today and continue the discussion in the next lecture. Thank you.