Turbulent Combustion: Theory and Modeling

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Lecture-17
Laminar Premixed Flames (contd…)

Okay, welcome back. So, we are in the middle of the discussion of the laminar premixed flame and what we have done so for is that looking at the correlation and they are curve for the laminar flame speed and flame thickness. So, we will look at more into the details.

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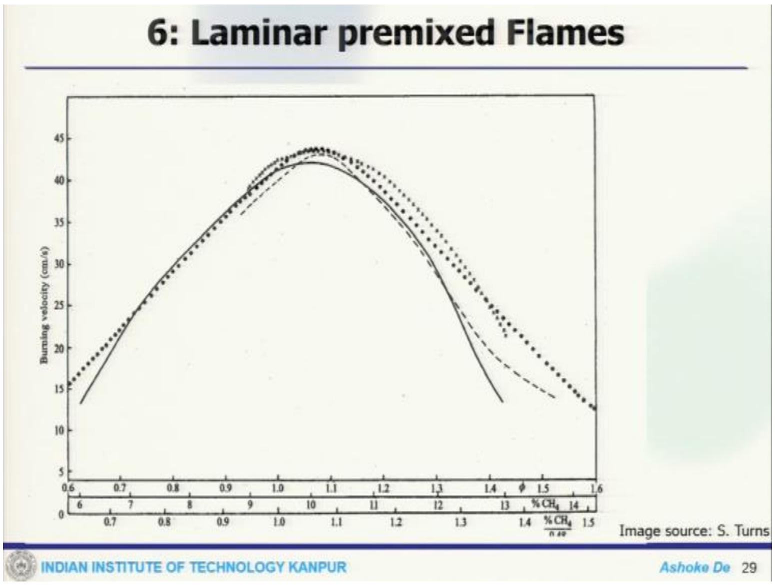

So, this is the curve what we have seen because of some correlation and then we obtained this.

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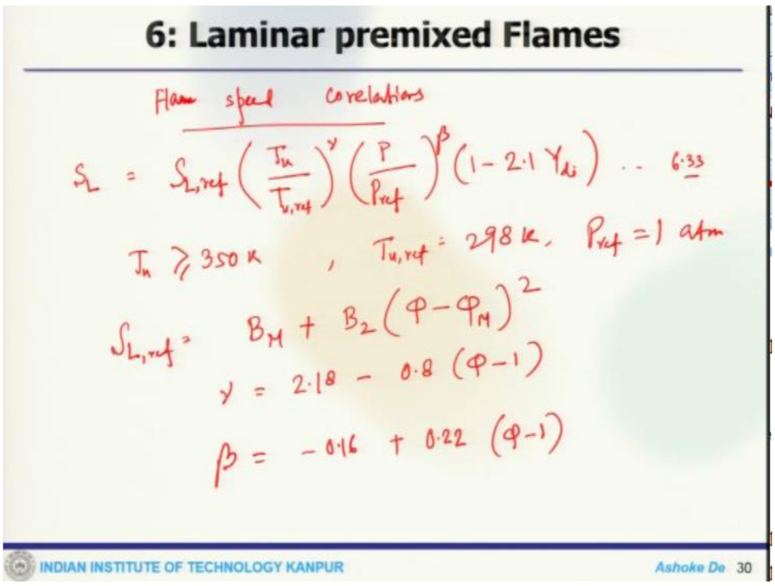

So, now, what we can do? We can get some flame speed correlation. So, how to do that will get:

$$S_L = S_{L,ref}\left(\frac{T_u}{T_{u,ref}}\right)^{\gamma}\left(\frac{P}{P_{ref}}\right)^{\beta}(1-2.1Y_{di})$$

So this is your equation 6.33. Now this is valid for $T_{unburnt}$ greater than equals to 350 Kelvin and where $T_{u,ref}$ is 298 Kelvin and P_{ref} is 1 atmospheric pressure.

So, what we get $S_{L,ref}$, it will be:

$$S_{L,ref} = B_M + B_2(\varphi - \varphi_M)^2$$

And gamma is:

$$\gamma = 2.18 - 0.8(\varphi - 1)$$

For while the beta is defined as:

$$\beta = -0.16 + 0.22(\varphi - 1)$$

So, that is what you get.

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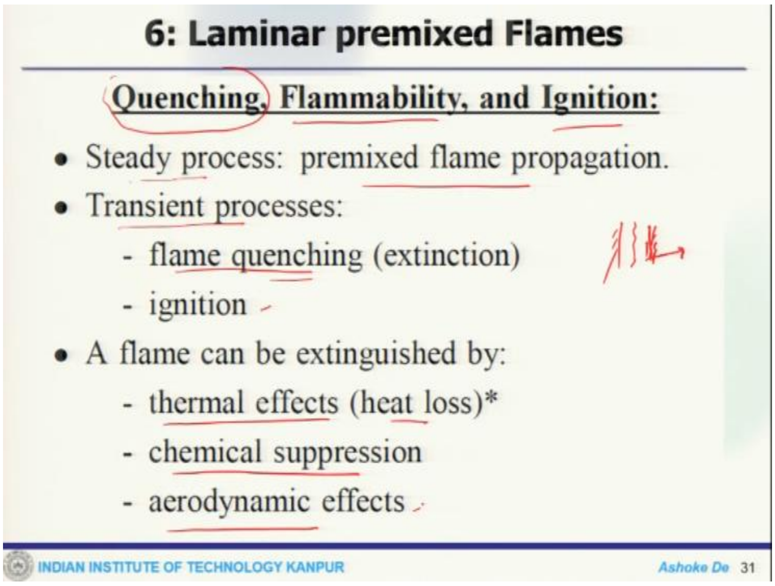

Now we can look at some other interesting things which actually occurs in a premixed flame. This is very specific to a premixed flame. One important aspect is the quenching. So, what does quenching mean? Quenching means that it says suddenly, certain areas where flame extinguishes and this flame extinction can happen due to so many other factors. And we will look at those factors. What are those things that actually caused this quenching to take place?

Then flammability limit, this is another important aspect that means it is not that I can have certain mixtures and the mixture will burn automatically. So that would not happen. And then the ignition because this is another area or it is process quite a bit of challenge, how to ignite the premixed flame mixture, but they are quite sensitive to the ignition and can lead to explosion because of some uncertainties.

So, we consider a steady process where premixed flame propagation takes place. Then the transient process where flame quenching actually takes place. So, in a steady case is it very much unlikely situation that flames quenching can happen. So, flame quenching typically happen when there is a transient situation and it would be the same if there is a flame there it says sparking location ignition also the same thing.

Now, what are the major factors that caused this extension, one is the thermal effect that is heat loss. Let us say the flame is coming close to this wall and the flame is coming close to this wall and there is a heat loss to the wall that could suddenly quench the flame there. Then chemical suppression, there is another factor which may cause the flame extinction, aerodynamic effect this aerodynamic effect means what we say that any burner fuel and this fuel-air mixture is injected through some pipelines. And other main slide swell or something like that. Now, the speed dynamics behind those things actually can cause this flame to extinguish also this is what we mean by aerodynamic effect.

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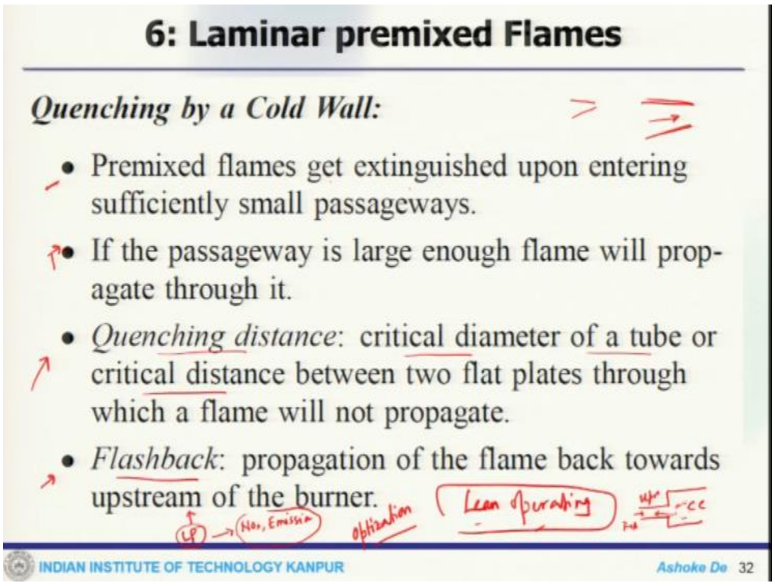

Now, we will go one by one and look at what happens when quenching takes place by a Cold Wall. Now, the flame front the especially the premixed flame front can get extinguished when it entering sufficiently small passage that means, if you allow to pass through various small passage, then it can quench that is one of the ways it may possibly happen if obviously the flip side of it is that if the passage is large enough or broad enough, then the flame will propagate through it. Okay?

Now, which immediately brings to an important question, how do you estimate the quenching distance? That means, I have a passage through is the premixed flame passing through and you want to estimate the quenching distance, so this one can identify as a critical diameter of tube or critical distance between two flat plates through which a flame will not propagate. So, that essentially you think about a simple geometry like this, these are the two flat plate and the flame is passing through that situation.

So, that is a critical distance through which the plane will not pass through, that is your quenching distance. Now, there is another phenomenon, which quite often happens in premixed flame especially in a lean operating condition. Now, this is called flashback that means, that if this is my access cumulative, this is my combustion chamber and this is my upstream mixtures fuel plus air which is coming in flame is supposed to be here within the combustion chamber because of some level of uncertainties or changing operating conditions at the upstream or here this flame will propagate upstream and may sit in upstream block. This is my upstream block. Now, whether this is a decide phenomenon not absolutely no because if this happens then if the flame sits on the upstream pipeline or upstream injection of this whole system, this can cause severe damage to the upstream injection system and all these things.

Now, which will not only the detrimental from the structural point of view also it is not safe or that can lead to any other accident. Now, does the flashback happen all the time? No, it is a very specific situation when flashback happens that this you operate the lean premixed condition usually normal operating condition, flashback does not happen when you try to operate the lean premixed condition then flash back is likelihood possibility and why these are all one after another connecting questions because flashback happens because of lean premixed condition.

Now, why would one operate the system at the lean premixed condition? Because this will reduce the NOx emission. So, the lean premixed condition has advantage on the emission. So, this will have a low emission. So, that is why this is a requirement from the health or environmental point of view. That is why, we try to operate of the lean, but if you operate it lean, there is a likelihood possibility of flashback

So, that means, again the whole point which comes here is as we slowly getting deep and deep of the discussions, you can see how things are connected which you started up in the introduction. So in some pictures that what could happen or what could not. But here you see, we got that is why the whole issues that it is an optimization problem with multifaceted issues. It is not a single dimensional problem, you need to operate at lean condition. But then lean condition also not only flashback, it will also lead to a blowout.

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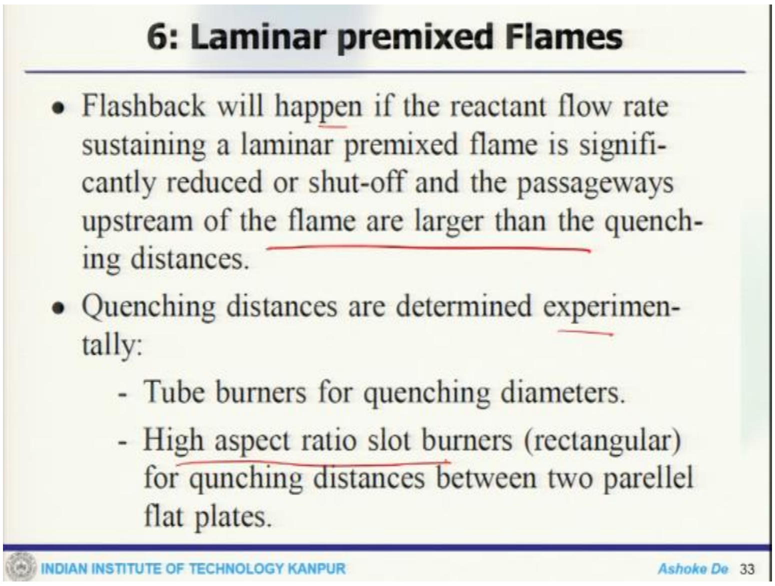

Now, these are the some of the things which we are talking that flashback can happen if the reactant flow rate sustaining a laminar premixed significantly reduced or shut off and the passageways upstream of the flame are larger than the quenching distance. So, these are some of the rules where people think that then the flashback can occur. Now, how do you determine the quenching distance? So, one can do experimentally that the tube burners for the quenching diameter that is one thing. Then high aspect ratio slot burners that could be another thing between two parallel plates.

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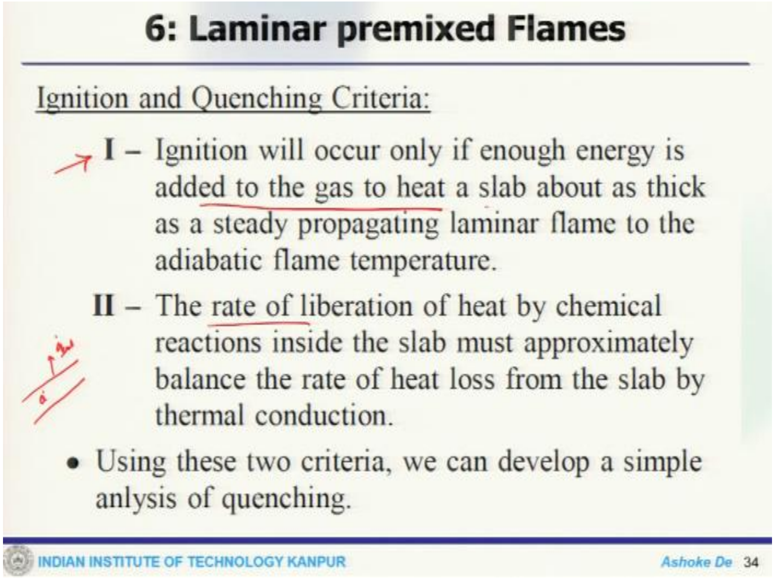

Now, there are some criteria's that one can put together, one is that ignition will occur only if enough energy is added to the gas to heat a slab about as thick as a steady propagating laminar flame to the activity temperature. So, that is what one criteria that ignition will take place. Now, the second criteria says that the rate of liberation of heat by the chemical reaction inside the slab must approximately balance the rate of heat loss from the slab by thermal conduction, if this is a slab.

So, what about heat generates here the heat rejection through there also should balance out. So, now, you can use these criteria and can develop a simplified model for quenching.

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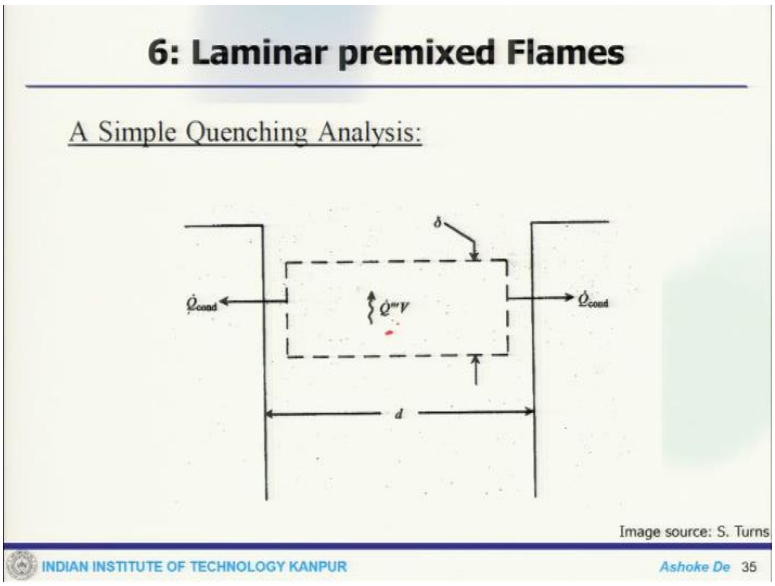

So, to do that simplified analysis, what one can do? Take a simple box like this is the control volume and the distance is d between these 2 pin, here is the loss due to conduction and this is the generation. So, the energy balances if we write.

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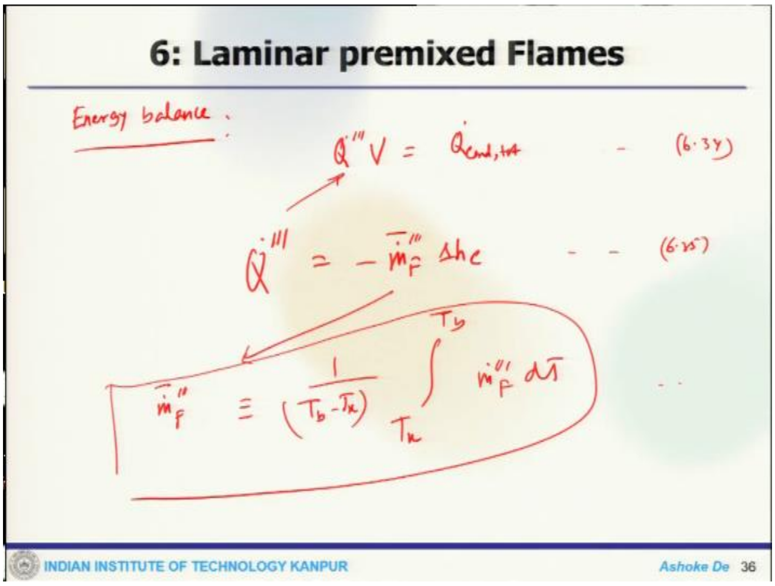

So, the energy balance if we write, so energy balance if we do so, it is equating the heat produced by the chemical reaction to the heat loss through the conduction. So, that means:

$$\dot{Q}'''V = \dot{Q}_{cond,tot}$$

So, that is your equation 6.34. Now, this volumetric heat release is related to that and reaction rate. So, this is nothing but my average reaction rate multiply by Δh_c.

So, they are connected like that and what is the average reaction rate? This is in terms of:

$$\overline{\dot{m}_F''} = \frac{1}{(T_b - T_x)} \int_{T_x}^{T_b} \dot{m}_F''' \, dT$$

This is what we have earlier seen.

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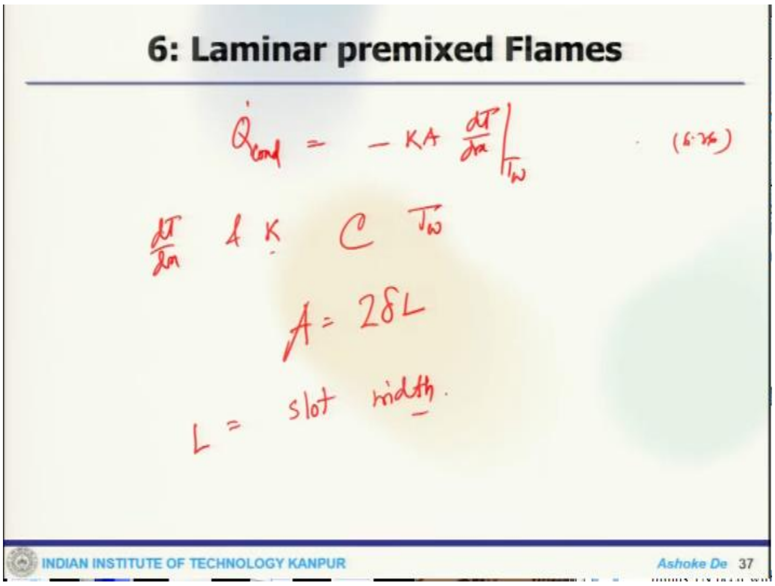

Now, through the slab of the wall, the heat loss by conduction, which follows the furious law. So, we can get the combustion heat loss which is nothing but:

$$\dot{Q}_{cond} = -\kappa A \frac{dT}{dx}\bigg|_{T_w}$$

Where both temperature gradient this one dT/dx and κ are evaluated of the wall temperature that at T_w, okay? Now area is 2δL where L is the slot width.

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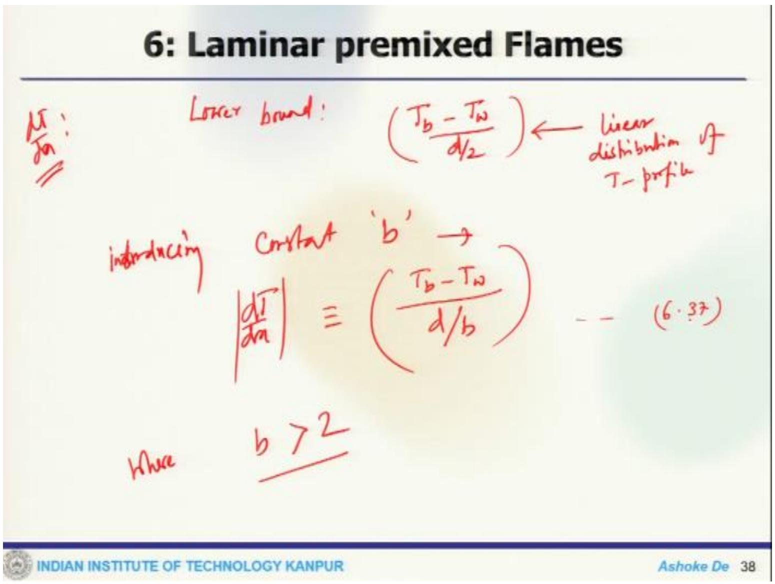

Now, that temperature variant is not straightforward to evaluate that. We have already seen earlier that dT/dx So, one can have a lower bound for dT/dx this evaluation of dT by dx is little tricky. So, the lower bound of that (T_b - T_w)/(d/2), that is the lower bound. So, what does it means? There is an assumption behind that and which is a linear distribution of T profile.

So, this linear distribution will give you this lower bound. Now, what may possibly happen? That your dT/dx could be higher than this or is likely to b greater than this one. So, we are introducing constant b which is defined as:

$$\left|\frac{dT}{dx}\right| \equiv \left(\frac{T_b - T_w}{d/b}\right)$$

So, some parameter that we introduced, so that the boundedness can be maintained where b must be greater than 2. So, that means it will satisfy the lower bound and the upper bound also. Now, what we can do this is our equation number 6.37.

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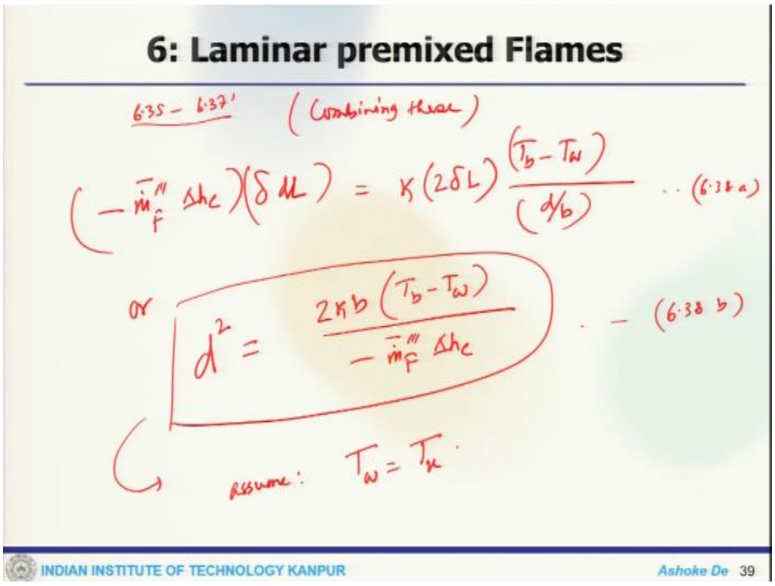

Now, we combine equation 35 to 37. So, we are combining all these what we get that:

$$\left(-\overline{\dot{m}_F'''}\Delta h_c\right)(\delta dL) = \kappa(2\delta L)\left(\frac{T_b - T_w}{d/b}\right)$$

So, this is our a or one can write:

$$d^2 = \frac{2\kappa b(T_b - T_w)}{-\overline{\dot{m}_F'''}\Delta h_c}$$

So, this is our 6.38 (b). Now, one can simplify this equation how one can simplify by, if we assume T at the wall is that $T_{unburnt}$.

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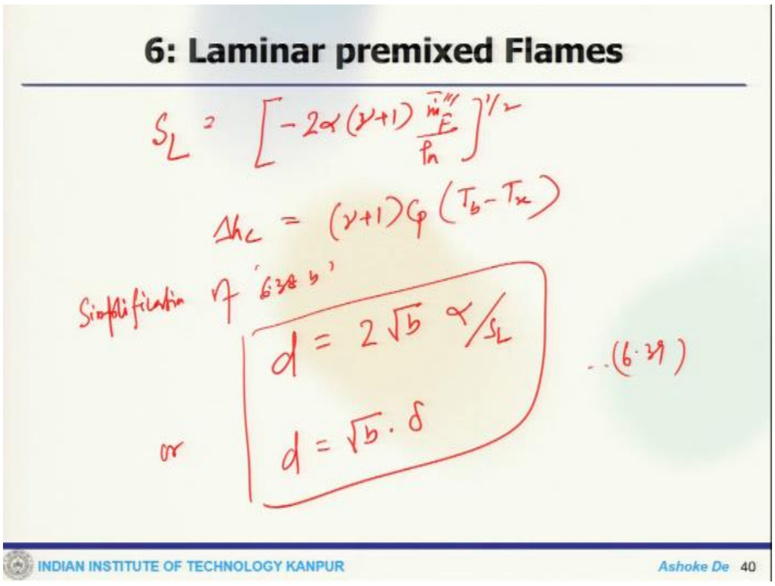

And also we can use the relationship of S_L as:

$$S_L = \left[-2\alpha(\gamma+1)\frac{\overline{\dot{m}_F'''}}{\rho_u}\right]^{1/2}$$

Where:

$$\Delta h_c = (\gamma+1)C_p(\mathrm{T}_b - \mathrm{T}_u)$$

Then we can simplify this guy 6.38 and that simplification gives me that simplification of 6.38 b which gives me:

$$d = 2\sqrt{b}\left({}^{\alpha}/_{S_L}\right)$$

Or

$$d = \sqrt{b}.\delta$$

So, this is a correlation that one can get for that quenching distance with the premixed thickness.

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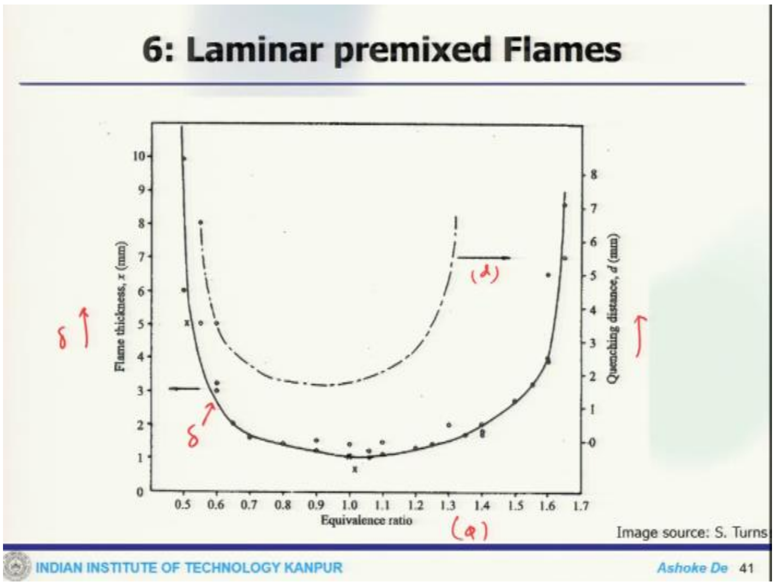

Now, if we plot that thing. This is my flame thickness that means the side is δ, this is quenching distance that is d millimeter and this side is φ. Now, there is a nice variation of the flame thickness. Now, the solid curve, this is for δ. So, one can see that, as you increase the equivalence ratio, δ comes down that means the flame thickness reduces, then slowly it again goes up with the increasing equivalence ratio. There is a similar pattern which is followed by quenching distance d, it also starts somewhere at the lower equivalence ratio and it comes down to somewhere close to the stoichiometric one minimum that again goes up. So, that is quite obvious, because d is directly proportional to δ, but with the factor b. So, the pattern of δ would be reflected in d as expected.

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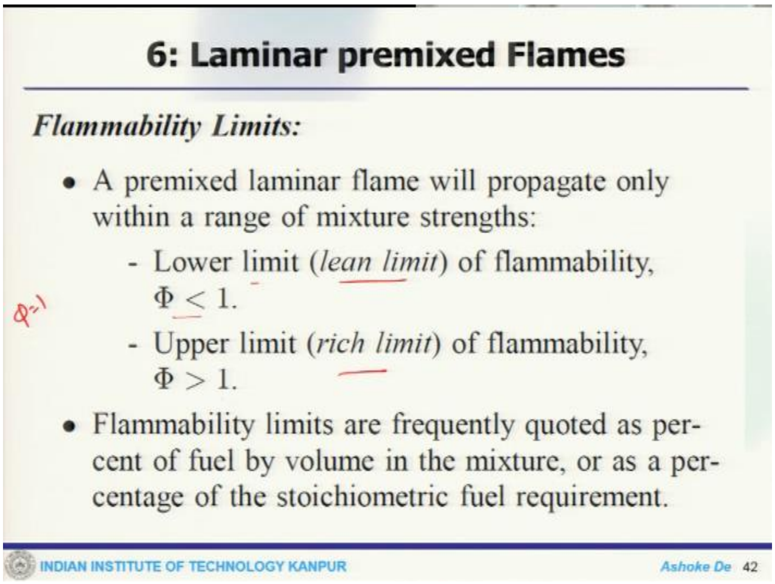

Now, we talk about the flammability limit. Now, the premixed laminar flame will propagate only within a range of mixture strength. One is the lower limit that is lean limit of flammability that means, φ is less than 1 or it will be the other side of it the upper limit or the rich limit, which is φ is greater than 1 because φ equals to 1 is stoichiometric condition. Now, this is quite frequently quoted as percent of fuel by volume in the mixture or as percentage of the stoichiometric fuel requirement.

Because then some people might talk if you go and look at these gasoline fuels in the gas station or the petrol pump or the diesel pump will see there is a limit dimension. So, these are the things that any particular fuel it has a flammability limit beyond this bound, there would be unlikely to the reaction to happen.

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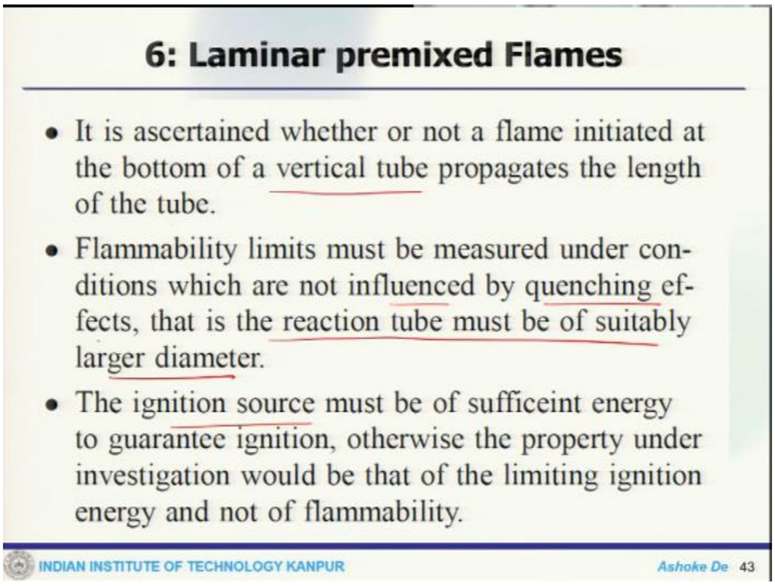

Now, it is also known that whether or not a flame initiated at the bottom of the particle tube propagate the length of the tube and flammability limit this can be measured under conditions which are not influenced by quenching effect that is the reaction tube must be of suitably larger diameter that means there is no pointing taking place then that means you are aligned to have complete flame structure and then only you can measure these limits that what is the lower bound and what is the upper bound where actually the flame extinction takes place.

Now, the ignition source must be of sufficient energy to guarantee the ignition otherwise the property under investigation would not be limiting the ignition energy.

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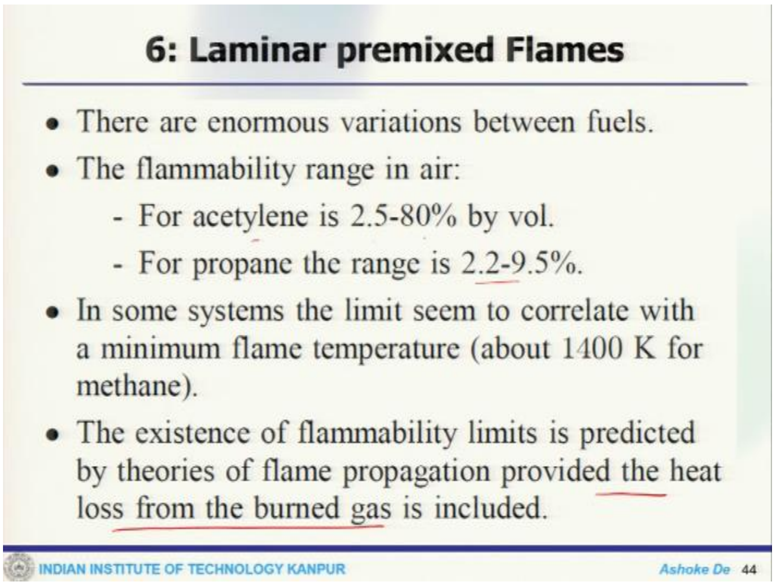

Now, there are some common terms or you can get there are huge variant of fuels which exists today and their flammability limits are also quite variable that is expected for example acetylene is 2.5 to 80% by volume. For propane, the range is 2 to 9.5%. Now, there is a sum correlation which has been observed to the flame temperature or the minimum flame temperature. Now, the important thing is that this existence of flammability limit is predicted by theories of flame propagation provided the heat loss from the burned gas is included.

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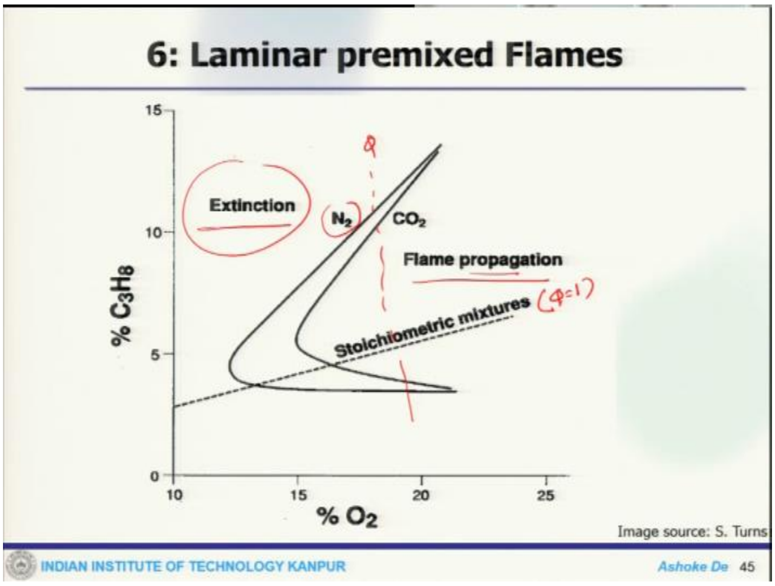

Now, similarly, one can look at this is propane and there is a representative curve for propane when it is with the percentage of oxygen. The reaction goes on what happened to that mixture. So you can see this side of the curve region, this is your nitrogen formation curve which goes like this to the percentage of oxygen and this is your stoichiometric mixtures φ 1 condition this is your CO_2 formation.

So, that means along this flame, there is a variation of φ. One can think about that is why the species will go like that. So, this side is the extinction limit that means, beyond this level or above this percentage of the propane there will be no flame or this side there is a flame propagation. So, that will determine, so every fuel one can determine this kind of limits and the boundary less which will allow you to have an idea of these flammability limits.

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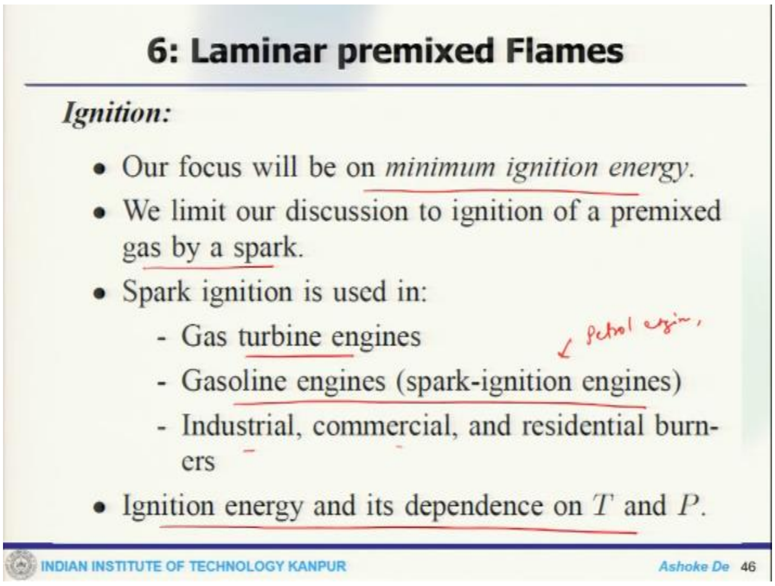

Now we will move to the third point which is ignition. So, what here we wanted to look at is that are the objective is that to on minimum ignition energy that means, what is the minimum energy that is required to move the reaction forward. So, that is what is quite important. Now we limit our discussion to the ignition of a premixed gas by spark only. And if you go to the textbook, you will find there are other methods also or other ways to do that analysis.

So, you are always welcome to go through that but will restrict so, that it will give you an idea how to get that ignition done. So, the spark ignition engine where it is used, it is in gas turbine engine it is in gasoline engine which is the spark ignition engine that means these are your petrol engine essentially, which are 2 wheelers or 4 wheelers like cars and all these things, industrial, commercial and residential burners. Now, important thing for this is the ignition energy and its dependence on the temperature and pressure there is a direct dependency.

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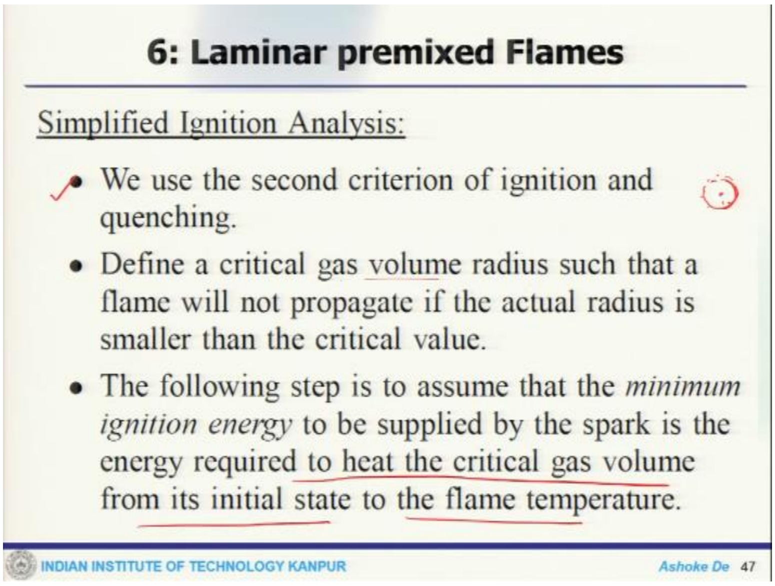

Now, how we go about the simplified ignition analysis, we use the second criteria of the ignition and quenching so, that is our first thing when we define a critical gas volume radius such that the flame will not propagate if the actual radius is smaller than the So, that means, we will define something like that there is a critical radius beyond that there will be flame temperature.

So, assume the minimum ignition need to be simplified by the spark is the energy required to heat the critical gas volume from its initial state to the flame temperature. So, that means if you issued define to gas volume idea is that what is the minimum energy the spark would be used to get the flame temperature from its initial state to get the flame temperature. So, this is how we will going to do the analysis. And we will stop here and continue the analysis in the next lecture. Thank you.