Fundamentals of Combustion

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Lecture - 39

Laminar Premixed Flames - Part 7

Premixed Flame Stability

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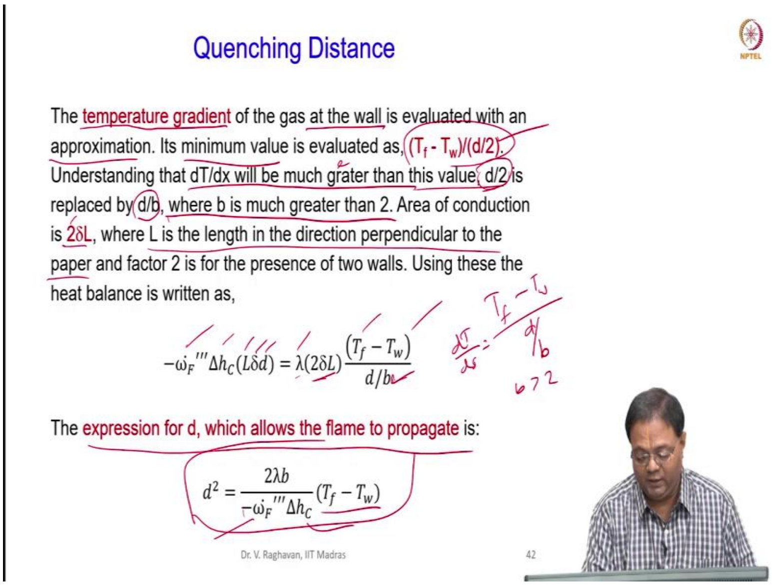

Now, what I am writing here is, the temperature gradient of the gas at the wall, so at the near the wall; the gradient is evaluated with an approximation only, because we do not know the exact profile of the temperature curve. So, that we can assume, and calculate it correctly; because numerically we are not solving this. So, the minimum value is evaluated as this, $(T_f - T_w)/(d/2)$.

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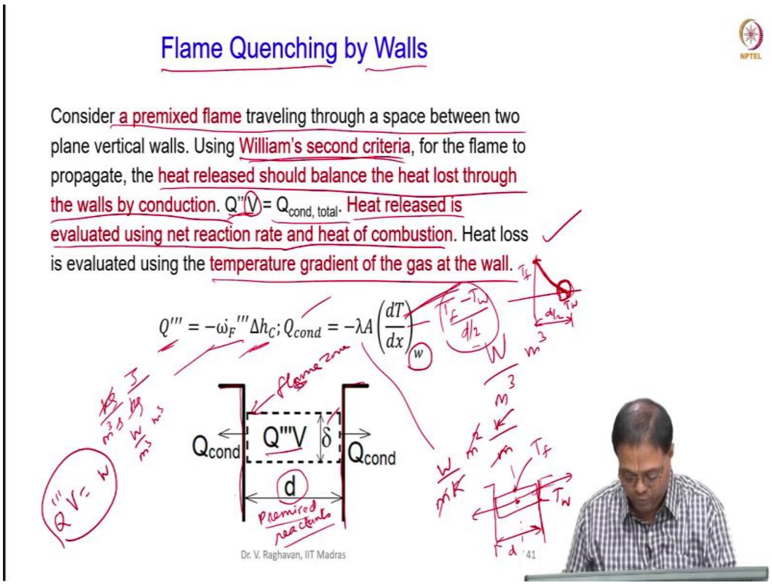

So, as I have explained in this previous slide this will be the temperature profile here and $(T_f - T_w)/(d/2)$ will be the gradient which is the minimum value. But since it is a non-linear variation, the gradient at the wall is expected to be different. So, that will be higher. So, understanding that dT/dx will be much greater than d/2. So, this is greater than d/2.

We can say d/2, we can replace by d/b, where b is greater than 2. So, we write $(T_f - T_w)/(d/b)$ so that b is greater than 2. So, that this dT/dx will be greater than what we get from this value, approximate value.

So, that is what the b I am introducing another variable which is greater than 2 so that I get the gradient properly and is some value; again we need some validation for this, we have to take some measurement or something like that and validate this. So, we have to understand that b will be much greater than 2, say 3 or 4 something like that.

The area of conduction is $2\delta L$, where L is the length in the direction perpendicular to the paper or perpendicular to the screen for example. So, 2 times that will be the area of conduction. The factor 2 comes because of two walls are present. So, the area of transaction is $\delta \times$ length perpendicular to the paper or the screen, so that will be the area on one side, both sides $2\delta L$.

Now, substituting this, you can see reaction rate $\Delta h_c V$, volume is δLd; volume of that where the heat is generated, the gases which has just burnt.

Now, right hand side; the negative sign disappears, because we are taking the absolute value of the gradient here. So, negative signs will not be there here, negative sign will not be there. So, this is the thermal conductivity, area of cross section and this is the gradient, where we have put d/b now, b >> 2.

Now, the expression for d, which allows the flame to propagate, just group d in one side. So, $d^2 = 2\lambda b / -\dot{\omega}_F'''$; this is heat released per unit volume into T_f - T_w. So, to eliminate the heat of reaction, we can put S_L or δ. Similarly, this can be replaced $(1 + s)c_p\Delta T$.

$$d^2 = \frac{2\lambda b}{-\dot{\omega}_F'''\Delta h_C}(T_f - T_w)$$

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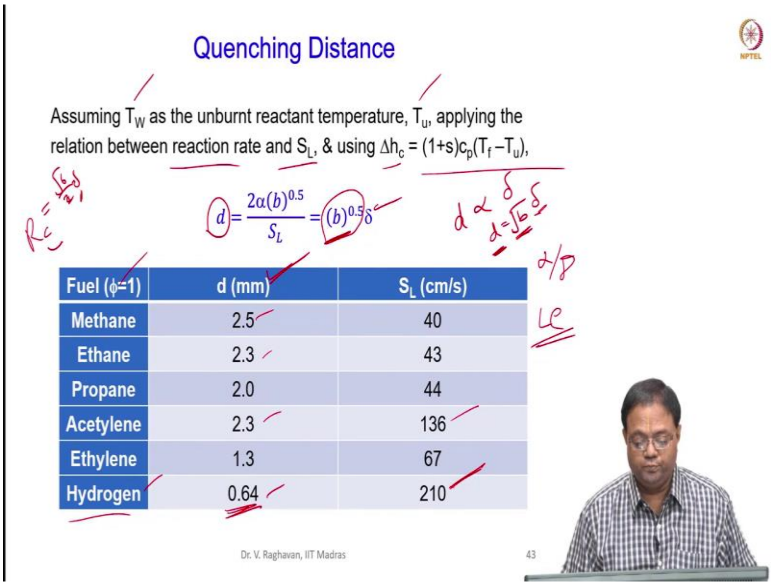

So, when you do that, same procedure. Now, one more assumption what I make is T_w, wall temperature is T_u, it is maintained at the unburnt reactant temperature and is equal to ambient temperature. So, that is the value here.

So, we can say that S_L can be used to eliminate the reaction rate and Δh_c can be eliminated by putting $(1 + s)c_p(T_f - T_u)$. Now T_w and T_u are going to be cancelled. So, we get $d = b^{0.5}\delta$.

So, d, the distance which can cause quenching, if it is less than this value then quenching happens. Or, if the dimension is greater than d, then it will allow the flame to propagate.

So, that will be some value $b^{0.5}$; this b we have already told it is much greater than 2, but we do not exactly know the value into δ which is flame thickness. So, that means, d is proportional to flame thickness; $d = \sqrt{b}\delta$ and $\sqrt{b} >> 2$.

So, we saw the same thing previously for the R_c; when I say R_c, the critical volume critical radius of ignition of the spherical volume of mixture we saw that this was $(\sqrt{6}/2)\delta$.

This is say few times, we told that R_c is few times more than del. Now, we are saying the quenching distance d is more, like much more than a few times; many times greater than

δ, because b >> 2 ok. So, that is the thing. So, this is a relationship between this. So, quenching distance will be much larger than the dimension required for the ignition.

So, some quenching distance values are given here for methane it is 2.5, ethane 2.3. So, you can see the order of millimetres for all these; but for hydrogen, quenching distance is 0.6. So, we are considering a stoichiometric mixture $\Phi = 1$ and I can see the quenching distance is very low 0.64 mm for hydrogen. So, that is the important thing, because the flame speed is very high for that.

So, the flame speed actually is very high here; but here you can see acetylene, even though flame is flame speed is higher, you can see that the quenching distance is not so high because of the other factors basically coming into play so the α etcetera.

So, the α, the Lewis number that is very important consideration; α/D. So, this is very important thing. So, you can see that why we are interested in d? Because when you want to do design of two things, one is called flame arrester.

If you do not want the flame to propagate through a particular regime from where it is formed, it would not propagate to another space; then you put a flame arrester which is a bank of these tubes of diameters less than d. When you do that, then the flame cannot travel; because it will lose the heat what it generates. So, it will quench. So, the quenching distance d is very important in two things; one is to design the flame arresters.

Another one is in some cases, we will have a pilot tube, which we can open it and close it whenever you want; this pilot tube can allow some mixture to propagate into it and the flame also will propagate along with the mixture igniting another source which is present elsewhere.

So, that is the pilot ignition tube. So, two applications are there for this; but anyway this is a very important property for this which we have to understand.

So, in the ignition part, here there is a critical dimension called R_c which will allow us to ignite using external source with a minimum ignition energy, at least some value of ignition energy

And in this case, quenching distance which is much larger than the flame thickness that will be important for designing the flame arresters and pilot tubes.

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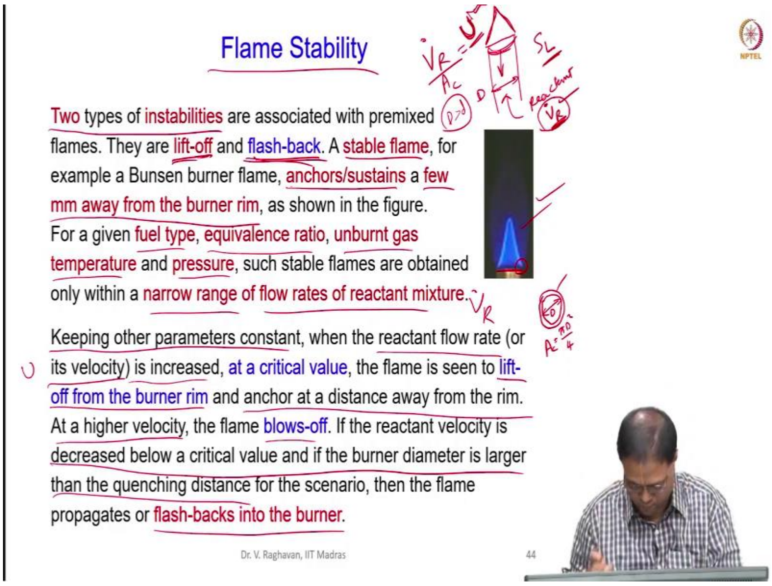


Now, the last topic what we are going to cover here is called flame stability.

So, in this case you can see that, I have put a Bunsen burners flame photograph here and you can see that the burner exit is here; burner exit is here and you can see the flame is at almost attached to the burner rim. So, if you see the top portion, the burner rim will look something like this, top view and this is called burner rim.

And in the front view you can see this burner rim is highlighted here and the flame is slightly away from this burner rim; it will not touch the rim, because it will lose its heat and radicals to the walls.

So, it means say, a few mm, 1 mm or 1.5 mm away from this it will anchor. So, this is called flame anchoring; flame anchors in this rim some few millimetres say 1, 1.5 millimetres away from that and it will anchor there.

And when you steadily supply the reactants and the flame does not change its shape; then we can say a steady flame or a stable flame is established. So, this is the important criteria here. In the Bunsen burner what we do is, we supply reactants and flame is formed.

And this flame basically anchors a few mm away from the rim, which is shown here, top view. And if your reactants are fed at the steady state, then the flame which is seen, does not change its shape or oscillate or anything; then we can say a stable flame is established. So, now, the reactant flow rate, I will say volumetric flow rate of the reactants if you increase, so, that is a small range of this volumetric flow of reactants, a small range, where we can establish stable flames. If you cross these limits or the range, so go lower than the lower limit of this or higher than the higher limit of this; then we will see two types of instabilities in the premixed flames.

In the premixed flames, we will see two types of instabilities; one is called lift off, that means volumetric flow rate there is a small range, only a small range of volumetric flow rate $\dot{V}_R$. So, the reactants are there; this volumetric flow rate will allow us to establish a stable flame in a small range of this flow rate.

When you increase the flow rate beyond the maximum value of this range then the flame will not be able to sit here very near to the rim, as we have seen in the stable flame case and it lifts off from the rim, burner rim. So, that is one of the instabilities which we will see, called lift off.

And when you increase the velocity or the volumetric flow rate further; then the flame will blow off that is the flame extinguish. This is convective extinction, because you are increasing the convection here. And what happens is, here basically when you say $\dot{V}_R$ /A_s, area of cross section of the burner.

This is the say diameter, area of cross section is πD^2/4. Now, this area of cross section, if you divide this, you get the unburnt mixture velocity U, average velocity. So, this velocity and the for the flame, there is a laminar flame speed; this locally, the unburnt gas velocity U and the laminar flame speed S_L should match.

Now, when you increase $\dot{V}_R$, you are increasing U; but S_L is not going to change, because S_L depends only on α and reaction rate, reaction rate depends on Φ. And we are not going to change anything else, only the velocity is changed now. So, what happens is, the U is going to be higher than S_L; so the flame will not anchor at the same position, it will lift off.

On the other hand, when $\dot{V}_R$, the volumetric flow rate is decreased in the range where we have a stable flame, if the V_R is reduced below the minimum value of the range, then we encounter what is called flashback. This flashback basically is the phenomena where, see in this tube the reactants are supplied; when you decrease this $\dot{V}_R$, the flame will try to propagate down the tube itself.

Provided the diameter of this tube is greater than the quenching distance d, or else this will not allow the flame to propagate, do you understand now. So, when the $\dot{V}_R$ is reduced to a value, so that U decreases; when U decreases well below the S_L value, then what happens? The flame will propagate down, because it is not going to wait for the reactants to reach it; it will try to come down consuming the reactants. When it does that, this process is called flashback, it is flashing backwards; instead of staying at the burner rim or at the exit of the burner. It is trying to flash back down.

The criteria is U should be less than S_L locally plus the diameter of the tube should be greater than the quenching distance; these are the two important instabilities which we encounter in the premix reactants. Now, a stable flame as I told here, anchors or sustains a few millimetres away from the burner rim as I told you; because if it is very close to the burner rim, it will lose its heat to the wall and also it will lose radicals to the wall, so that it may not establish itself there.

Now, for a given fuel type, then the equivalence ratio, unburnt gas temperature and pressure, stable flames can be obtained; but the flow rate of the reactants that is $\dot{V}_R$ is in a narrow range, very small range of flow rates you can accomplish this, stable flames, but after that we cannot do.

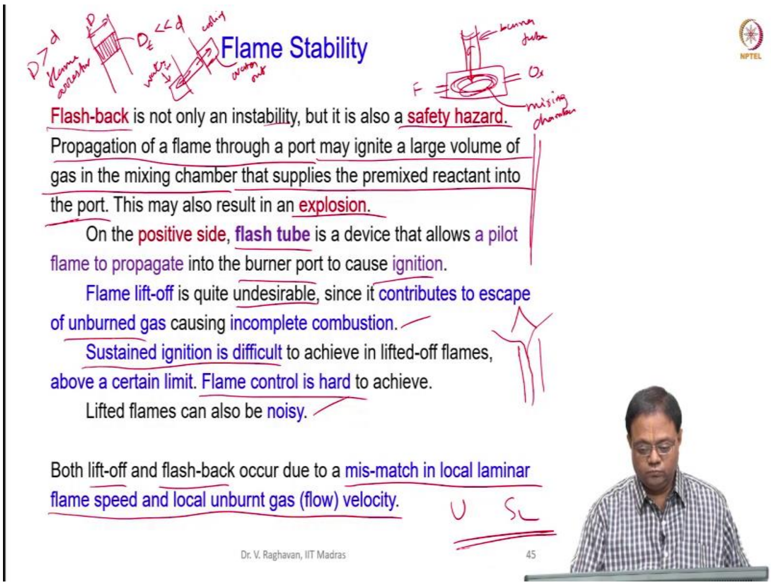
So, for a given burner diameter basically, when other things are fixed; fuel type is fixed, equivalence ratio is fixed, unburnt temperature is fixed, etcetera. Then only in a certain range of flow, we can establish stable flames which will not change its shape or anything for the given steady flow of the reactant.

Now, keeping other parameters as constant, but the reactant flow rate is associate with the U value or its velocity U is increased. At a critical value, the flame is seen to lift off from the burner rim; as I explained you now, because of the U, the unburnt reactant velocity is higher than the flame speed now.

So, it is trying to push the flame away and the flame will go away from the burner rim and anchor at some distance, where there is a match of the local unburnt velocity U and the flame speed S_L. At a higher velocity, the flame will blow off; because it cannot have any match anywhere and also atmospheric interference will be higher, so the flame will blow off.

On the other hand, the reverse of that, when the reactants velocity is decreased below a critical value and the burner diameter; there are two conditions, burner diameter is larger than the quenching distance. So, D should be greater than small d which we just now saw, so quenching distance; then the flame can flash back into the burner.

So, these are the two instabilities, which is primarily due to the values of U, the unburnt, average unburnt reactant velocity and the laminar flame speed for the given condition. (Refer Slide Time: 17:04)



Now, flashback is dangerous, because it is not only an instability; this is a safety hazard.

For example, normally what I do is, I take a chamber, mixing chamber like this. So, I supply fuel and supply oxygen, oxidizer in this and there will be a burner, this is the burner tube and this is the mixing chamber.

Now, when they are mixed here. The reactants are thoroughly mixed here and they are supplied into this. Now, if a flame comes down it will see a large volume of the reactants in the mixing chamber and instantaneously it will ignite it; the flame coming down will ignite it. So, it is a safety problem.

Propagation of a flame through a port or a burner may ignite a large volume of the gas in the mixing chamber that supplies the premix reactant to the port. So, unless if you do not provide any flame arrester, that is what we call flame arrester; if you put the bank of tube where the diameter of each tube is less than the quenching distance, the flame cannot propagate beyond that value or you increase the heat loss.

So, what you do is, there is a port or the burner rim; now you put some bank of tubes here, bank of tubes. This bank of tubes will have diameters less than the quenching distance. This diameter D may be greater than the quenching distance. But the diameter of each tube here, I will say D_{tube} will be lesser, much lesser than d. So, it will not allow the flame to propagate or we have to actually cool this.

So, supply water and cool this. So, this point is cooled now. So, flame coming to this point will lose more heat and it will quench. So, either you have to put some cooling device or you have to put some bank of tubes to arrest the flame propagating down this. So, it is a safety hazard basically, the flashback.

But in any burner or combustion chamber where you have burners this type of instability can happen. So, we have to anyway go for the flame arrester; this is the flame arrester or cooling, cooling of the burner tube, so that it will not allow the flame to propagate down.

So, if we do not provide any of this, the flashback occurs, then it may ignite the large volume of premixed reactant in the mixing chamber that may cause rapid combustion and explosion. As I told you, this is one of the applications. This flame arrester for calculating quenching distance, I said that flame arrester can be designed using that.

Another one is the flash tube; flash tube is the device where you allow the premix reactants to flow through this and the flame can propagate through this into the burner port to cause ignition.

In a big domestic cooking thing etcetera; ignition can be achieved by igniting a small flash tube, which will ignite that and the flame will propagate and ignite the real combustor. So, the flashback is a dangerous instability.

Lift off is also an instability, but it is not dangerous; because it is going to only quench the flame. But it is undesirable why? Because once you do not notice the lift off and eventually it blows off; then unburnt gas will leave to the atmosphere.

It can also cause incomplete combustion in several scenarios when lifted flame cannot burn properly. Now, you cannot sustain ignition when the flame is lifted; when the flame is anchored very close to the burner rim, subsequent preheating of the reactants and continuous combustion can be easier.

However, if the flame is lifted off, see flame is now standing away; this comes in and this can diffuse away, the reactant can diffuse away and may not be properly pre heated. So, to sustain an ignition itself is a challenge in the lifted flame.

So, lifted flame will contribute to blow off and it can contribute to incomplete combustion, escape of unburnt reactant gases, reactant gas; then it can also provide difficulty in igniting the incoming mixture.

Flame control is very hard; when you want to operate in lifted flame, it is very hard to control lifted frames. They are noisy, it will produce some buffing sound. So, these were the instability problems and we need to avoid instability.

Normally when you design a burner, the burner has to be tested for the range of flow rates in which it can be operated in a stable manner. But as I told you, these lift off or flashback both are due to mismatch of local laminar flame speed with the unburnt velocity. Say mismatch in the local values of U and S_L will cause this.

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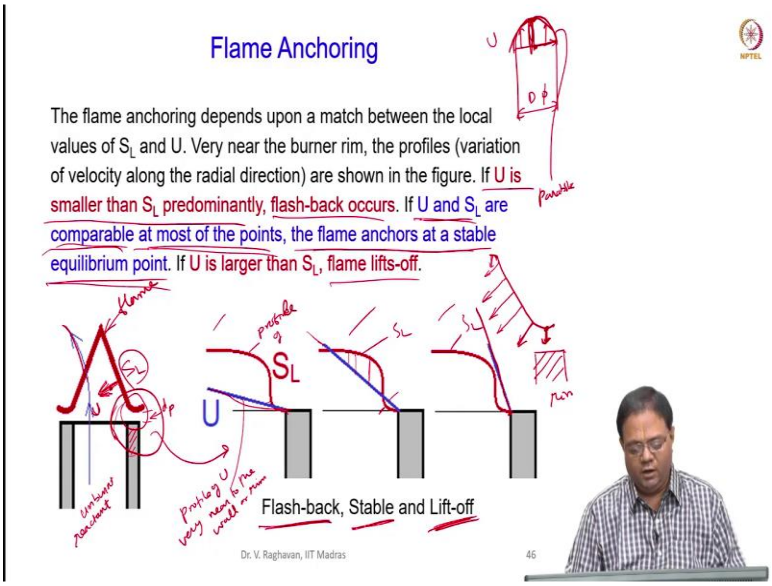

Let us try to explain this more. So, you can see this is the premixed flame; as I told you some mm, I have exaggerated this, some millimetres its away. So, this is the distance I will say d_p, where some gap is produced; then after that the flame anchors.

Now, when you take the flame surface, perpendicular to the surface you get the value of S_L; the flame will propagate in the perpendicular direction of it, so the value of the flame speed is perpendicular to this. When you draw this, unburnt reactant is coming in through this and it changes the direction and goes almost perpendicular to the flame and goes out. So, this has a component U.

So, this has a velocity U here. So, based upon the local value of U at any point if you take, based on a local value U and the S_L, which is higher, it should be almost the same but in the major area it should be almost the same. If it is not same, then this type of instability will occur. If $U << S_L$, flash back occurs; if $U > S_L$, lift off occurs and so on.

So, to analyze this, what we try to do is, we concentrate our focus on a very small area, very near to the burner rim. So, this is the burner rim, burner rim; very near to the burner rim let us focus our attention and draw some scenarios. Now, for a given mixture, the laminar flame speed; see please understand one more thing, this is the flame.

The laminar flame speed is not constant. So, let us take this; this is the flame, this is the rim and this is the flame. Now, laminar flame speed in this here, it will be low here anyway because of the heat loss to the walls, radical losses to the walls, the laminar flame speed will be low here. Now, it increases basically.

Then it decreases to a constant value, it will remain constant for some time then it again decreases, towards this top it decreases. So, it is not uniform; the S_L value along the flame is not uniform. So, this is the profile of S_L.

So, near the wall it is very low and it increases and becomes almost constant for some time; then it goes and decreases. Please understand I am focusing my attention only to a small distance from the rim, this is what I am drawing here.

So, within a small distance, you can see there is an increase in the S_L and remains constant. So, that is the profile of S_L. When I plot the S_L as a function of the distance from the rim towards the center of the burner; then it increases slowly and sharply and you know remains constant. And it continues for sometimes, then again decreases towards the other wall. Now, this is the profile of S_L.

So, this profile of S_L is drawn here. For a given reactant, this will be the profile of S_L; but now let us try to perturb, perturb the scenario. For example, if the value of U; U how it varies? In a pipe for example, circular pipe, say diameter D, D is the diameter. Now, you know that, for a fully developed flow, you will get a parabolic profile like this.

So, this will be the profile of U, that is how U varies along the radius or the diameter. So, this is the radius. Now, when you go near to the rim like this; I can approximate this parabolic profile, this is a parabolic profile. So, this profile is parabolic when I go near to the wall, very near to the wall, this parabolic profile can be taken as a linear profile.

So, that is what this line represents. So, this is the profile of U very near to the wall or rim, the burner rim. It goes to 0 value at the wall and it increases to a maximum value at the center and again decreases. So, this is the way. So, near to the burner rim, we can assume linear variation.

Now, first scenario is flashback; why? Obviously, S_L locally if we take any point in this any line if we draw; S_L is predominantly higher than U. So, see, why I am only concentrating on this portion near to the rim? Because there only the flame anchors; this is the flame anchoring point.

So, I have to focus only my attention near to the flame anchoring point and see whether the flame will anchor or not. So, just slightly away from this, you can see that there is a large difference between U and S_L so that the flame will try to come down only, it will not be able to anchor above the burner. So, flashback will occur.

If this is a stable case, you can see that locally here the S_L may be slightly less than; in this case, S_L is slightly less than this U, but here you can see that S_L is actually higher than this. Then after this point, again you can see this S_L is lower than this. So, predominantly you will see there is a match between the S_L and Q. So, this will produce a stable flame.

On the other hand, in this case, the third case, U is always higher. So, it will not allow the flame to anchor in this position, the flame is lifted off. So, this is the lift off thing. So, it is only a local mismatch between the U value and S_L value, which will allow the flame to be stable or it will flash back or it will lift off.

So, if U is smaller than S_L predominantly; please understand it is only small area where it should be, then flash back occurs. If U and S_L are comparable like this, then almost at most of the points, the flame anchors as a stable equilibrium point.

So, I am interested only in the anchoring region. See in the central portion, it is fine, that is not a problem. So, that is the way. Since the profile of velocity is higher at the center of this tube; the flame is actually taking the conical shape because of that. If the velocity is almost uniform, then you get a flat flame. Already we have seen that.

Since this profile is non-uniform for the U, the flame also behaves like this. Then if U and S_L are comparable, mainly at all the points or almost at all the points then a flame is stable now, it anchors at a stable position.

So, that stable position is also called equilibrium point. Then if U is larger than S_L in the third case, then flame lifts off, because the local mismatch is heavy there. So, this is the important thing we should understand. The instability of the premixed flame is due to mismatch between the U and S_L.