Advanced Thermodynamics and Combustion
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Module - VIII
Combustion and Flames
Lecture - 29
Laminar Premixed Flame (Part II)

Dear learner’s greetings from IIT Guwahati. I welcome you all to this course Advanced Thermodynamics and Combustions. We are in the module 8 that is Combustion and Flames.

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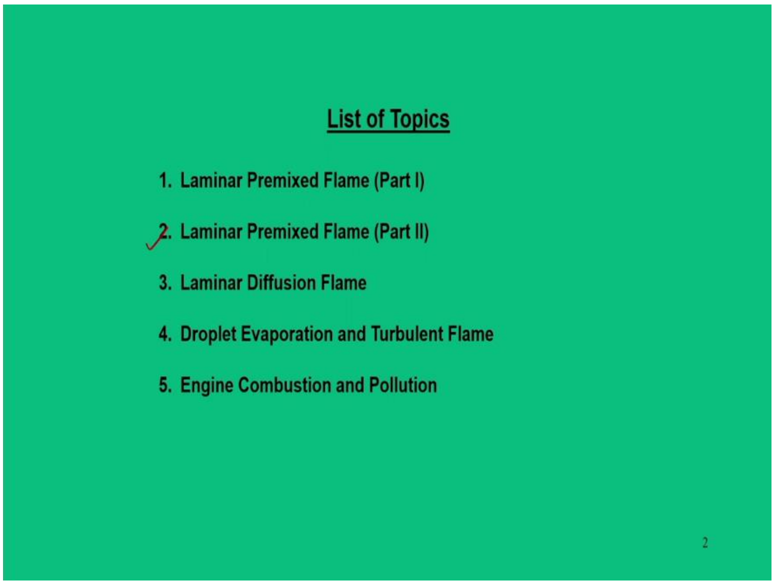

In the first lecture of this module, we were discussing about laminar premixed flame part I. Today we will move on some important aspects of laminar premixed flame part II.

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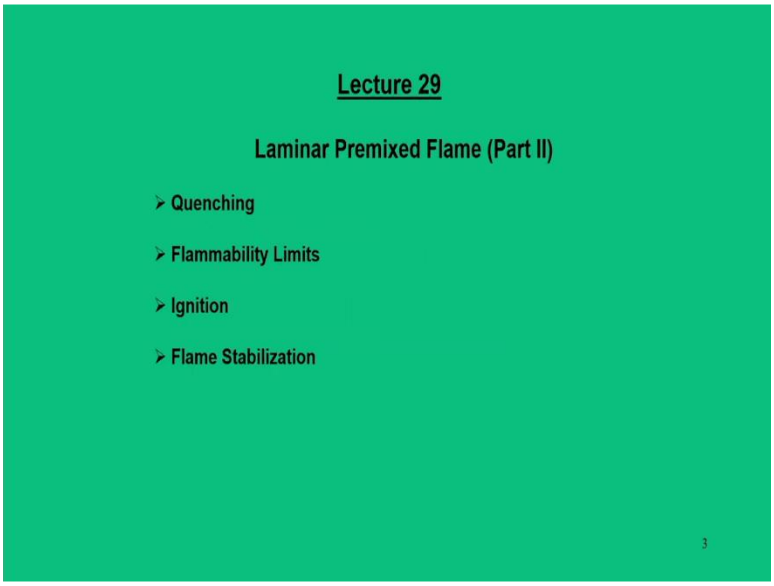

And in this lecture that is lecture number 29, we will be discussing about important aspects like quenching, flammability limit, ignition and flame stabilizations. So, ideally the viewpoint of this lecture is that we expect the flame to be self sustain; that means, the flame whose thickness is very small and it carries forward the mass and fuel reactions further, if it has to be self-sustained so that we can use it for a variety of applications. Other aspect is that we should not be in a position that the flame should not create any kind of hazardous situations. So, explosion is one such situations, in some cases flame travels much faster.

So, to control those conditions we also expect or we also should know what is quenching means we should design our burners in such a way that flame should move forward, it should not come backward. So, there is a parameter called as quenching distance.

Second thing is that flammability limit. So, we should know that for a given fuel air mixtures what is range of equivalence ratio; that means, minimum which is in the lean range, or maximum which is in the rich range during which flame is able to sustain. So, we should know the flammability limit.

Third point is ignitions. So, ignition is another aspect that if you have fuel and air and without some kind of ignition that means, we are not adding enough energy to the fuel for its combustion to happen. So, ignition required to ignite the fuel and air mixtures. So, after knowing all these things we also should expect that flame should be in a stabilized mode.

That means, you should make use of this flame or combustion applications unless you are very sure about the stabilization of the flame which means that it will give hazard free operations. So, let us discuss them one by one.

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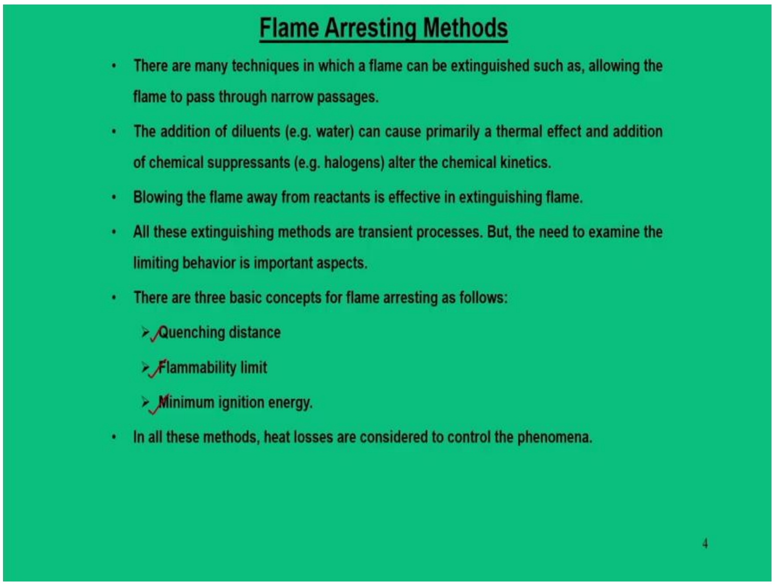

So, first thing that we are going to discuss is that flame arresting methods which means is that we should know that under what circumstances the flame should not propagate further. So, these are the conditions if you know then probably it is possible for us to design suitable burners and to avoid dangerous situations such as explosions. So, if you know you can arrest the flame then we can extinguish the flame as and when it is required. So, there are many techniques in which flame can be extinguished.

While the flame enters in a narrow passage; that means, fuel and air mixture I mean they do not have in sufficient quantity, if they are unable to pass then the flame terminates then and there. In other cases, like addition of diluents like if you add water into fire then the fire stops. So, which means that addition of diluents can cause the primarily thermal effect and also the addition of suppressants like halogens and all which alters the chemical kinetics.

So, all these things we can add chemicals to the flame so that we can extinguish the flame. Other way is that simply if you blowing away the reactants is another method of extinguishing the flame and in fact, all these extinguishing methods are transient methods, but we need to examine their behaviors. So, to do that we needed to know the 3 basic concepts: first is quenching distance, second is flammability limit, third is minimum ignition energy.

So, these three parameters are very vital to have two dual purposes. First thing we should avoid dangerous situations if you know how to extinguish the flame. Other way is that if you know how to extinguish the flame, also we should be able to create an environment for flame stabilizations. So, for both the scenario these concepts are very important.

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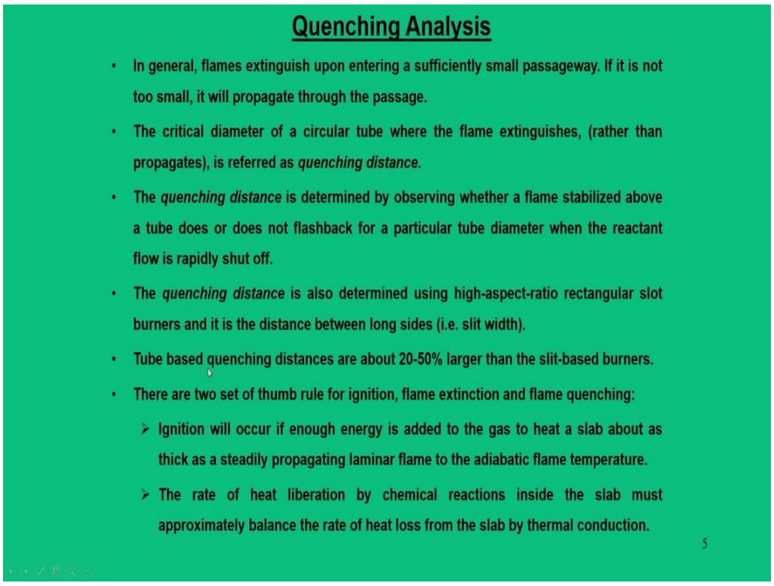

So, let us start the first thing which is called as quenching analysis. So, the first parameter of flame extinguishing is the quenching. So, in general flames extinguish upon entering sufficiently small passage way and if it is not too small the flame will propagate further.

If it is not too small means; that means, the flame has sufficient strength to move further or the air front fuel mixture has sufficient strength or pressure to move further. Now, when you look at these flames in basically in two types of burner; one is slot burners which is nothing but a square or rectangular cross sections, other conventional way is that circular tube burners. So, if you stick to the circular tube, the critical diameter of the tube where the flame extinguishes rather than propagates is known as quenching distance.

So, basically quenching distance you define the diameter of the circular tube where the flame extinguishes; that means, that is the minimum diameter of the tube that should be there. So, that flame should extinguish. I will talk about more importance of this why we call it extinguishes since at later point of the slides. Then based on this quenching distance, we can determine whether the flame is stabilized above the tube or does not flash back.

So, it means why it is important. By this quenching distance you can make a visualization that flame should propagate, you should not traverse back through the tube because when it traverse back it can come back to the a location where the fuel air mixture or source of the fuel is there. So, this will create a kind of explosion that is the reasons we expect that flame should not flash back for a particular tube diameter when the reactant flow is completely shut off.

Then the quenching distance is also determined for high–aspect-ratio slot burners, when you say slot burner it is a rectangular and it is the largest distance or longest distance that is the slit width that decides the quenching distance. If you actually compare tube based burners and slot based burners, tube based burners have quenching distance larger than the slit based burners.

So, these are some fundamental aspects of quenching, but with respect to view point of combustions what is the thumb rule for ignitions. So, there are two set of thumb rules for ignitions, flame extinction and flame quenching. First one is ignition will occur if enough energy is added to the gas to heat a slab about as thick as a steadily propagating laminar flame to adiabatic flame temperature.

So, basically adiabatic flame temperature is the ultimate or maximum temperature that you can achieve for a given air fuel ratio; that means, we should give sufficient amount of energy during the ignition process. So, that flame while propagating it should reach the adiabatic flame temperatures. Other aspect of thumb rule is that the rate of heat liberation by the chemical reactions inside the slab must approximately balance the heat loss from the slab by thermal conductions.

So, the heat that generated in the flame zone has to be taken back through thermal conductions by the slab. Slab in this case is the diameter or thickness of the tube other case slab means it will the thickness of the slot burner.

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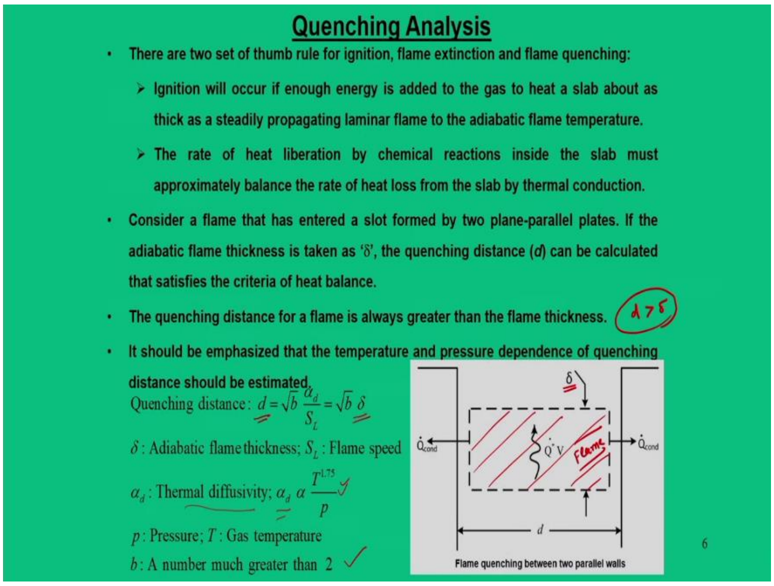

So, with this concept let us give some mathematical insight into the quenching distance. So, what we consider here? If you refer to this figure, we are looking at a flame that enters to the slot of diameter d and this flame has thickness δ. So, this we say is a flame, now within this flame if you see this is the entire volume in which the flame is being produced.

And entire energy which gets generated within this volume has to be dissipated through the slab or to the walls of the slab through conduction. Then, what we can define is that if the adiabatic flame thickness; that means, when the flame has reached maximum temperatures it is defined as δ and the quenching distance d can be calculated that satisfies the criteria of heat balance.

And this quenching distance of the flame is always greater than the flame thickness. So, quenching distance which is d has to be always greater than δ. It is a first criteria. It should be emphasized that the flame also have dependence on pressure and temperatures.

So, I am not going to the mathematical details of these analysis, but what the end results that we are going to get out of it is that by making a heat balance that is heat generated within the flame which is being lost through the walls through conductions by doing so we are able to find the quenching distance $d = \sqrt{b}\frac{\alpha_d}{S_L} = \sqrt{b}\delta\delta$.

So, α_d which is called as thermal diffusivity and with respect to this flame point of view this $\alpha_d \alpha \frac{T^{1.75}}{p}$. So, this is just an experimental observations, which we have elaborated in our last lecture about the dependence of thermal diffusivity with respect to temperature and pressure or in other words flame speed with respect to pressure and temperatures.

And b is generally a number which is always greater than 2. P and T is the pressure and gas temperature. So, based on this we can say that d is always greater than δ and also the d is proportional to the flame speed. This particular expression is very vital in designing the size of the burner tube.

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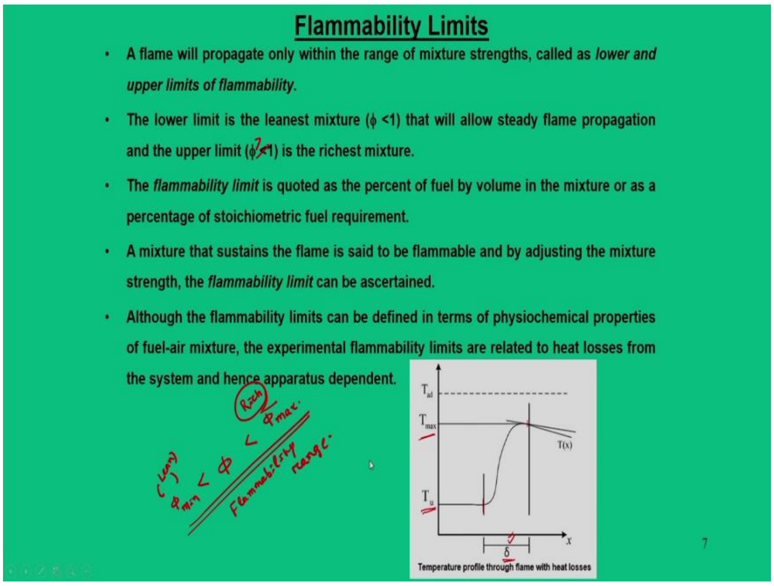

The next aspect that we are going to discuss about is the flammability limit. So, we know that a mixture is rich or lean and that is decided by the equivalence ratio ϕ. So, equivalence ratio decides whether the mixer is rich or lean. We also should know that during this rich or lean mixture what is the range within which we can have a self sustained flame and that parameter is called as a flammability.

So, for example, if I say ϕ is the equivalence ratio, then we call $\phi_{min} < \phi < \phi_{max}$ as the flammability range. And most important thing is that this minimum range falls in the lean zone and maximum limit falls in the rich zone.

So, for a given air fuel ratio or given equivalence ratio or given air and fuel combinations we have a flammability range by which we can decide whether we can have a self sustained flame or not and that range we call as a flammability limit. See lower limit phi less than 0 allows the steady flow propagations, upper limit is phi greater than 1 is the richest mixture. The flammability limit is quoted by the percentage of fuel by volume in the mixture or percentage of stoichiometric fuel requirement.

So, the mixture that sustains the flame is said to be flammable and by adjusting the mixture strength flammability limit can be ascertained. Now, although the flammability limit can be defined in terms of physiochemical properties of fuel-air mixtures the experimental flammability limits are related to heat loss from this system and hence apparatus dependent.

So, this particular figure talks about the temperature profile through heat loss. So, what happens is that when we are talking about adiabatic flame temperatures it all depends a mathematical estimation which remains constant irrespective of x, but actually within the flame we do not reach to this point.

If you look at this particular point is that when Tu is your unburned mixture temperatures and after the combustion happens it reaches to the maximum temperature which is called a Tmax. Now, after this point it is generally desired that entire energy has to be lost through the conduction through the thickness of the tube and after that the temperature is going to start down. And this delta is nothing but the flame thickness that remains; that means, starting from the unburnt temperature to the maximum temperature we define this flame thickness delta.

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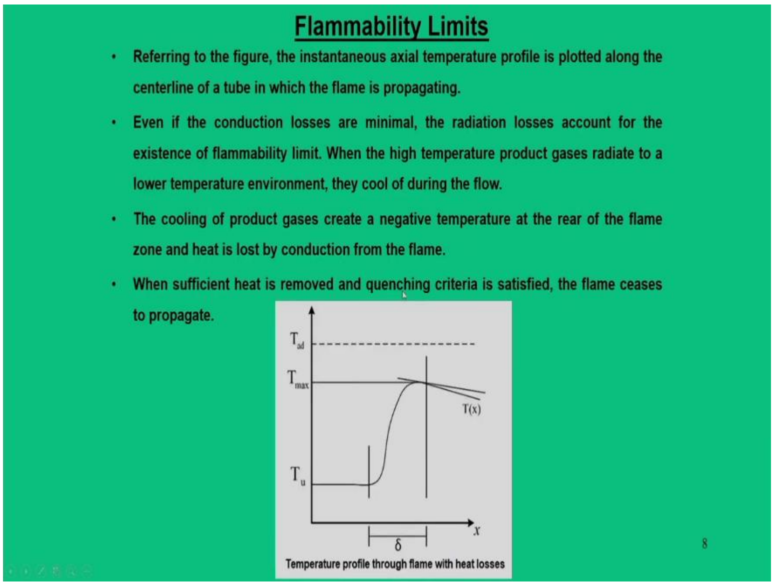

Now, after this we can clearly see there is a drop in the temperatures and that drop is mainly due to the issues that heat is lost by conductions from the flame. So, the cooling product gas create a negative temperature at the rear of the flame zones which means that heat is lost from this flame. When sufficient heat is removed the quenching criteria is satisfied. So, flame chooses to propagate; that means flame does not move further.

That means if more and more heat is taken away from this flame, the flame does not have a strength to propagate further. So, it extinguishes. So, the flammability limit decides what maximum temperature the flame can attain. At the same time whether a sustained flame can remain or not.

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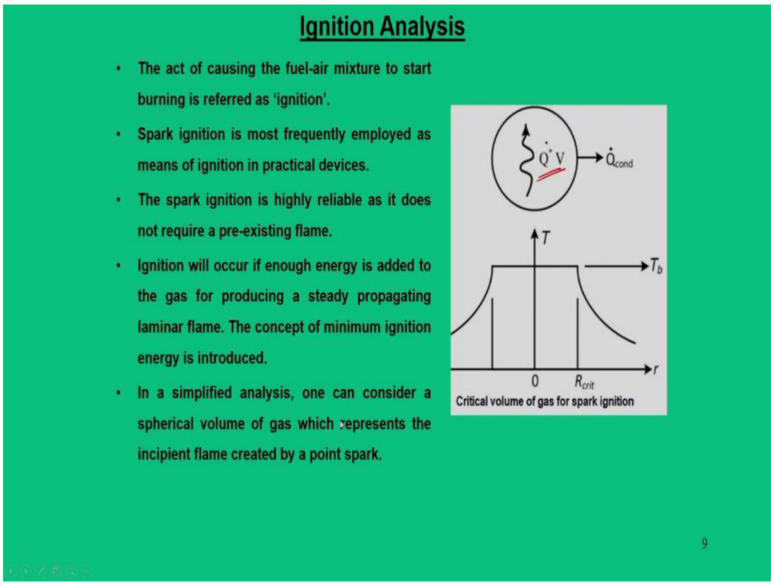

Next important topic of discussion is the ignition. So, the act of causing fuel and air mixture to start burning is referred as the ignition and in particular we normally refer with respect to spark. We know that in a engine spark ignition engines that is a spark plug through which we ignite the fuel.

So, this ignition is impulsive in nature. All of a sudden or instantly within this very small period of time we dump enough energy to the fuel so that it can ignite. Now, when the ignition takes place and this ignition takes place, we say that we have added enough energy to the gas for producing a steady propagating laminar flame. Because of this reason we introduced the concept of minimum ignition energy.

So, in a simplified analysis what we consider a particular situation where we are looking at a spherical flame within which we generate certain amount of energy and that energy has to be taken away what we call as Q conductions.

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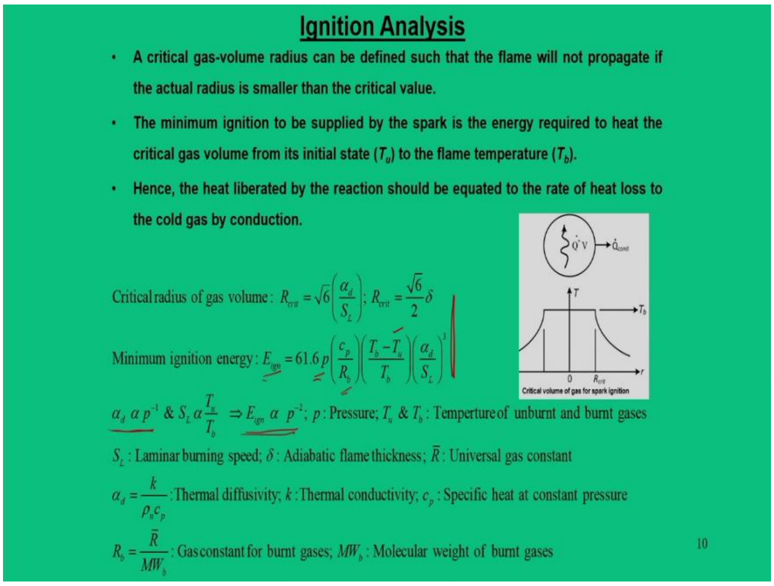

So, what we are looking at is that by creating this spark whether we are able to give sufficient energy or not. So, to do that we can find a critical gas volume radius which can be defined such that, flame will propagate if actual radius is smaller than the critical value. So, in other words; that means, for a flame propagating situation; that means, it has enough energy in it so, that it can propagate further and at the same time there is a heat loss from the flame through the conductions.

So, a balancing approach is to find a critical volume radius at which the flame will not propagate further. So, that analysis gives us the amount of energy and we call this as a minimum ignition energy which needs to be supplied by the spark and which is required to heat the critical volume of the gas from its initial temperature Tu to the flame temperature Tb.

So, we can define this minimum ignition energy expressions. So, there are mathematical treatments which are available in the book, but what I have taken here is the end results. So, for a spherical gas volume we are going to find out the critical radius for the gas volume and that critical radius is a function of the α, diffusivity, flame speed or in other words a critical radius is expressed in terms of flame thickness.

And based on this, we also have expressions for minimum ignition energy which is given by these expressions $E_{ign} = 61.6p\left(\frac{c_p}{R_b}\right)\left(\frac{T_b - T_u}{T_b}\right)\left(\frac{\alpha_d}{S_L}\right)^3$. So, here the important thing that we need to be noted is that these are the theoretical derived expressions, but what the experimental observations what we see is that the dependence of pressure and temperatures.

And here we have two temperatures; one is burnt gas temperature Tb and u stands for unburnt gas temperatures and S_L stands for flame speed, α_d is the thermal diffusivity which is dependent on the ratio of $\frac{k}{\rho_u c_p}$ and again we have Rb. Rb is nothing but the gas constant for the burnt gases. And that is nothing but $\frac{\bar{R}}{MW_b}$.

So, from this expressions important thing that need to be addressed is that there is a direct dependence of ignition energy with respect to pressure, but there is a indirect dependence of ignition energy with respect of α_d. If you look at the experimental observations the α_d thermal diffusivity is inversely proportional to 1 by p or inversely proportional to pressure and from this we can say that ignition energy is inversely proportional to square root of the pressures. So, the pressure is more means ignition energy is less; that means, the flame has sufficient strength to move further.

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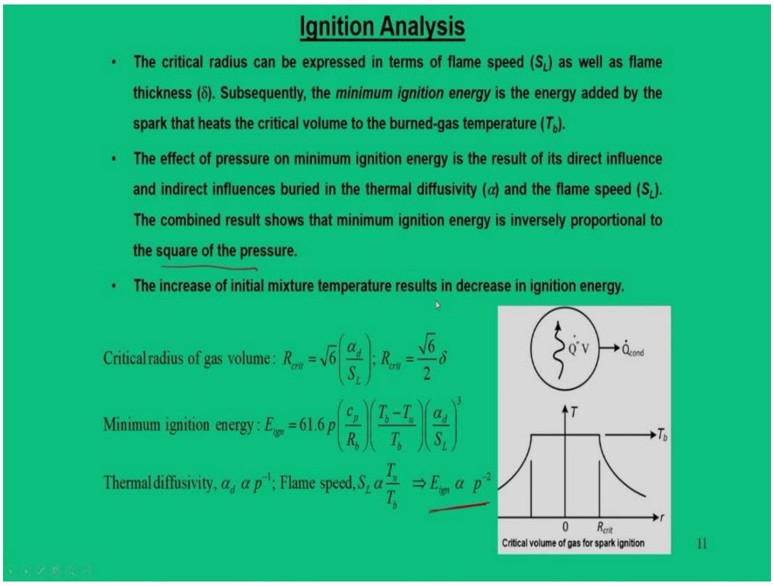

So, this gives a conclusion that we can find the critical radius and this critical radius can be expressed in terms of flame speed as well as the flame thickness delta, minimum ignition energy is the energy added by this spark that heats the critical volume to the burnt gas temperatures that is the minimum ignition energy.

The effect of pressure on minimum ignition energy is the result of direct influence and indirect influence is buried in the thermal diffusivity and the flame speed. The combined result shows that minimum ignition energy is inversely proportional to the square root of the pressures. So, this is how we get out of these expressions.

From this expression if you have increase in the mixture temperatures, it results decrease in the ignition energy; that means if your mixture temperature is higher we require less amount of ignition energy.

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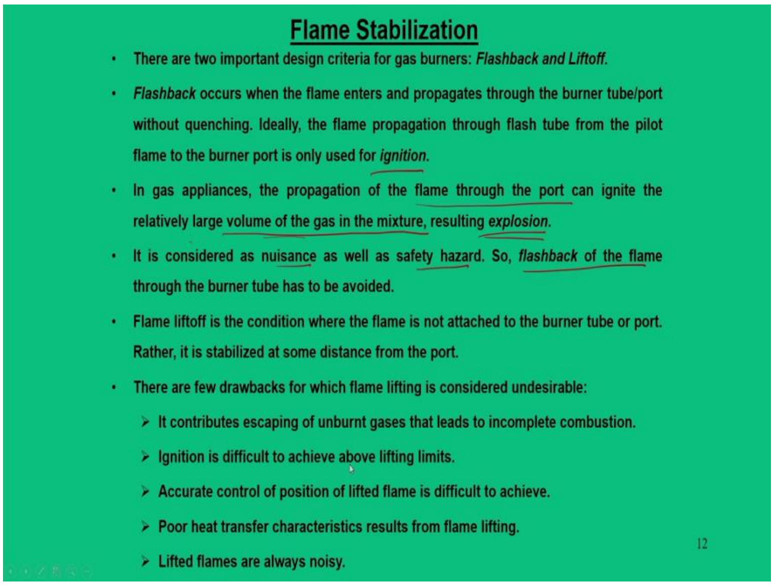

The next important aspect that we are going to discuss is the flame stabilizations. So, all these points in our all-previous discussions we mainly focused that how to arrange the flame. That means, we are more focused towards the concern of safety hazards so that explosion should not occur.

To do that we should know that within what flammable range, how much amount of energy is required and what is the quenching distance, all these parameters is required. But the other side of the story is that if you view with respect to gas burner normally cooking stoves is one such cases where the fuel comes from the cylinder through a tube and it receives air from the atmosphere, burner is in the top. So, the flame starts burning.

Two important design criteria for any kind of gas burner is that flash back and lift off. Flash back means that once the gas is released from the fuel source that is from the cylinder through the tube, it should travel further and when it reaches to the burner and suddenly if the fuel supply is stopped, the flame which is supposed to be in the burner since the fuel supply is stopped, it tries to traverse back. But, it could not do because that burner tube has been designed that it follows the quenching criteria.

That means, flame cannot move back to the fuel source that is one aspect. So, that concept we call as flashback. Other aspect is that the flame should not get lifted up from the burners; that means, our knob or the burner knob is regulated that we can go maximum fuel supply or minimum fuel supply and that regulation will allow us that flame should not get lift up from the burner.

So, that is what we call as a lift off distance; that means, if the flame stands certain distance away from the burner we call this as a lift off. So, those two things are to be avoided. So, let us understand one by one. First one is the flashback. The flashback occurs when the flame enters and propagates through the burner tube or port without quenching.

So, ideally flame propagation through the flash tube from the pilot flame to the burner port is only used for ignitions. And the gas appliances propagation of the flame through the port can ignite relatively large volume of the gas in the mixtures, creating explosion. And in fact, this explosion created as a nuisance in terms of space safety hazards. So, the flash back for the flame through the burner tube has to be avoided.

So, the diameter of the tube is designed in such a way that flash back should not occur. Flame lift off is the conditions where the flame is not attached to the burner tube or port rather it is stabilized at some other distance from the port. There are few drawbacks for which flames lifting can be considered as undesirable. First of all, when the flame gets lift off; that means we have some gap between the flame standoff distance and the burner port, this will give us unburnt gases to get out without being getting combustion.

So, it will give incompletely combustions. Again, ignition is difficult to achieve above this lifting limit. So, considering this we need to control the actual position of the lifted flame and it is difficult to achieve and during this lift off zones poor heat transfer characteristics that can result the flame lifting. Always when we say lifted flame, they are always noisy. So, because of these reasons we expect that flame should not get lift off.

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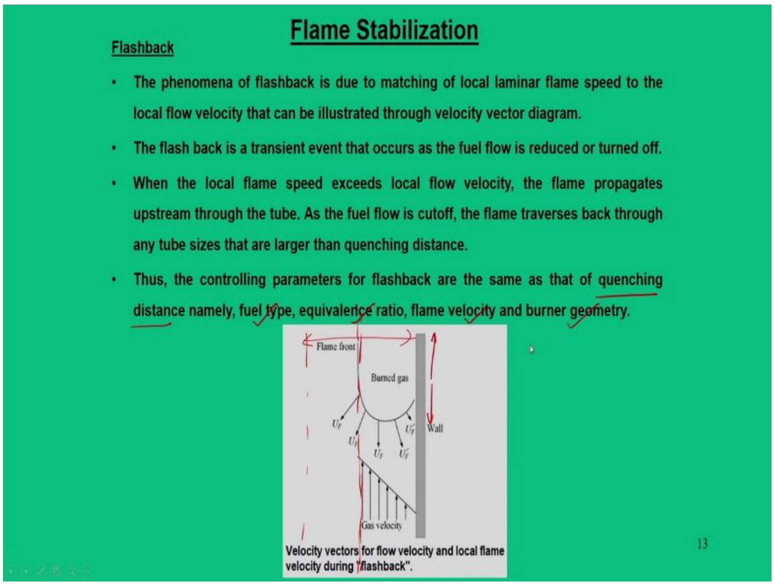

Now, let us understand one by one why the flash back has to occur. So, why it occurs that is because if you look at actually flash back how it happens that there are two speeds that controls the motion of the flame. First is flame speed at which the flame moves ahead and there is the gas velocity that pushes the flame further. And these two things allows that we have a steady flow laminar flame, but when there is a mismatch between the local laminar speed to the local flow velocity.

So, if you look at this particular figure and this is the wall, bottom we have gas velocity and if you can see that this is one of the walls of the tube. So, velocity is 0 and if you say it is like a one half of these things and this is the central line. So, the maximum velocity that can occur at the central line and the one part of this analysis if you see that when the gas velocity is highest, the flame prompt is very steady or it is higher.

In other locations the front is relatively less and it is almost going to 0 at the wall. So, because of this mismatch of this local velocity, the flash back can happen. When the local flame speed exceeds the local velocity, the flame propagates through the tube that is quite natural, but as the fuel is cut off, the flame traverses back to any tube size which is larger than the quenching distance.

So, for example, if you have this particular tube diameter and if the flame sees a larger tube diameter than the quenching distance instead of moving further the flame tries to come back and there the explosion can happen and if the tube size is not designed as per the quenching distance.

Now, here the controlling parameters of the flash back are similar to that of quenching distance; that means, we should regulate the quenching distance and those parameters are fuel type, equivalence ratio, flame velocity and the burner geometry. So, these four parameters regulate the issue of flashback.

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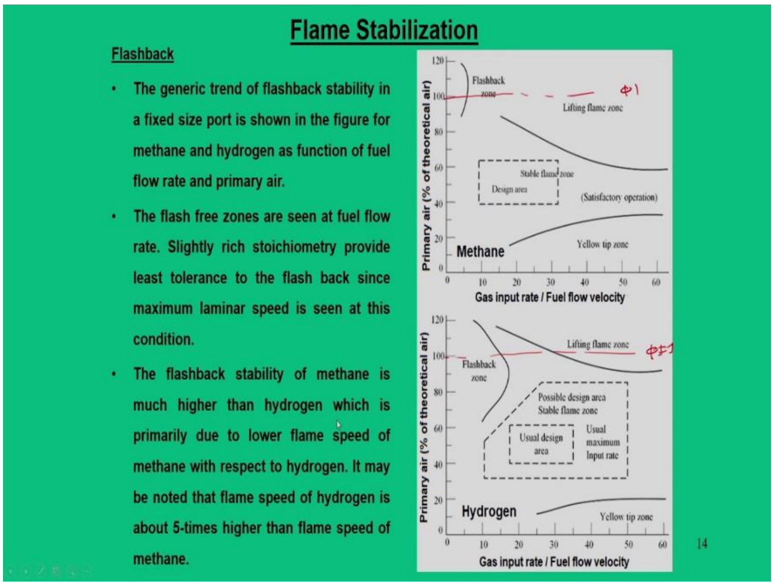

If you look at this particular figure and we are trying to see for a given a type of burner what happens, what is the range for which the flashback cannot happen? So, there are many parameters that we defined fuel types, burner tube diameter, flammability limit, all these things are given. And also, what has been plotted here is that for two generic trends for two types of gases, one is methane for which the flame speed is relatively smaller and other is the hydrogen for which the flame speed is relatively higher.

The x axis gives some generic number; that means, gas input rate or fuel flow velocities when it is increased, we are trying to put primary air that is percentage of theoretical air. So, when a theoretical air is 100, we say it is phi is equal to 1. Now, what we can see is that how we should go about the critical points of our discussion. First thing we need to think about the flashback.

So, if you look at methane case it is limiting or percentage of theoretical layer is something around maybe 90 to 120 and if your burner is operated below that then there is a chance of flash back. In other words, your gas input rate or probe velocity should be such that it should cross the flashback zone.

And this particular domain seems to be a very safest zone; that means, in the range of 100 to 30 units of input velocity or gas input rate percentage of theoretical air within 40 to 60 could be a stable flame zone for methane. But, if you look at hydrogen it has a larger domain of flashback zone which means that safest zone has to be shifted further.

So, this is one aspect that the design criteria of the gas burner have to follow. So, generic trend of flash stability in a fixed size burner is shown in this figure for methane and hydrogen and they are essentially the function of fuel flow rate and primary air. The flash free zones are seen at fuel flow rate slightly reached stoichiometry provide least tolerance to the flash back.

So, this is the condition we say that rich stoichiometry provide least tolerance since the maximum laminar speed is seen at these conditions. Another important point that I have already mentioned, the flash back stability for methane is higher than that of hydrogen because methane has lower flame speed with respect to hydrogen. It may be noted that flame speed of hydrogen is about 5 times faster than the flame speed of methane.

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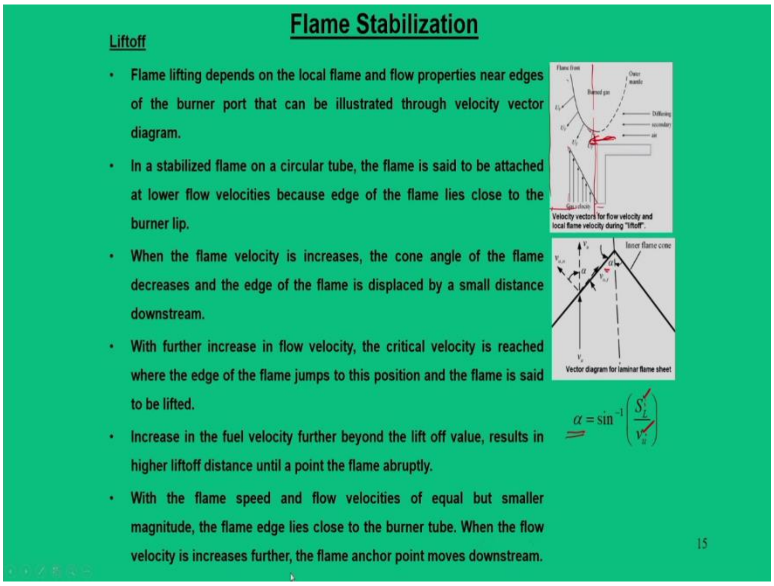

The next important aspect as I mentioned is that lift off. We except that burner that the flame should sit on the burner port it should not get lifted. To counter this argument if you see this particular figure here why the flame gets lift off and in fact, here also the same philosophy we say this is the half of this burner tube and where least gas velocity is 0, maximum is at the centerline velocity and the nature of the flame we can see through this profile.

Now, what happens during lift off? If you look at this velocity vector diagram when there is a lift off means that there is a mismatch; that means, gas velocity has lifted the flame above. And during this process what happens? There is a diffusing air that enters into this domain. And there are two important aspects that we need to understand here. As the flame velocity increases, we can correlate this as the angle or the local angle alpha with respect to the flame speed as well as the unburnt gas velocity.

Now, when the flames velocity increases, the cone angle of the flame decreases because of this reason the edge of the flame is displaced by a small distance downstream, the flame distance moves down stream. And due to this miss balance between these and changing of this angle alpha, the flame moves downstream or we call this as a flame as lifted. With further increase in the flow velocity, we can have a critical velocity exist where edge of the flame jumps to the position and the flame is said to be lifted.

Further increase in the fuel velocity beyond lift off value results high lift off distance until a point flame becomes abrupt. Now, with this flame speed and flame velocity of equal, but smaller magnitude then within this critical limit what may happen is that the flame will tries to make a balancing approach or other words we can say the flame edge lies close to the burner tube, but when the flow velocity is increased further the anchor point moves downstream again.

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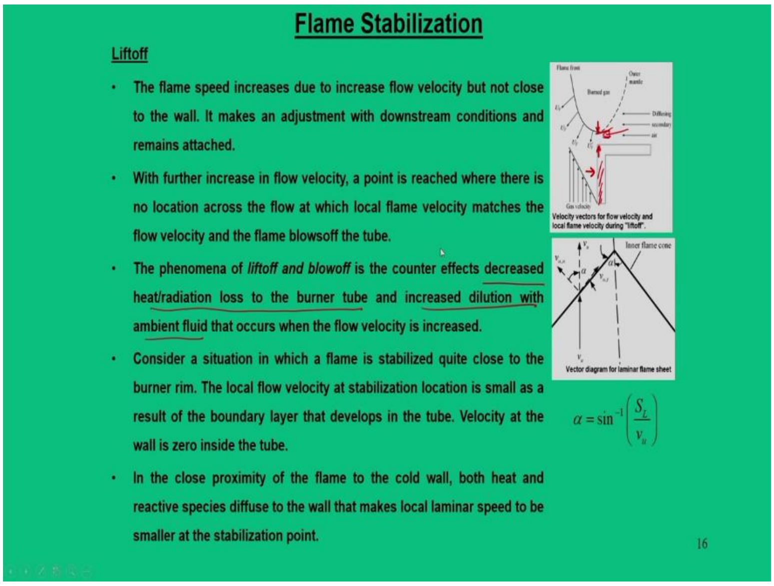

So; that means, subsequent increase in the flame velocity will make the flame to its best possible extent to adjust with respect to downstream conditions, because there are two counter effects when it gets lift off. One is decreased heat radiation loss to the burner tube, other is increased dilution with respect to ambient fluid, because the ambient fluid tries to enter through this lift off distance.

Now, when these two things, ambient fluids try to enter and of course, we have enough gas velocity that goes away without being ignited or burnt. And at the same time these two things make the flame to get lift off, or in other words the flame front sees an adverse phenomenon in which it feels that it gets a push from the local gas velocity so that it stands at certain distance.

So, there are other critical things that how much it gets this location or this distance mostly depends on many factors, two important factors is heat lost to the burner tube, other is increased dilution of ambient fluid. In the close proximity of the flame to the cold wall both heat and reactive species diffused to the wall that makes the laminar speed to be smaller at the stabilization point.

So, basically there are issues that the heat from the flame has to go to this wall of the tube, but unfortunately since the flame gets lift off and at the same time the diluent fluids or the secondary air enters into the lift off zone, because of these two effects the flame stands at a distance and we call this as a lift off distance.

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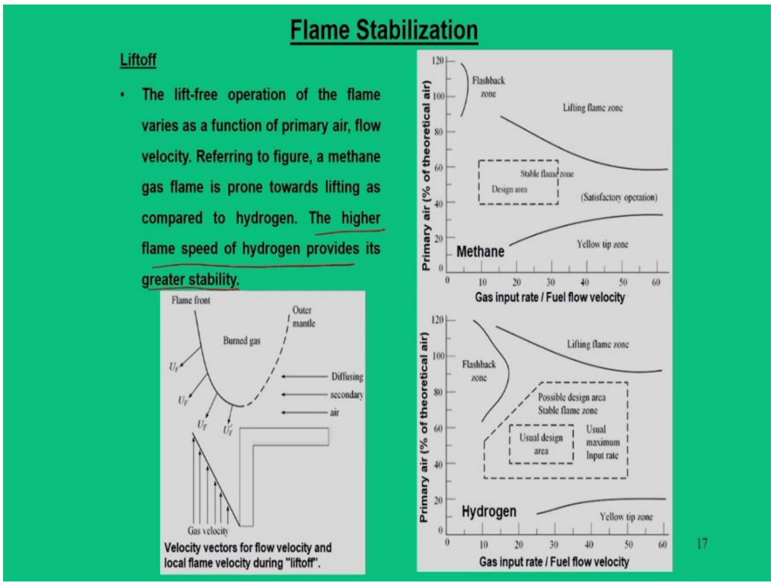

The next important thing is that we have to recall the same figure. We just want to see that what is the lift free operations. In the similar philosophy of flashback zone, we also have another trend where we can say this graph for methane there is a satisfactory operation for the flame lift off zone.

Means that by regulating your input gas or regulating the fuel flow supply at the same time amount of theoretical layer that is required for a sustained flame. If you keep on increasing this fuel velocity, there is a particular range for which we need to have a stable flame or we say flame is stabilized. When I say flame is stabilized which means that we have ensured that we have crossed the flashback zone.

Second thing we also ensure the flame does not lift away from the burner. So, when these two conditions are satisfied, we can have a design area of a stable flame zone and this design area of the stable flame zone varies with respect from gas to gas or fuel to fuel. So, for a methane we have a very wide range of stable range and whereas, for hydrogen we may not have enough choice because hydrogen has a very high flame speed.

So, the higher flame speed provides greater stability for hydrogen, since the flame speed is higher for hydrogen in terms of lift off it is more stable than the methane. So, this is the most important aspect. The higher flame speed of hydrogen provides greater stability with respect to methane. So, this logic is also true for other types of fuels.

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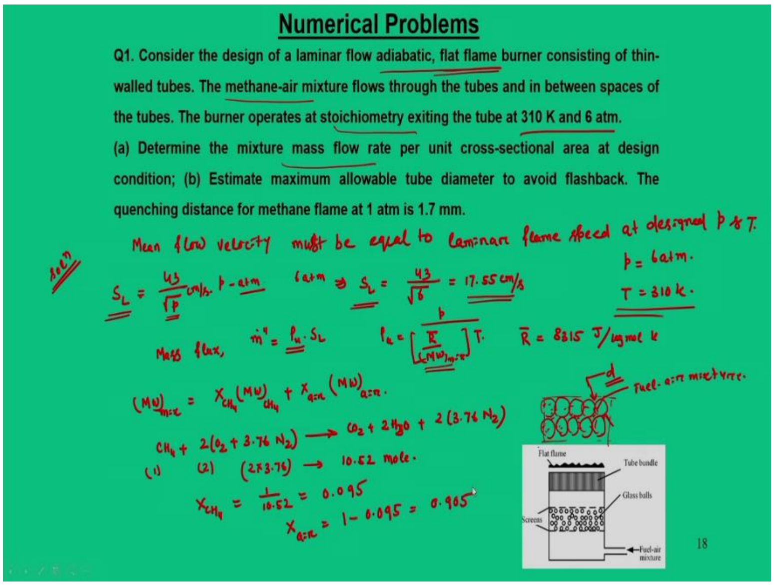

Now, with this we are now in a position to discuss some numerical problems what we have understood so far. The first problem is about the design of a laminar adiabatic flame burner and we expect that we need to have a flat flame; it consists of thin-walled tubes. So, if you recall our one of the pictures this is a case for an adiabatic fuel burner, in which fuel air mixture comes through it and we have some glass balls or some regions or you can say they are pre heated zones.

Ultimately what we get charge that enters the tube bundles. So, if you look at the top surface of this and top view of this then we can see that there are circular tubes of of equal diameters and all of them are filled with the charge or fuel air mixture. So, the question is here we need to find, what is the diameter of the tube?

So, these are the diameter of each of the tube, we require diameter of this tube. So, that we can have a flat flame and it is the condition is that we have laminar adiabatic flame and the burner operates at stoichiometry at 310 K and 6 atmosphere. So, we required to find out two parameters, one is determine the mass flow rate per unit cross sectional area at the design conditions. Second is estimate the allowable tube diameter to avoid the flask back.

So, first thing we should know that when we have a adiabatic flat flame which means mean flow velocity must be equal to laminar flame speed at designed pressure and temperature. So, our design p is 6 atmosphere, temperature is 310 K.

$S_L = \frac{43}{\sqrt{p}} = \frac{43}{\sqrt{6}} = 17.55\ cm/s$

So, we know that at design conditions the flame speed is this, but what has been asked, what is the mixture flow rate? So, to find this mixture flow rate we require basically mass flux and that mass flux is equal to $\dot{m} = \rho_u S_L$. ρ_u is the density of the mixture. Now, we can use the ideal gas equation.

$$\rho_u = \frac{p}{\frac{\bar{R}}{(MW)_{mix}}T};\ (MW)_{mix} = X_{CH_4}(MW)_{CH_4} + X_{air}(MW)_{air}$$

To do that we recall it is a stoichiometry.

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 2(3.76N_2);$$

$$X_{CH_4} = \frac{1}{1 + 2 + 2 \times 3.76} = 0.095; X_{air} = 1 - 0.095 = 0.905$$

$$(MW)_{mix} = 0.095 \times 16 + 0.905 \times 24 = 27.765; \rho_u = \frac{6 \times 101325}{\frac{8315}{27.765} \times 310} = 6.55\ kg/m^3$$

$$\dot{m} = \rho_u S_L = 6.55 \times \frac{17.55}{100} = 1.15 kg/s.m^2$$

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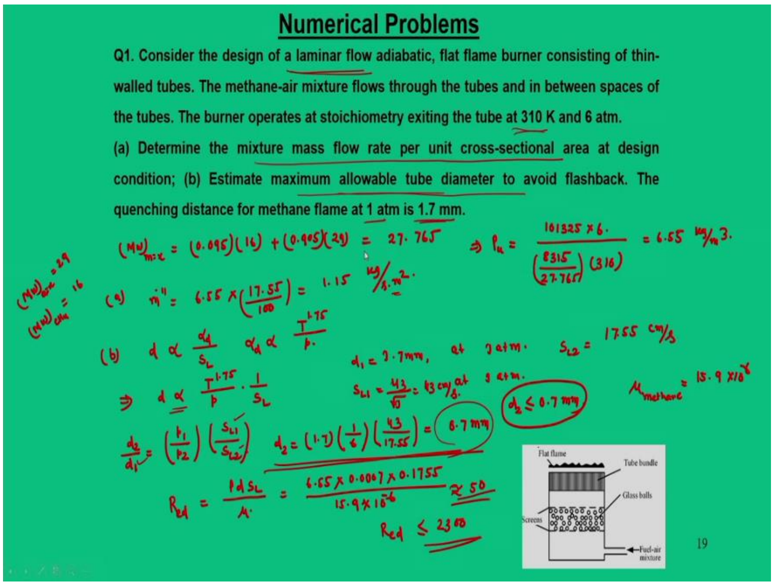

So, this gives mixture mass flow rate per unit cross sectional area. The second part is we need to find the maximum allowable tube diameter, for that we recall our relations

$$d \propto \frac{\alpha_d}{S_L}; \ \ \alpha_d \propto \frac{T^{1.75}}{p}$$

$$d \propto \frac{T^{1.75}}{p}\frac{1}{S_L}; \frac{d_2}{d_1} = \left(\frac{p_1}{p_2}\right)\left(\frac{S_{L_1}}{S_{L_2}}\right)$$

Now, here we are not talking about temperature change. So, temperature effect is not there and d1 is nothing but the quenching distance at 1 atmosphere.

So, condition 1 we say d1 is 1.7 mm at 1 atmosphere. And what other things? S_{L_1} at 1 atmosphere is $\frac{43}{\sqrt{1}} = 43\ cm/s$. So, SL2 we have 17.55 centimeter per second. So, all the parameters are known. So, we can say what is $d_2 = 0.7\ mm$.

So, allowable tube diameter should be maximum 0.7 mm or $d_2 \leq 0.7\ mm$. Now just to cross check whether this particular tube diameter will give you a laminar flame or not. So, for that we have to recall this Reynolds number expression about its diameter this is $Re_D = \frac{\rho d S_L}{\mu} = \frac{6.55 \times 0.0007 \times 0.1755}{15.9 \times 10^{-6}} = 50$.

And, for a circular tube your laminar flow will occur if it is less than or equal to 2300. And this again falls in this range which means that it is a laminar flow burner, by ensuring the flame speed and gas velocity it is a flat burner and based on this, we also find the quenching distance with respective tube diameter. So, this particular concept gives the idea how the diameter of the tube is to be designed so that flash back should not occur.

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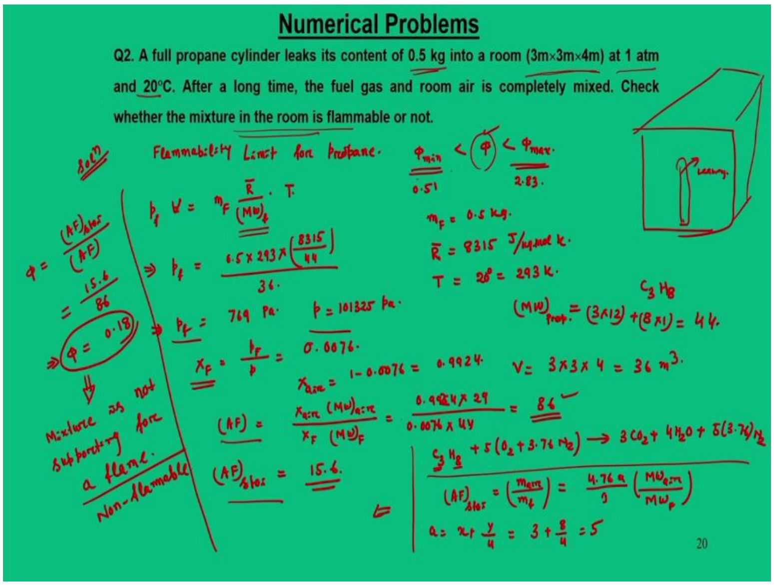

And the second problem is about the flammability limit. So, what we have is that a full propane cylinder it is there in a room it contains 0.5 kg. The room size is 3 meter into 3 meter into 4 meter and room condition is 1 atmosphere and 20 C. So, after a long time the fuel and room air is completely mixed. So, we have a room in which we have a gas cylinder, gas is leaking.

So, we expect whether the mixture is flammable or not. So, while leaking it mixes with the room air. So, to do that first thing we should know the flammability limit for propane. So, this limit we can get it from the book and for us we say $0.51 \leq \phi \leq 2.83$.

So, our problem is that if we want to find a phi if it falls within this range then we will say our answer that it is flammable, if it is not, it is not flammable. So, this is the question to do that we have to simply recall find out what is the partial pressures of fuel. So, this can be found out from the ideal gas equations.

$$(MW)_f : C_3H_8 = 3 \times 12 + 8 \times 1 = 44$$

$$p_f V = \frac{m_f \bar{R}}{(MW)_f} T; p_f \times (3 \times 3 \times 4) = 0.5 \times 8315 \times \frac{293}{44}; p_f = 769\ Pa$$

$$X_f = \frac{p_f}{p} = \frac{769}{101325} = 0.0076; X_{air} = 1 - 0.0076 = 0.9924$$

Now, from this mole fractions we will be able to find air fuel ratio.

$$AF = \frac{X_{air}(MW)_{air}}{X_f(MW)_f} = 86$$

Then we also do not know what is the stoichiometric. So, for stoichiometric air fuel ratio we have to recall the propane reactions.

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 5(3.76N_2)$$

So, this is the stoichiometric propane air mixtures.

$$AF_{stoich} = \frac{m_{air}}{m_f} = \frac{4.76a}{1}\frac{(MW)_{air}}{(MW)_f}; a = x + \frac{y}{4} = 3 + \frac{8}{4} = 5;\ AF_{stoich} = 15.6$$

$$\phi = \frac{AF_{stoich}}{AF} = 0.18$$

So, this is exactly what we are expected to find and this means it is not within this limit. So, this will imply mixture is not flammable or mixture is not supporting for a flame. So, it implies it is non flammable. So, this problem gives you the very basic insight whether a gas cylinder which is leaking in a room is flammable or not.

So, with these two problems let me close today’s discussions.

Thank you for your attention.