Fundamentals of Combustion
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Lecture - 38
Laminar Premixed Flames - Part 6
Piloted ignition and Flame quenching

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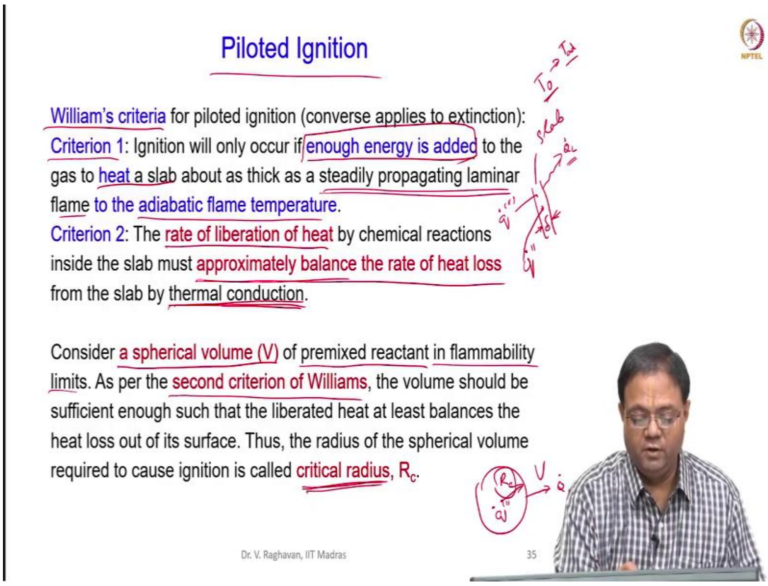

Now, we go to what is called Piloted ignition. Piloted ignition is the one where we need an external source like spark or pilot flame to accomplish the ignition, just the hotness of the chamber will not be able to provide the ignition source. The temperature prevailing in the chamber will be less than that of the auto ignition temperature of the mixture.

If the temperature crosses the auto ignition temperature then auto ignition can take place otherwise, we need an external source to cause a localized ignition. Now, for analyzing this the Professor Forman Williams have given actually two criteria

The criterion 1 is ignition will occur, we have already seen this particular second point we have seen, the first point we will see now. Ignition will occur when enough energy is added to the gas, to heat a slab, let us take a slab like this.

So, energy is added to the slab, basically this is a slab, energy is added to the slab. How much energy? Enough energy is added to the slab. To accomplish what? To increase the temperature of the slab; so, initially the temperature of the slab may be T_0, to increase the temperature of the slab from T_0 to T_{ad} (adiabatic flame temperature).

So, you add heat to this slab such that the temperature of the slab increases from the initial value to the adiabatic flame temperature. What is the dimension of the slab? This slab has a thickness of delta which is the thickness of the steadily propagating laminar flame delta.

So, if you have a region which is of the reaction zones dimension. And, if that particular region is increased from its initial temperature of T_0 to adiabatic flame temperature then ignition occurs, that is it. So, that means, you are forming a flame which is going to now consume the other. So, you have a localized region where the flame is formed first.

The flame has a typical thickness of a laminar premix flame; so, which is delta and if you can heat up this region to adiabatic flame temperature; that means, you accomplish ignition there; that is one of the thing. So, for that you need to add enough energy. So, what is the minimum energy which we need to add that is one of the criteria we should see.

Second one is what we already seen, the rate of liberation of heat, that is heat which is released by the chemical reactions inside this slab of δ thickness must approximately balance the rate of heat loss from the slab ok. Now, here you can say conduction so, this is $\dot{q}_L$, I will say. So, this is the rate at which the heat is lost.

So, this basically by thermal conduction, in the previous case where the mixture was fed inside, convection heat transfer was predominant. In this case there is a still premixed gas and localized ignition is provided at a particular point. So, by conduction the heating is taking place. So, thermal conduction is assumed here.

So, the rate of liberation of heat by the chemical reactions inside the slab of δ thickness. So, this will provide a heat generation, so, this is heat generated, volumetric heat generated. So, I will say R, that is the heat which is due to reaction which is generated; now this heat is added to this.

So, now this and q_L should match, if that balance occurs we have already seen at the critical point $q_R = q_L$. Similarly, here the heat which is generated by the chemical reaction should balance the heat lost. So, when I say, approximately it is slightly higher.

The heat which is generated will be slightly higher than the heat which is lost by thermal conduction we are going to consider thermal conduction here. So, predominantly when there is a mixture which is not moving, we provide a spark to ignite it or any other piloted ignition we will do it. So, mainly we are going to talk about the spark ignition in this case.

Now, for this what we should do is we should consider a spherical volume of say value V m^3 and this having a premixed reactant in the flammability limits.

As I told you the mixture should be ignitable, it should not be leaner than the lean flammability value or richer than the rich flammability limit. Now, we will apply the second criteria of Williams that is nothing, but the heat liberated should balance the heat lost.

Now, this volume, a spherical volume; so, this is volume V and let us take radius of this spherical volume as R and we call this radius as critical radius R_c because this is the minimum volume which will be required to cause ignition.

That means, if we take a volume with the radius, spherical volume with the radius which is less than R_c then the heat which is liberated cannot balance the heat which is lost. So, this heat will be liberated here in this, that is lost to these surrounding.

Now, this should match. If the R value that is the radius is less than the critical radius then the volume volumetric heat generation cannot match the heat loss. So that means, that the critical radius is assumed here where ignition will occur. So, what is that value?

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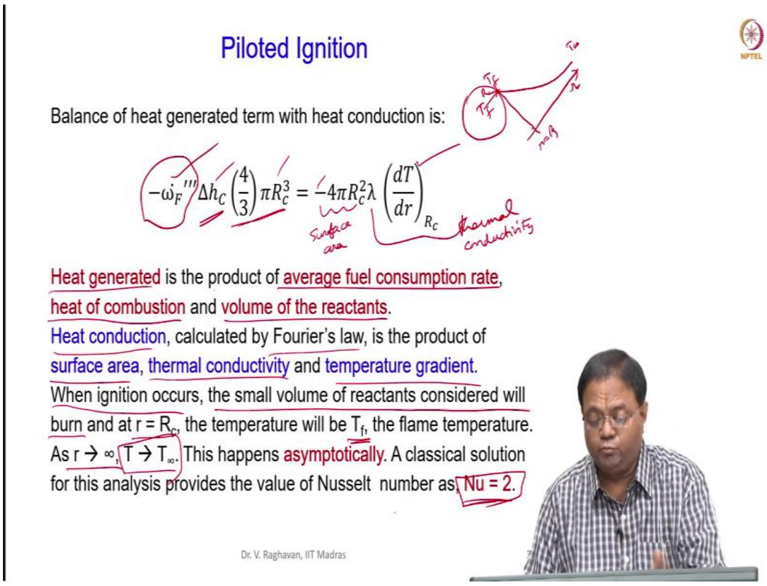

Now, again we try to balance the heat which is generated with the conductive heat loss. Now, here again this is the negative term, you can see this negative term is the rate of consumption of fuel; so, that is negative. So, negative into negative is positive into Δh_c which is the heat of combustion and this is the volume of this, the spherical volume $(4/3)\pi R^3$.

So, here the R is critical radius. Now, that will be heat which is lost by conduction that is this here is negative because, heat flows in direction of decreasing temperature. So, this negative sign appears because this is negative and $4\pi R^2$ which is the surface area and this is the thermal conductivity.

Now, this is the heat which is lost by conduction, if they are balanced then ignition can occur. So, if they are balanced actually the left hand side will be slightly higher than the right hand side.

So, heat generated as we have already seen it is the product of average fuel consumption rate, $\dot{\omega}_F'''$ and multiplied by the heat of combustion Δh_c and the volume of the reactant which is $(4/3)\pi R_c^3$.

So, heat conduction is analyzed by the Fourier's law, where it is a product of surface area $4\pi R^2$, thermal conductivity and temperature gradient, temperature gradient in this case is negative. So, negative sign appears there.

So, actually the heat flow direction is in the decreasing temperature direction So, when ignition occurs a small volume of reactants considered will be burnt.

So, this volume small volume what we are considering, critical volume what we are considering, the minimum volume that it will burn. So, that the temperature of that there will be T_f.

So, T_f let us assume, it can be assumed to be homogeneous also. So, once they instantaneously burn then the temperature reaches from the initial temperature to the flame temperature.

So, at $r = R_c$ we can say temperature is T_f which is the flame temperature. Now as r goes to infinity; so, you can see this, this has burnt now. So, temperature here is T_f. So, $r = R_c$ here, temperature is T_f and it actually decreases asymptotically to a value of T_∞. So, this is T_f and r is increased here. So, this is at very far r; so, r_∞ I will say. So, this is $r = r_s$.

So, this asymptotically reaches the ambient temperature of T_∞. So, T_∞ is the ambient temperature, this is the exponential decay and asymptotically it reaches, asymptotically means after long radial distance the temperature reaches T_∞.

So, for this case, the heat which is conducted at the surface is lost by convection. So, the Nusselt number for this limiting case of asymptotic analysis is $Nu = 2$. So, Nusselt number will be equal to 2, this is known to us by the analysis.

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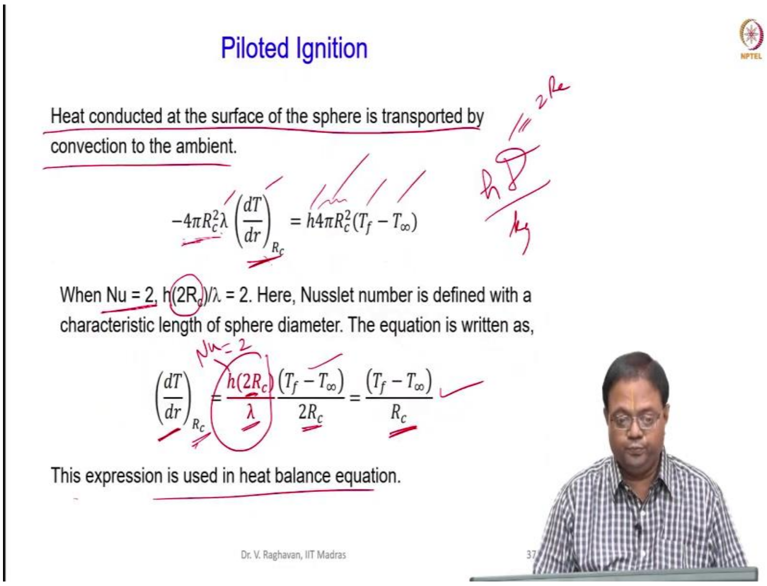

So, heat conducted at the surface is transported by the convection to the ambient. So that means,

$$-4\pi R^2\times\lambda(dT/dr)_s = h\times 4\pi R^2(T_f - T_\infty).$$

Now, for this limiting case we know the Nusselt number is 2, exponentially and asymptotically reaching the value of T_∞. So now, what is Nusselt number? Nusselt means defined as h some characteristic dimension D divided by k of the gas. Now, this characteristic dimension is now the diameter, take out the diameter of the volume that is the spherical volume. So, that is equal to $2R_c$.

So, $h\times 2R_c/\lambda = 2$, now you know that. So now, you can write the temperature gradient dT/dr calculated at R_c; obviously, at that surface will be equal to now rearrange the term h is here, $h\times 2R_c$; I multiplied by $2R_c$ and divided by $2R_c$, divided by this λ from the left hand side. So, this is the Nusselt number basically.

$$\left(\frac{dT}{dr}\right)_{R_c} = \frac{h(2R_c)}{\lambda}\frac{(T_f - T_\infty)}{2R_c} = \frac{(T_f - T_\infty)}{R_c}$$

So, this is Nu which is equal to 2 that also we know that into $(T_f - T_\infty)/2R_c$; what we have multiplied and divided here $4\pi R_c^2$. So, now this has a value of 2 so, 2 and 2 cancels. So, the temperature gradient can be written as the flame temperature minus the ambient temperature divided by the critical radius R_c.

So, just to get the temperature gradient in terms of temperature and radius we have done this small analysis of considering the heat which is conducted from the surface of the sphere what we considered is lost to the ambient by convection. It is actually a natural convection basically. So, we can see that the asymptotic value of this scenario is Nu = 2. When you substitute Nusselt number equal to 2, you get the temperature gradient as $(T_f - T_\infty)/R_c$; so, natural convection. So, when you add forced convection the Nusselt number value increases from 2. So, in this scenario we get the dT/dr at R_c as $(T_f - T_\infty)/R_c$. So, this expression is now used in the heat balance equation.

$$-\dot{\omega}_F{}'''\Delta h_C\left(\frac{4}{3}\right)\pi R_c^3 = -4\pi R_c^2\lambda\left(\frac{T_f - T_\infty}{R_c}\right)$$

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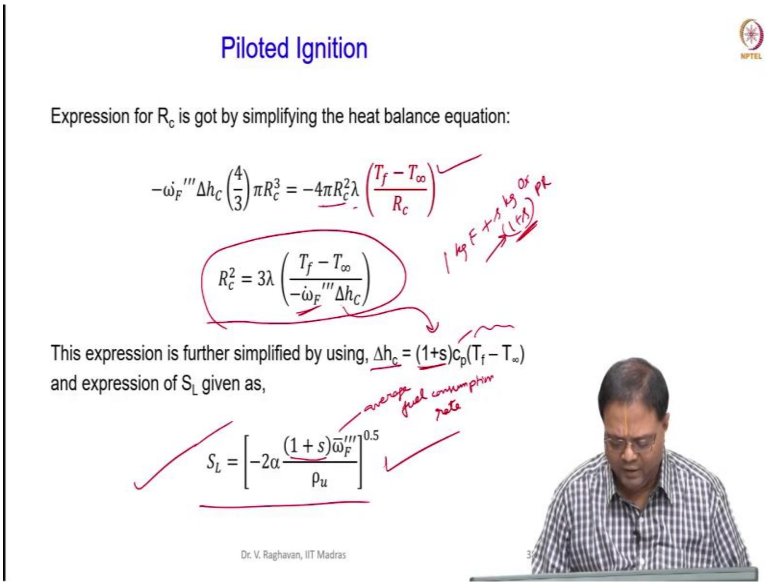

So, substituting that; when you substitute $-\dot{\omega}_F'''\Delta h_c$ the volumetric heat generated equal to heat loss $4\pi R^2\lambda(dT/dr)$ at the radius R_c is written as $(T_f - T\infty)/R_c$. Or, you get an expression for R_c as

$$R_c^2 = 3\lambda\left(\frac{T_f - T_\infty}{-\dot{\omega}_F{}'''\Delta h_C}\right)$$

Now, we know the expression for S_L from the simplified analysis, where S_L equal to $-2\alpha(1 + s)$; that is, we are considering equation 1 kg of fuel + s kg of oxidizer → 1 + s kg of products. So, in this equation 1 + s is the mass of the product which is produced per kg of fuel.

$$S_L = \left[-2\alpha\frac{(1+s)\bar{\omega}_F'''}{\rho_u}\right]^{0.5}$$

So, that (1 + s) $\dot{\omega}'''_F$, this average reaction rate, fuel consumption rate. So, this we know. So, for $\dot{\omega}'''_F$ here we can apply this, in terms of S_L we can write. Similarly, Δh_c can be written as mass of the product.

This is mass of the product into c_p which is assumed to be constant for reactants and products into ΔT. ΔT is nothing, but $T_f - T_\infty$. So, actually product carries the heat away from the reaction zone to the ambient. So, as it travels the temperature of the product slowly decreases to the ambient temperature after a long distance so, for Δh_c we can substitute $mc_p\Delta T$ here.

So, when you substitute this you can see $T_f - T_\infty$ of this Δh_c term will cancel with the numerator. Similarly, when substitute for $\dot{\omega}'''_F$ in terms of S_L and do the algebra, you can get this value.

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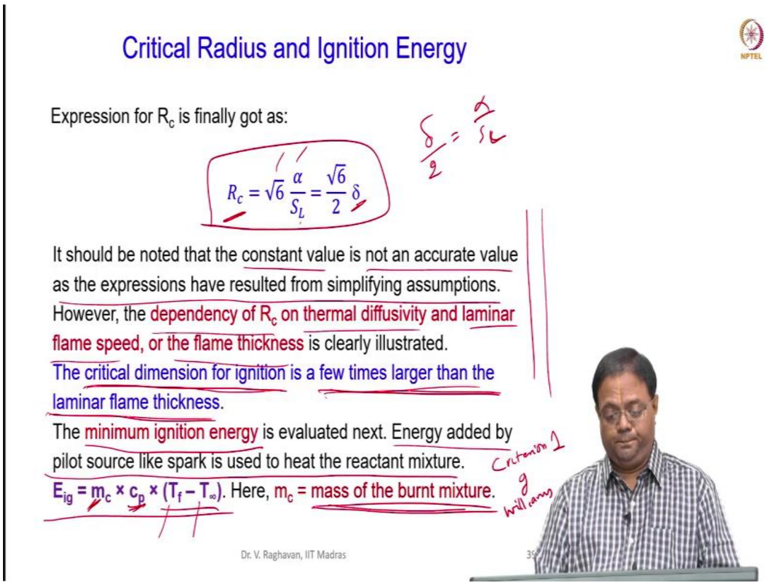

Now, the critical radius is nothing, but square root of $6\alpha/S_L$.

$$R_c = \sqrt{6}\,\frac{\alpha}{S_L} = \frac{\sqrt{6}}{2}\,\delta$$

Please understand that, this square root of 6 etcetera is not accurate only because you can see that in this several assumptions are made. See for example, first of all this is a single step reaction.

Then we are taking some asymptotic value of Nusselt number then this S_L itself is got from several assumptions. So, there is no significance of this value square root of 6, this may be varying little bit; so, it is not a problem.

So, we can see that when you write α/S_L as 2 or $\delta/2$. So, $\delta/2$ is α/S_L, that is the $\delta = 2\alpha/S_L$. So, you know this; so, if you substitute this you will get this value.

So, we can say that R_c is a few times higher than the flame thickness that is it. See, what Forman's analysis is we have to have a slab of thickness which is equivalent to the laminar flame thickness. So, that is what we are trying to get here also. So, this is almost R_c is proportional to the flame thickness. And, this proportionality is a few times larger say maybe 1.2, 1.52 something like that.

So, few times larger than the laminar flame thickness is the critical dimension. So, with the volume, any volume can be taken as a single dimensional thing. So, for example, dimension of a spherical volume can be radius, dimension of a cube can be its side and so on. So, cuboid can be side and so on.

So, similar to that you can take the critical dimension of ignition that is R_c, it may not be spherical. So, I am saying dimension here, you know I am not saying radius. So, critical dimension of ignition can be few times larger than the laminar flame thickness, that is what we are going to analyze here. So, it is very important to understand the logic here.

So, the thing is you need not have a very big volume to ignite, you need only a smaller volume to ignite; that volume will be in the order of the flame thickness, that is what we need to understand here. Now, it should be noted that the constant value root 6/2 is not an accurate value as expressions have resulted from simplifying assumptions.

However, the dependency of R_c on thermal diffusivity here α, laminar flame speed S_L or the flame thickness δ is illustrated clearly, that we have to understand.

So, we have found the first criteria, where the minimum amount of charge or the premixed reactant mixture which is required to cause ignition. Now, second criteria is how much energy has to be supplied. First criteria is, enough energy should be supplied.

So, what is that? So, for this we need minimum energy of ignition, that is how we will analyze it. So, energy added, first criteria of Williams. The pilot source like spark is used to heat the reaction mixture from the initial value to the flame temperature; so, criteria criterion 1 of Williams.

So, here, criterion 1 ignition will occur only if enough energy is added to heat a slab as thick as that of R_c, the critical thickness of the spherical volume what you consider which is proportional to δ, the flame thickness. So, we have to increase the temperature from the initial value which is ambient temperature to adiabatic fluid temperature.

So, we write here the ignition energy should be equal to m_c, mass of the charge which is nothing but the mass of the burnt mixture also; that because the entire charge will burn to cause ignition. So, mass of the charge m_c will be equal to the mass of the burnt mixture into c_p of this, into I have to increase temperature from the initial value which is T_∞ to the flame temperature T_f.

So, that is what the energy which is required for causing ignition, E_{ig} is the energy to cause ignition and it will be equal to the mass of the charge m_c, which is the mass of the burnt mixture also into c_p, which is specific heat into ΔT, $T_f - T_\infty$.

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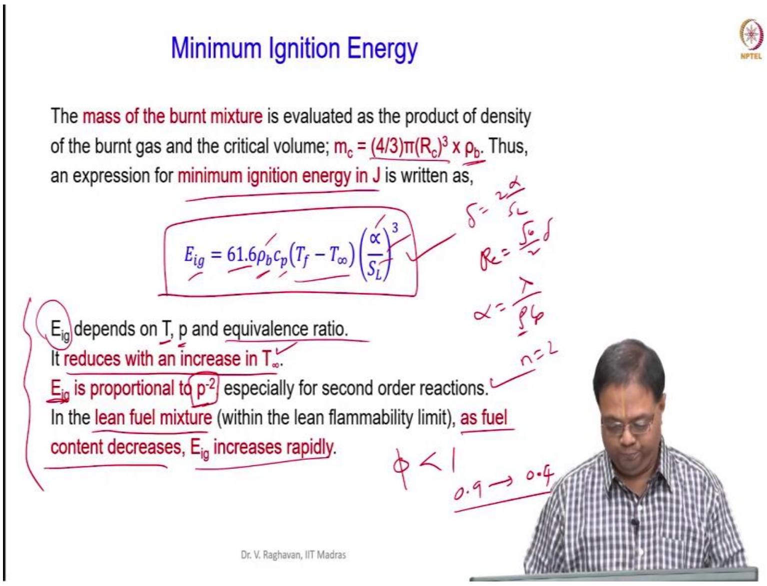

The mass of the burnt mixture is what the critical volume, that is nothing but $(4/3)\pi R_c^3 \rho_b$ (density of the burnt mixture). So, that is the mass. Now, the minimum ignition energy in Joules can be written; so, substitute this and substitute the value of R_c etcetera. R_c you know $(\sqrt{6}/2)\delta$; so, δ is nothing, but $2\alpha/S_L$.

So, $\delta = 2\alpha/S_L$ then R_c itself it is equal to this $(\sqrt{6}/2)\delta$ and so on; from the analysis what we have got just substitute them. You get the minimum ignition energy which will cause the ignition, because we are applying this to the minimum volume which is required correct, the enough volume of this.

$$E_{ig} = 61.6\rho_b c_p (T_f - T_\infty)\left(\frac{\alpha}{S_L}\right)^3$$

$61.6\rho_b c_p(T_f - T_\infty)(\alpha/S_L)^3$, R_c cube term will contribute to this. Now, from this you can understand that E_{ig} depends on temperature, pressure and equivalence ratio because S_L depends on temperature, pressure and equivalence ratio and so on.

Similarly, α also depends on all these three. α is the thermal diffusivity that is $\lambda/\rho c_p$. So, this also depends upon the equivalence ratio.

If more air is there and less fuel is there then the properties itself will vary correct. Similarly, density is a function of pressure and so on. So, you can see this, the ignition energy is dependent on all the parameters like temperature, pressure and equivalent ratio.

Now, if you increase T_∞; obviously, it is not auto ignition temperature, but it is less than the autoignition temperature. T_∞ is less than the auto ignition temperature. But, within that range if you try to increase T_∞, the extra energy which is required to be provided to the mixture is low. So, the E_{ig} will decrease with increase in T_∞, that is understandable.

Similarly, seeing these dependencies we can say that E_{ig} will be proportional to p^{-2}; especially considering second order reaction. So, second order reaction is considered, n = 2 here. For that, by substituting the pressure dependency of all the terms here that is this ρ_b is pressure dependent, α is pressure dependent, S_L is pressure dependent we know this. When you do this, you get overall pressure dependency of E_{ig} as p^{-2}. Now, consider one more aspect of this lean fuel mixture we will take, lean fuel mixture; that is $\Phi < 1$. With low value of Φ try to increase the Φ, from say equivalence ratio of 0.9 it decrease to say 0.4 or something.

As the fuel content decreases, you need more energy to ignite; obviously, because the heat generation will be reduced; when the equivalence ratio reduces then what happens? The fuel content decreases; so, heat generation will drop. So, that you need more energy to ignite for a given T_∞ or you have to increase T_∞. So, these are some observation which you can make from this.

So, to achieve piloted ignition you need to go for a minimum volume of the charge, premixed reactants and minimum ignition energy to cause the ignition. So, two types of ignition process we have seen auto ignition which is the temperature at which the premixed reactants based. See, this is not a universal temperature. For a given fuel, for a given equivalence ratio, unburnt reactant temperature etcetera it varies.

There is a particular temperature called autoignition temperature, when that is reached then ignition is accomplished; the autoignition will take place. We do not need external source of ignitor there. On the other hand, if you take piloted ignition you need to use spark or any piloted flame etcetera.

The energy supplied by the spark or the piloted flame should be a minimum value which is given here. And, this should be applied to a minimum volume of the reactants also. So, these are the important things.

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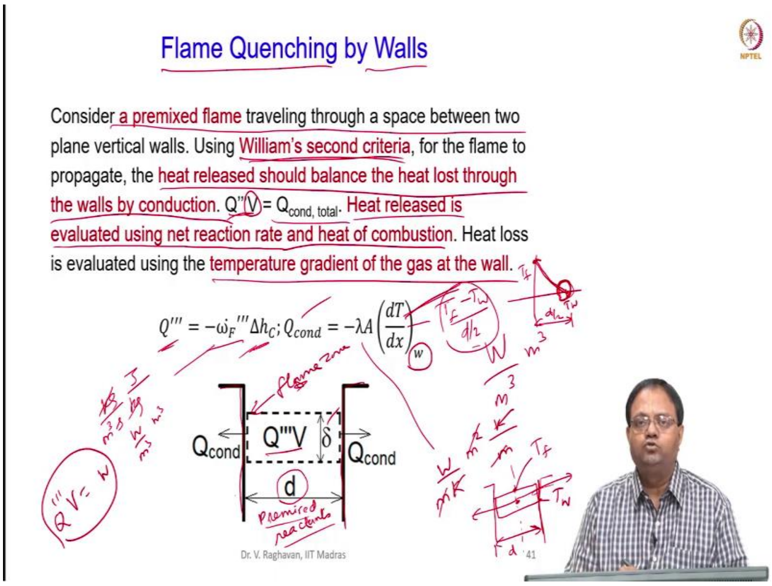

The next topic is flame quenching. we have seen the ignition. So, ignition please understand this ignition is a transient process.

Now, the flame quenching is also a transient process. We are considering flame quenching by walls ok. So, how it can quench? For this we consider two parallel walls like this, two parallel walls through which there are some premixed reactants here.

Now we have flame, this is the flame actually, this zone is the flame zone with the thickness δ. Now, this flame is trying to propagate down consuming the premixed reactants. So, maybe I have ignited it somewhere here. So, the flame is formed and the flame is coming down.

What is the diameter of this or the distance between these two walls which will be necessary for the flame to propagate? Or we can also do otherwise like what is the value of d which will prevent the flame to propagate? You can see both criteria. So, either the distance should be sufficient enough for the flame to propagate, if you want the flame to be propagated down.

Or, if you do not want the flame to propagate, what will be the diameter which will prevent that? We can see both. So, for this we have to use Williams second criteria. So, what we are trying to do is we are considering a premixed flame which is propagating in a space between two parallel walls, vertically oriented walls.

And, for this to propagate what is the criteria for the propagation? Determined by the William second point, second criterion which is nothing but the heat release should balance the heat loss through the walls by conduction. Here obviously, the wall does the conduction. So, the stationary mixture is there, flame is propagating down and losing the heat through the walls.

And what will be the balance here? So, the heat generated in the flame is Q''' V, Q''' is W/m^3 into volume is m^3. So, this is the heat which is generated or released and what is heat lost by the conduction, I am putting total here considering the two surfaces.

Now, heat released is evaluated as usual. Heat released is evaluated by the net reaction rate and heat of combustion. We have already seen how to do this. Heat loss now is dependent on the temperature gradient of the wall, thermal conductivity, so Fourier's law; so, let us apply this.

So, you have to understand that here what we are trying to do is we are trying to see a space, the dimension of a space through which the flame can propagate. If the dimension is more, the flame will surely propagate.

We are trying to know the minimum dimension of the space between two parallel plates. It can be a circular tube also or the diameter of the circular tube through which the flame is going to propagate. If the diameter is less than that or the dimension d is less than this value what you are going to estimate now, the flame will not be able to propagate. So, we have several applications for this, let us see.

$$Q''' = -\dot{\omega}_F{}''' \Delta h_C; Q_{cond} = -\lambda A \left(\frac{dT}{dx}\right)_w$$

So now, Q''' is nothing but the rate of consumption of the fuel $\dot{\omega}_F'''$ Δh_c. Heat loss by the conduction is λA(dT/dx). So, now this Q dot this will be kg/m^{3}s and this will be J/kg.

So, now, this will be W/m^3. So, when you multiply that by the volume here, m^3, you get W. So, Q''' V will be in W. So, right hand side already we have, this is W/m-K and area is m^2 and this will be K/m. So, now, you get this as Watts. So, when you do Q''' V and that can be balanced with Q conduction; so, that we are going to balance now.

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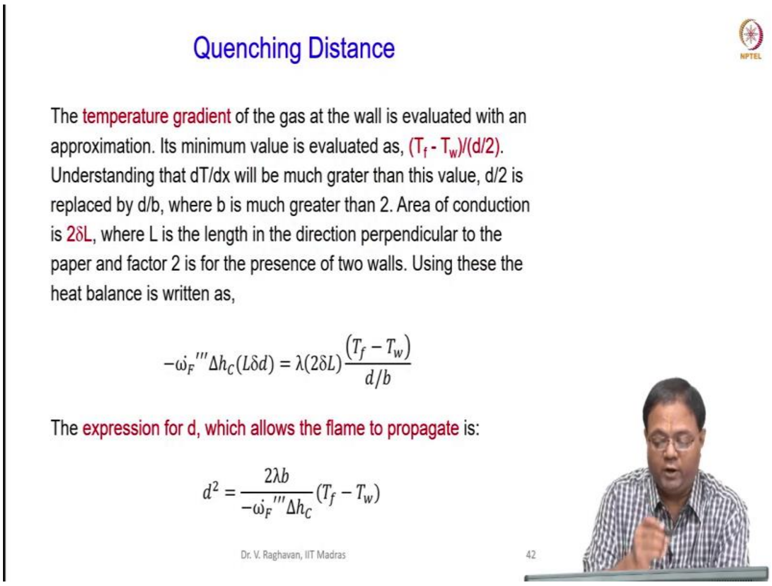

Now, before doing that, this is very important to understand how will you estimate the temperature gradient.

Now, please understand the temperature gradient basically, if you take these two parallel plates here, so, this is d. Now, maximum temperature here is T_f and this will be T_w.

So, worst case scenario if you take; so, I want the gradient at the wall please understand. So, I have to go near to this once. Since the heat is lost in this direction; in this direction heat is lost, in both the direction basically heat is lost. So, in the flame zone since heat is lost from both the directions, the temperature T_f cannot be uniform and suddenly lose to the wall, we suddenly reach the wall temperature T_w.

So, there is a temperature profile for this, from a maximum value of T_f it goes to T_w. So, if you say this is T_f and it decreases to T_w within the distance of say d/2. But this profile what we have, that I want to calculate the gradient near to the wall, if it is linear then its fine; but it should not be linear.

So, what happens here? Near the wall how will you estimate this gradient, that is the question. So, what is the minimum value this gradient will assume? The minimum value a gradient will assume is $(T_f - T_w)/(d/2)$; that is the minimum it will assume; minimum value of this gradient will be this. But you know very near to the wall this will not be correct. So, the gradient estimated by this expression will be under predicted actually. So, this cannot be applied, this can be applied only as an approximation; so, how to improve this we will see.