Fundamentals of Combustion

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Lecture - 33

Laminar Premixed Flames – Part 1

Laminar flame propagation

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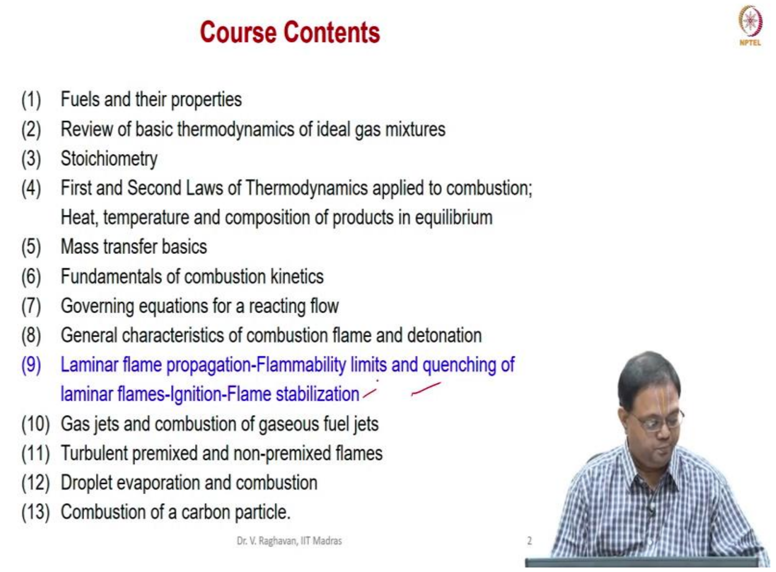

Course Contents

(1) Fuels and their properties
(2) Review of basic thermodynamics of ideal gas mixtures
(3) Stoichiometry
(4) First and Second Laws of Thermodynamics applied to combustion; Heat, temperature and composition of products in equilibrium
(5) Mass transfer basics
(6) Fundamentals of combustion kinetics
(7) Governing equations for a reacting flow
(8) General characteristics of combustion flame and detonation
(9) Laminar flame propagation-Flammability limits and quenching of laminar flames-Ignition-Flame stabilization
(10) Gas jets and combustion of gaseous fuel jets
(11) Turbulent premixed and non-premixed flames
(12) Droplet evaporation and combustion
(13) Combustion of a carbon particle.

Today’s topic is a Laminar Frame Propagation. So, we will see the aspects of how a laminar flame fields are calculated and some theory about that, then we will touch upon flammability limits, then ignition and quenching of flames and finally, flame stabilization.

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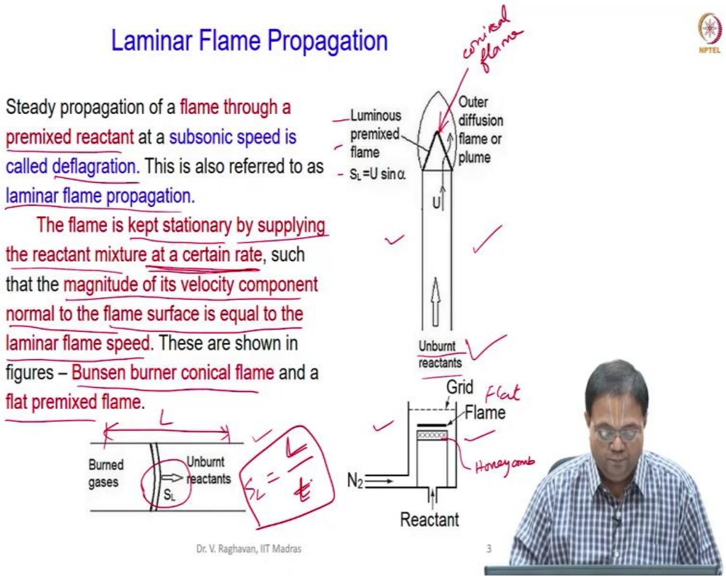

Laminar Flame Propagation

Steady propagation of a flame through a premixed reactant at a subsonic speed is called deflagration. This is also referred to as laminar flame propagation.

The flame is kept stationary by supplying the reactant mixture at a certain rate, such that the magnitude of its velocity component normal to the flame surface is equal to the laminar flame speed. These are shown in figures – Bunsen burner conical flame and a flat premixed flame.

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So, we have already seen when we covered a topic of deflagration and detonation that if we have a long duct which is filled with premixed reactants; homogeneously uniform reactants at any unburnt temperature, like unburnt reactant temperature. And if it is ignited at the open end, then we saw that a steady flame propagates through the mixture based upon the equivalence ratio, unburnt temperature and the fuel type etcetera the flame speed will be set; then it will vary.

So, this deflagration was called laminar flame propagation. When the same setup one side it was closed and it was ignited at the closed end we saw that the flame actually accelerates and subsonic to supersonic speeds can be achieved in that case and that was called detonation.

But in normal applications like domestic and industrial applications; we seek premixed flames where we have subsonic velocities basically; only in special applications we go for detonation type of things like pulse detonation engines and so on; we have already seen that.

So, flame propagates through premixed reactant mixture basically and we want to see how the flame propagation varies and how we have to analyze that and so on in this particular course. Now, this is actually some test apparatus where we allow the flame to propagate through a particular reactant mixture and so on.

But, in actual scenario and applications, we need to supply reactants at some rate and we normally seek flame to be stationary. See for example, the flame can be kept stationary on a burner port. Again, two examples here one is called Bunsen burner where unburnt reactants enter and it passes through a chamber or a duct or port whatever you can say and at the end of this, we have a flame which is formed.

So, for example, the luminous premixed flame. A conical shaped flame forms over the Bunsen burner, it is only a cylindrical duct basically through which we pass on the unburnt reactants. So, if you see this, the flame is stationary and it actually stands over the end of the duct.

By supplying the unburnt reactant at a particular rate or a given range of flow rates we can achieve such flames which are stationary over the end of the duct, we call this the exit of the burner. Similarly, we can also have a flat flame which can be established over a burner.

So, this is called flat frame burner where the reactant mixture is sent through and there is a honeycomb structure; so, this is honeycomb structure which will actually guide the reactant to come out in a uniform manner. When ignited, we get a flat flame almost flat which is just over the exit of the burner.

So, this type of burners we use for several applications basically; so, the flat flame burner or Bunsen burners. So, the flame is kept stationary by supplying the reactant mixture at a certain rate. As I told you, there is a certain range of flow rates which can give us a stationary flame; if you increase or decrease that, the flame will no more be stationary; so those aspects we will see later.

So, at a certain range of rates or a certain rate; if the unburnt reactant mixture is supplied, then the flame can be kept stationary. So, this is going to give several applications for us. For example, this may be a gas stove where we have multiple ports through which the reactant mixture comes out and burns, so that a stationary flame survives there. A moving flame cannot be used for any application.

So, the rate at which the reactant mixture is sent through the burner should be such that the magnitude of the velocity component normal to the flame surface is almost equal to the laminar flame speed. That means, the local velocity of the reactant mixture and the laminar flame speed locally there at a particular point should match. If such a balance happens, then the flame can be kept stationary over the burner rim.

So, the flame is kept stationary by supplying the reactant mixture at a certain rate such that the magnitude of the velocity component normal to the flame structure. So, you please understand that a definition of laminar flame velocity will be the normal component; you can see this, we have already discussed this; the normal velocity component of the flame when the flame actually propagates the normal component of the velocity is called laminar burning speed or laminar burning velocity.

And when you supply the reactants; its velocity component normal to the flame surface should be almost same as the laminar flame speed. So, if you have a given fuel and equivalence ratio and unburnt flame temperature; we have a small range of laminar flame speed.

So, if your velocity reactant velocity is more or less same as that then we can keep the flame stationary. So, as I told you the Bunsen burner with the conical flame here, this is called conical flame and a flat premixed flame here; the flat flame, these are the examples where the flame is kept stationary over the burner port. So, these type of burners are suitable for several applications; a moving flame will not be used in any application.

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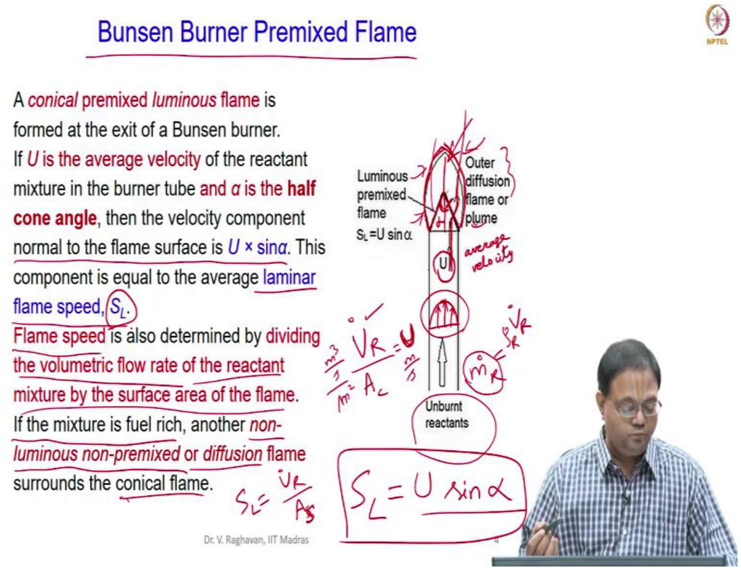

Bunsen Burner Premixed Flame

A *conical* premixed *luminous* flame is formed at the exit of a Bunsen burner.

If *U* is the average velocity of the reactant mixture in the burner tube and *α* is the **half cone angle**, then the velocity component normal to the flame surface is *U* × sin*α*. This component is equal to the average laminar flame speed, S_L.

Flame speed is also determined by dividing the volumetric flow rate of the reactant mixture by the surface area of the flame.

If the mixture is fuel rich, another *non-luminous non-premixed* or *diffusion* flame surrounds the conical flame.

$$S_L = \frac{\dot{V}_R}{A_S}$$

$$\frac{\dot{V}_R}{A_C} = U$$

$$\boxed{S_L = U \sin\alpha}$$

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Now, let us see some characteristics of Bunsen burner flame. So, in a Bunsen burner the reactant mixture is supplied in a long tube, vertically oriented tube and at the exit of the burner, we can see a conical flame. So, a conical flame is formed at the end of the burner port.

So, it is based upon the equivalence ratio etcetera the conical flame; the length of that etcetera or the angle if you see this, it has an angle here. So, this angle is α or cone angle; so, the angle etcetera varies based upon your velocity. So, this comes with the average velocity of U, the reactant mixture comes into the duct with an average velocity.

Please understand that, the velocity profile if you draw; it will be almost a parabolic shape for a fully developed flow inside a circular duct. So, you can see the velocity profile will be like this, but I am talking about the average velocity; this will be U.

So, the average velocity basically is U; its unburnt reactant velocity and this if you see this is a typical stream line. The unburnt gas flows and changes its direction; almost perpendicular to the flame surface and goes away again.

So, now the component of the velocity normal to the flame surface; this is the surface normal to the flame surface, what is the component of this U? That is what we are interested in; that will be the laminar flame speed. So, a conical premix luminous flame is formed at the exit of the Bunsen burner.

If U is the average velocity of the reactant mixture in the burner tube and α is the half cone angle as indicated here; then the velocity component normal to the flame surface is $U\sin\alpha$. So, dissolve this; you know the half angle and you know the velocity and perpendicular component to the flame surface is $U\sin\alpha$.

This will be equal to the laminar flame speed; that means, $S_L = U\sin\alpha$; sin of half cone angle. So, in this case what happens is we have a reactant mixture which is actually flammable in nature.

So, if you see this, without requiring additional fuel or additional oxidizer, this reactant mixture will burn. So, it burns and forms a conical flame over the exit of the burner and how to calculate the laminar flame speed in this case?

See, in the previous case you can see a long duct is there and open end is ignited, a flame which is slightly curved propagates over this tube. And you know the starting position and ending position; you can mark some two positions of distance L and calculate the time the flame takes to propagate through this distance L; you can get the S_L value.

So, let us say this is the distance L covered by the flame in time t. So, S_L can be calculated as L/t. So, it is almost any propagation; you can also divide into several lengths and see whether the flame propagation is steady; that means, if you take any distance, it takes a particular time. If you take another distance at another position; same distance, then it will take almost the same time to cover; so that is called steady propagation.

So, if you know the time taken for the flame to cross over a particular distance L, then you get the laminar flame velocity. So, in a moving flame we can get the laminar flame speed by just measuring the time which is taken for the flame to travel through a given distance L.

Now, on the other hand; if you have a stationary flame like this, Bunsen burner conical flame. So, the laminar flame speed in this case is the normal component of the velocity. So, you know you are supplying the mixture now at a particular flow rate. So, you know the mass flow rate of the reactant mixture $\dot{m}_R$.

Now, from this you can calculate the volumetric flow rate of the reactant mixture. So, that is nothing but $\dot{m}_R$ = ρ × volumetric flow rate. So, you know the volumetric flow rate now. So, volumetric flow rate of the reactant/area of cross section that will give you the velocity; so that will become the average velocity U.

So, the volumetric flow rate of the reactants that is m^3/s divided by the area of cross section which is in m^2. So, that will give you the velocity in m/s; the average velocity, superficial velocity. But please understand that the velocity actually varies in a non uniform manner across the radius.

Now, this U is the average velocity; having measured the flow rate, mass flow rate you can calculate the average velocity U. And you can see the flame which is formed and by taking a photograph of the flame, you can measure optically the cone angle α; the half cone angle α.

So, once you know the half cone angle α and the velocity U; the laminar flame speed S_L can be determined by Usinα. So, here you see that the flame is stationary and you are measuring the velocity of the unburnt reactant; reactant mixture and measuring the cone angle, by doing so, you can calculate the S_L value.

The laminar flame speed can also be determined by dividing the volumetric flow rate V_R of the reactant by the surface area of the flame. So, S_L can be directly found by dividing the volumetric flow rate divided by surface area of the flame; now you know the cone surface and you can measure.

So, a conical flame is formed; the surface of the cone can be measured correct. A_S is the surface area of the cone. So, once you know that then the volumetric flow rate of the unburnt reactant divided by the surface area of the flame that will give you the S_L value; that is another method.

So, please understand that both of this can be used; almost same result will be got, either you measure the α and calculate velocity unburnt gas velocity, average velocity U and substitute that like this. So, Usinα; you get S_L or you can get the volumetric flow rate divided by the area of the flame that will also give the S_L value.

Now, please understand here in this flame we have put the luminous premixed flame which is conical in shape and that is a outer diffusion flame. This will form based upon the equivalence ratio of the mixture. See for example; if the equivalence ratio of the mixture is lean, less than 1 or less than or equal to 1, stoichiometric or lean in fuel, there is excess oxygen.

So, what happens is complete combustion takes place; so all the combustion is over in this cone itself; then only hot gas surrounds this. Hot gases will go up, rise up above the flame. On the other hand, if the fuel mixture is rich that means the equivalence ratio is more than 1 then what happens?

Only you are supplying oxidizer to burn a given amount of fuel; then the excess fuel which is there, will not have oxygen. It will go out of the flame and that will burn as a diffusion flame. The excess fuel which is coming out of this conical flame, you will have air which is coming from the ambient. So, air will be entering from the ambient and a flame will be formed; so that is called outer diffusion flame.

So, only at the point where this excess fuel which has come out of the premixed flame and the air from the ambient mixes; so, it is a mixing controlled, the ambient air comes towards the flame surface and the excess fuel which is leaving the conical flame will also reach that surface.

So, where they mix at stoichiometric proportion, this outer diffusion flame will be formed. So, in the case of lean or stoichiometric mixture; you do not have fuel, fuel almost burns like in the stoichiometric case, the fuel almost burns. And the lean case; fuel will burn and only the hot products with excess oxygen comes out.

So, there is no problem in that, but if you go for rich mixture, then the excess fuel which is not able to burn within the cone because it does not have enough oxygen to burn; it comes out and the ambient air entrains into this and they mix and form a diffusion flame. So, two flame structure will be formed.

So, when the reactant mixture is rich; then another non luminous non premixed or diffusion flame surrounds this conical premixed flame. So, this is the important thing we should understand. So, in the Bunsen burner we typically form a conical flame and by measuring the average velocity and the half angle of the cone, we can get the laminar flame speed.

It is also measured by measuring the surface area of the flame and dividing it by the volumetric flow rate of the reactants. Now, if the fuel the Φ is rich, greater than 1, then what happens is the excess fuel which is coming out of the conical premixed flame without having enough oxygen to burn; that will burn with the oxygen from the atmosphere.

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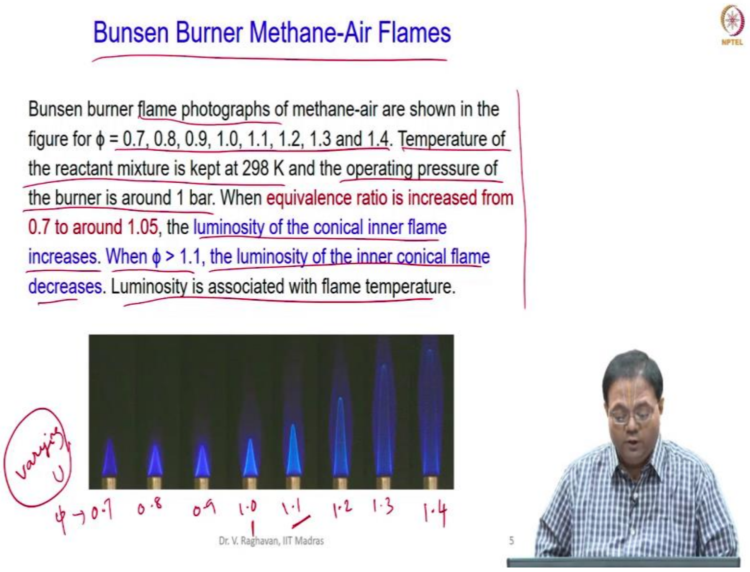

Bunsen Burner Methane-Air Flames

Bunsen burner flame photographs of methane-air are shown in the figure for ϕ = 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3 and 1.4. Temperature of the reactant mixture is kept at 298 K and the operating pressure of the burner is around 1 bar. When equivalence ratio is increased from 0.7 to around 1.05, the luminosity of the conical inner flame increases. When ϕ > 1.1, the luminosity of the inner conical flame decreases. Luminosity is associated with flame temperature.

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5

Now, for methane-air flames, several equivalence ratio are used here and the flame shape, photographs is shown in this particular figure. So, equivalence ratio is varied from 0.7 to 1.4; all the values are given. So, 0.7, 0.8, 0.9; this is 1 and this is say 1.1 and I will write everything; so 1.3, so this is 0.8, 0.9.

So, if you vary the equivalence ratio; you can see that the flame shape, height, the luminosity, luminosity is the bright portion of the flame, everything varies. So, if you take this; this is stoichiometry. So, when you say 0.7, 0.8, 0.9 etcetera, you have excess oxygen. And now we can see that the diffusion flame in the outer; outside the conical flame, premixed flame the diffusion flame is not present.

Once you go out of this say 1.1 etcetera, you can see that you have another flame. You can see this clearly, when you go for richer and richer mixtures. So, the conical part is luminous that is brighter and the outside is not so luminous; it is called non luminous. So, when you use a methane type fuel; you get this.

Now, Bunsen burner flame photographs is a direct flame photograph of methane and air. So, methane is the fuel and air is the oxidizer. So, several equivalence ratios varying from 0.7 to 1.4 has been illustrated in these photographs. Now, you can see that the cone angle varies; you know when you want to supply a mixture at a particular flow rate, you have a particular velocity U.

So, you are using a same burner; so we have to see at what velocity, a stable flame will be got for a given equivalence ratio. Please understand that you cannot have a single velocity U and only vary the Φ and get this. See please understand that U is also varying, this is not a constant U. Please understand that the velocity of the reactant mixture is not constant; we cannot get the stable flames when I do so.

So, what we do is based upon the equivalence ratio, we need to vary U in a small range so that you will get a stable flame. What is stable flame? This flame is seen to anchor in the burner exit like this, you can see the flame will be; it will be slightly away, it is like 1 or 2 mm or 3 mm away from the burner rim, but it will be very close. If you see the overall thing, you will not even see any gap between the burner rim and the flame anchoring point.

So, this is the edge of this; base of the flame will be almost very close to the this. So, based upon the equivalence ratio, you have to vary the U; the average reactant velocity such that the stable flames are formed and such flame, that means, in these cases please understand that the U is not constant.

If you want to have U constant, then you have to vary the burner diameter. Since the same burner is used, the U has to be varied to get the stable flames. Now, you can see that the angle; the cone angle etcetera are very crisp. When you go till say 1.1, you can get almost a crisp cone angle; cone shape and you can measure the cone angle easily.

But when you go to richer side, you can see that the cone is not as crisp as the previous case the length increases and a curvature forms on the top and so on. So, actually speaking the velocity; the cone angle here you have to average, you have to average it and take. So, it will be not very accurate when you measure the cone angle in this case.

But the surface area of this bright flame can be measured by integrating the contour line of the bright surface; we can get the surface area and volumetric flow rate you know. So, volumetric flow rate divided by the surface area gives the S_L value. So, we can get the S_L values by this.

So; obviously, you can see that based upon the equivalence ratio; there are two things which is changing; flame shape itself changes. For example, the flame height is higher; it decreases and decrease again. Then at 1, it increases; then you can see increasing trend in the flame height.

Then, you can see the luminosity of the flame; here it is not so luminous, but if you take 0.9 or 0.8, 0.9, 1; you can see the luminosity increases. Even till 1.1, you can see that the luminosity increases, as the equivalence ratio is increased. So, luminosity is the bright inner cone part that increases as the equivalence ratio is increased from the lean side; 0.7 onwards to say 1.1, 1.1 is slightly richer.

After that you can see there is a notable decrease in the inner flame luminosity. So, you can see at 1.2 etcetera there is a sharp decrease in the luminosity. So, temperature of the reactant mixture is now kept same; in all these cases. U is varied and the Φ is varied to get these photographs.

Now, what happens? Similarly, operating pressure also is kept at around 1 bar. Now, equivalence ratio is increased; the luminosity of the conical inner flame increases, when you increase the two points to say 1.1, 1.1 also we can say. At 1.05 we get the maximum luminosity.

Then, what happens when the Φ is greater than 1.1; the luminosity decreases. So, luminosity is associated with the flame temperature, we will see that. So, when you increase the Φ, gradually from a lean value to a richer value, you will see notable changes in the flame shape; the crispness of the cone angle, then the luminosity of the inner cone.

And in the rich cases, you will see the diffusion flame which is formed which is not seen in the lean cases. It slightly it forms in the stoichiometric region due to some leak of some radicals etcetera away from the flame. But after that, you can see in the rich side the fuel coming out unburnt; burns with the help of the atmospheric air and the diffusion flame forms over this. That will be one of the reasons why the luminosity decreases. So, this is the important characteristics of the Bunsen burner flames.

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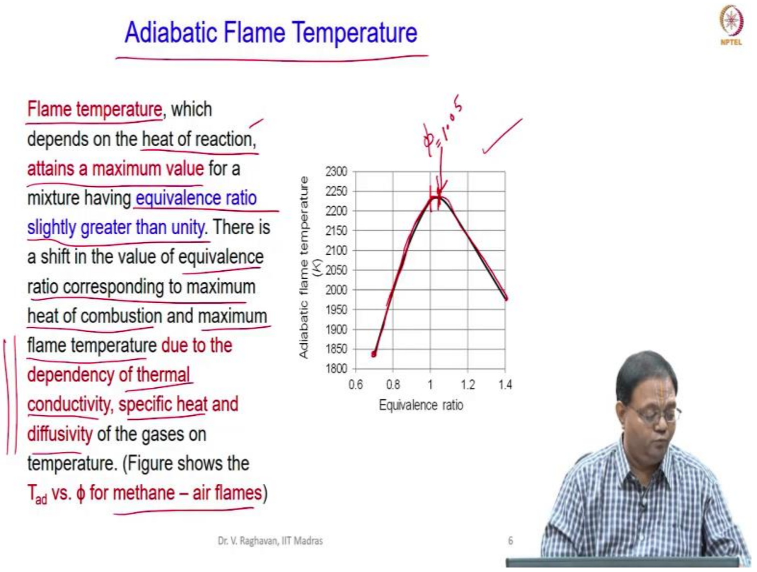

Adiabatic Flame Temperature

Flame temperature, which depends on the heat of reaction, attains a maximum value for a mixture having equivalence ratio slightly greater than unity. There is a shift in the value of equivalence ratio corresponding to maximum heat of combustion and maximum flame temperature due to the dependency of thermal conductivity, specific heat and diffusivity of the gases on temperature. (Figure shows the T_{ad} vs. ϕ for methane – air flames)

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6

Now, let us see how the adiabatic flame temperature varies with equivalence ratio? Because that is very important; the flame as I told you the luminosity varies as the flame temperature. Similarly, the flame speed also varies or it is affected very much by the adiabatic flame temperature.

So, adiabatic flame temperature is the maximum efficiency attained; so that is the characteristic temperature which we want. So, the flame temperature actually depends on heat of reaction, but the heat of reaction attains a maximum value for a mixture, when it is stoichiometric; 1; $\Phi = 1$, the heat of reaction attains the maximum value.

So, when you increase this; what happens is the heat of reaction will be the maximum. Then if you go to the leaner side, the dissociation etcetera will take place. So, it will decrease again. So, heat of reaction variation is different; see I am not talking about the standard heat of reaction, any heat of reaction, given some temperature for the products.

Now, flame temperature attains the maximum value when the mixture has an equivalence ratio which is slightly greater than unity; it does not happen at $\Phi = 1$. So, you may wonder that the flame temperature actually follows the heat of reaction, but it attains the maximum value.

See, a typical case for methane and air flames; again 0.7 to 1.4, the equivalence ratio is varied and the adiabatic flame temperature is calculated and it has been put here. You know this is the stoichiometric line and you can see the maximum is attained at around 1.05. So, this is equivalent ratio of 1.05; so $\Phi = 1.05$.

So, slightly richer point; you can get the adiabatic flame temperature becoming maximum you can see that. So, there is a clear shift in the equivalence ratio, corresponding to the maximum heat of combustion and maximum flame temperature; why? This is because of the properties; see for example, the thermal conductivity, specific heat and mass diffusivity etcetera are functions of temperature.

So, due to these variables, these properties changing with temperature; the maximum flame temperature itself changes, slightly shifts; this maximum occurs slightly to the right of the $\Phi = 1$ line; so, it occurs at the richer portion; so this variation we should understand.

So, what happens when the mixture is lean? Say 0.7, what happens? You have excess nitrogen; lesser fuel to burn with excess oxygen and excess nitrogen; so obviously, the dilution effects come into play; so the flame temperature is less. As you increase the fuel in the mixture due to more heat release this increases, actually the maximum heat release occurs at this point equivalence ratio 1.

So, we would expect that the adiabatic frame temperature also will reach the maximum here, but due to the dependency of the properties like thermal conductivity, specific heat and mass diffusivity etcetera. See thermal conductivity, specific heat, density etcetera will contribute to α; this is the thermal diffusivity. So, thermal diffusivity then mass diffusivity etcetera, those vary with temperature and also affect the calculation of the adiabatic flame temperature.

So, you know to measure it; so the thermal process are affected by the variation of the properties with the temperature. As a result of that, you get the maximum flame temperature at slightly richer part; not at the $\Phi = 1$ line; so this shift you should understand. So, this is the characteristic variation; now it reaches the maximum at the slightly richer part, then what happens? Dissociation etcetera continues, you have more fuel than what we can burn with the oxygen which is supplied.

So, what happens in this case is the fuel only burns partially; due to which the heat release decreases and also the flame temperature. In this wing, you can see that both the flame temperature as well as the heat release decreases; so that is fine. So, this decrease is due to the partial combustion of the fuel only; so it needs more air to burn; at this point this decreasing trend is seen.

So, the adiabatic flame temperature variation should be understood because the flame speed variation follows pretty much this variation; that is what we are going to see next.