Fundamentals of Combustion

Prof. V. Raghavan

Department of Mechanical Engineering

Indian Institute of Technology, Madras

Lecture - 43

Laminar Diffusion Flames - Part 3

Diffusion flame characteristics and flame structure

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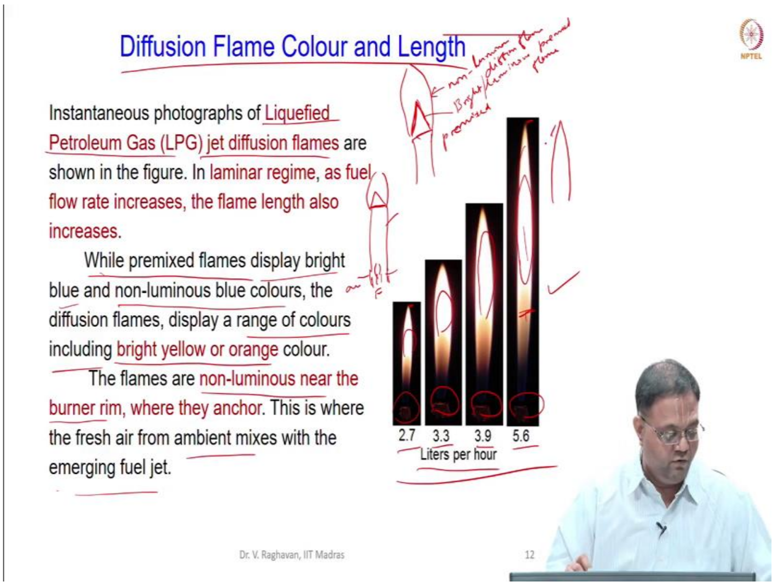

Diffusion Flame Colour and Length

Instantaneous photographs of Liquefied Petroleum Gas (LPG) jet diffusion flames are shown in the figure. In laminar regime, as fuel flow rate increases, the flame length also increases.

While premixed flames display bright blue and non-luminous blue colours, the diffusion flames, display a range of colours including bright yellow or orange colour.

The flames are non-luminous near the burner rim, where they anchor. This is where the fresh air from ambient mixes with the emerging fuel jet.

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We will see some characteristics, colour and length of the flames. So, for example we have chosen the LPG flame. So, take a burner of some diameter. So, some radius r and try to inject the fuel. For example, the fuel flow rate can be in liters per hour (lph), volumetric flow rate can be lph and I fix a value say 2.7 lph of LPG is injected to this port or the circular burner and when you ignite this you get a flame like this.

As I increase the flow rate say 2.7 to 3.3, 3.9 and 5.6 you see an increase in the flame length. This is a visible flame, and the visible flame length increases as the flow rate of the fuel is increased. So, this is the main characteristic. So, as I told you, at a given flow rate what is the length at which the complete combustion of things take place.

For example, this is the length that the flame height, the tip of the flame indicates this point where the fuel has found enough oxygen to burn that is what the flame height indicates. So, the instantaneous photographs, where you can see some small oscillations may be there.

So, when I take a photograph at a given time instance the flame looks like this. Say jet diffusion flame, that means only LPG comes out of the nozzle or the port or in this case, it is a circular pipe, only LPG comes out of that. And due to the momentum, it entrains air from the atmosphere and mixes and where air and LPG has mixed at stoichiometric proportion, we get the flame boundary.

And based upon the flow rate of the fuel, there is a particular height the diffusion flame has attained. So, the flame height actually depends upon the flow rate. So, that is how we got this. So, now let us see, when we saw the characteristics of a premixed flame, again same Bunsen burner, we got a conical flame here. Conical flame which is actually bright, bright blue colour conical flame. And there was another flame which is non luminous, we called it non luminous diffusion flame.

This was the bright or luminous premixed flame. So, this is about the premixed flame. Overall, the flame was shorter. So, let us try to compare the premixed and diffusion flame in the same circular burner. Say for example, if I take Bunsen burner, I have a nozzle which will inject fuel. So, fuel is injected and there will be holes through which air entrains and a premixed flame forms.

So, if we shut up these holes for air entrainment, only fuel comes out and I get the diffusion flame. When I allow the air to enter, then I get the non-premixed flame. So, non-premixed flame or jet flame is got by arresting the air flow into the mixing chamber of the Bunsen burner. So, same burner can produce both non-premixed or the premixed flame. So, now, let us see the characteristics.

When we saw the premixed flame, we saw a bright or luminous premixed cone, conical flame which is short. Then again non luminous blue colour diffusion flame which is there, above the premixed flame. So, this is the characteristic. Shorter flames, slightly bright blue colour, but not very orange or any bright colours as what we see in this. So, here you can see that range of colours are present.

Range of colours, you can see some black colour, some bright orange color then a very bright white colour then again in the base you can see some slightly bluish colours and so on. So, different types of colours are exhibited by the diffusion flame and they are luminous.

That means, if you have a dark room and you use a diffusion flame it will lighten up the room, but on the other hand if you take a premixed flame. It will not light up the room; that means, it will not be luminous basically.

So, when we have a premixed flame, bright blue inner cone, non luminous blue colour in the outer mantle, diffusion mantle was seen. But in the diffusion flame like this you can see a range of colours including bright yellow or orange colors etcetera.

Now, near the burner rim, this is the burner rim basically, near the burner rim flame is non luminous because you can see that there momentum is higher and the entrainment takes place and proper mixing occurs, just away from the potential core. Potential core is a triangular region there.

So, just away from the potential core, you can see proper mixing of air which is coming in due to the high momentum of this jet due to viscous effects and the air entrains there and proper mixing takes place. So, once you go away, some products also leave. So, the air is not anymore very fresh.

So, at this location, the base of the flame normally the fresh air comes in and premixes. It comes and mixes and you get a flame which is characterized by a non luminous colour.

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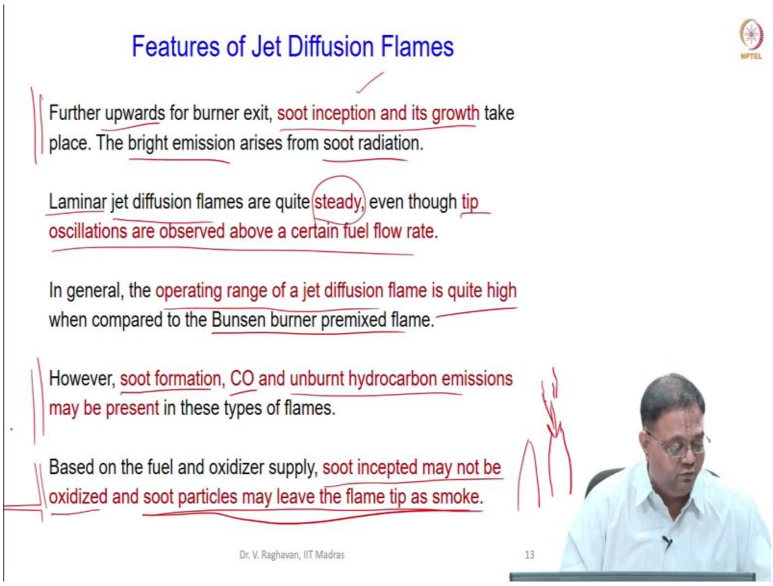

Features of Jet Diffusion Flames

Further upwards for burner exit, soot inception and its growth take place. The bright emission arises from soot radiation.

Laminar jet diffusion flames are quite steady, even though tip oscillations are observed above a certain fuel flow rate.

In general, the operating range of a jet diffusion flame is quite high when compared to the Bunsen burner premixed flame.

However, soot formation, CO and unburnt hydrocarbon emissions may be present in these types of flames.

Based on the fuel and oxidizer supply, soot incepted may not be oxidized and soot particles may leave the flame tip as smoke.

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So, now when we go further upwards, soot inception and its growth will take place. Normally, all fuels we can say. So, even in methane people have talked about soot. So, when we actually go for say ethane, propane etcetera soot production will be there.

But the thing is whether the soot, which is produced is oxidized or not within the flame, that is the question. Basically, the bright colours what you see here these are all due to soot radiation only. So, LPG basically has both saturated and unsaturated hydrocarbons. So, that actually leads to production of soot.

So, in this particular case, soot inception and growth are inevitable and this is going to be there. But the thing is that, soot which are incepted and formed inside are also oxidized within the flame. So, that is the thing. So, the bright emission that bright color comes due to the soot radiation. The soot also can radiate the light. So, the soot radiation is the reason for the bright colour of this particular LPG flame.

Normally, you can see that these are very steady flames. Some oscillation in the axial direction, slight oscillation in the radial direction is also seen basically. But, they are in the laminar regime they are not very high fluctuations. High degree of fluctuations will not be seen and the flames are phenomenally very steady. Some tip oscillations basically can be observed. Beyond a particular flow rate, tip oscillations can be formed. So, in the laminar regime they are the diffusion flames are quite steady, small flames.

See even in candle flames you can see that the flames are phenomenally steady, but sometimes there are some vigorous oscillations we can see in the candle flames also. So, it is very similar to a jet diffusion flame, but from a condensed fuel. But this is a diffusion flame coming from a gaseous fuel.

Now, one more difference. So, that means that you can see, even if you take a premixed flame as I told you the soot etcetera will be very minimum there because you know you already provide a lot of oxidizer. So, oxidizer may actually oxidize the soot which is formed. Basically, for soot to form, you need precursors of soot, but if you are aware of premixed flame this precursor formation itself will be very little.

So, the soot inception and soot formation is normally very low in a premixed flame. But in the case of diffusion flame soot actually forms and whether the soot is oxidized within the flame or not is the question. So, there is a flow rate which will determine that. At lower flow rates basically, the soot which is incepted and formed, it will be actually oxidized within the flame itself.

The third important characteristic of the diffusion flame is, it has an operating range which is actually quite high. When you compare to the premixed flame, say take Bunsen burner premixed flame, you have only a certain small range of velocity of the premixed reactant which will give a stable flame. Or else we have seen that there are two instabilities which can occur, flash back and lift off.

But compared to that operating range, for a premixed flame, the operating range of a diffusion flame is much higher. So, that is why in many applications these are preferred. Not only that, the flashback instability what we saw in the premixed flame will not be present in the diffusion flame because only fuel is coming out.

So, the flame cannot go inside the fuel alone because it needs oxidizer. So, the flashback cannot be observed in the diffusion flames, but in the premixed flame that is another important instability what we get. However, disadvantage of the diffusion flame is as I told you the soot formation. In some cases when the flow rates of the fuel are very high or higher than a critical value then you can see that the soot which is formed cannot be oxidized within the flame and it will come out as smoke.

Then CO; actually, there is no premixing taking place. If proper entry of oxygen is not there or it is diluted by products or anything like that, then unburnt hydrocarbons and CO can be present in the emissions.

These are the disadvantages. In premixed flames you can see that these are all very low. All these three are very low and negligible in the premixed flames, but in the diffusion flames, if we do not properly control that, we will end up with these emissions; soot, CO, unburned hydrocarbons and so on.

So, these are the comparison. So, comparison of this characteristic of diffusion flame as well as I am trying to compare these characteristics with the premixed flames. Now, as I told you based upon the flow rate soot incepted may not be oxidized and the soot particle may leave the flame tip as smoke.

When you go back to this you can see that the tip is closed like this. So, you can see the flame tip is like this, closed properly. And the bright yellow colour which is forming here at the tip, it is not as bright as the yellow, the bright colour which is shown below the tip.

So; that means, the soot which is formed somewhere at this location radiates and within the length of the flame soot is oxidized also. So, the flow rate of fuel is such that it may entrain enough oxygen not only for its oxidation, but also for soot oxidation. So, the soot is not escaping this.

So, soot which is formed is well oxidized within the flame itself, but there is a particular flow rate where the soot may not be oxidized. So, the soot particles may leave the flame tip and we will see smoke. That is the carbonaceous particles will leave the flame itself. That means, the tip which is closed like this, may open up, and you can see the soot particles, the smoke coming out of this.

So, the tip may open up and the particles can come out. So that means, see there are favorable conditions required for oxidation, not only oxygen presence, basically some radicals OH etcetera is required plus temperature should be suitable for oxidation to be occurring and so on.

So, if the scenario is not enough for the soot oxidation to be completed within the flame then the flame may open up. Tip may open up and the soot particles can leave and that is called smoke. So, these are the actually important disadvantages. These two, soot formation, CO formation, unburned hydrocarbons etcetera are the disadvantages.

Also, when you increase the flow rate you can see this. When you increase the flow rate, I want the operating laminar regime. So, the laminar regime, when I increase the flow rate you can see laminar flame height is growing. So, we have to have some control of that also. If in some cases the flame height, I mean, cannot be more than a particular value, but we need to produce much power, so, I need to supply more fuel and so on.

So, we have to see lot of controls for this. So, other disadvantage is the control of this flames. We have to take care of it properly. But the main advantage is basically it is safer than the premixed flame because the flashback is not there, then the operating range is much wider than the premixed flame. So, these are the two main advantages.

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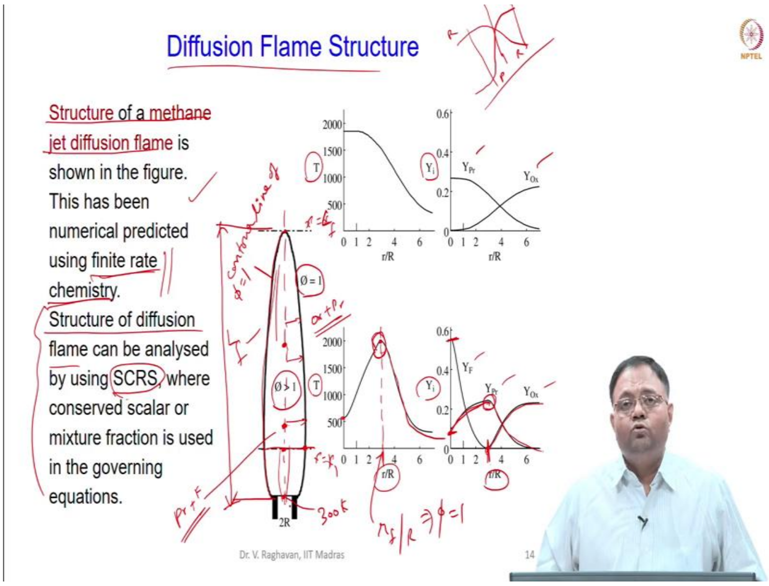

Diffusion Flame Structure

Structure of a methane jet diffusion flame is shown in the figure. This has been numerical predicted using finite rate chemistry.

Structure of diffusion flame can be analysed by using SCRS, where conserved scalar or mixture fraction is used in the governing equations.

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Now, as we saw the structure of a premixed flame, we will now see the structure of a diffusion flame. So, structure of a premixed flame we know that the temperature, unburnt reaction temperature increases to the flame temperature. So, this reaction zone basically and this is premixed zone what we call. So, premixed and reaction zones and the reactants are consumed like this. Reactants and products are formed and heat release happens. So, this was the typical structure of a premixed flame.

So, across the flame when I try to plot the profiles of temperature mass fraction etcetera, I get the structure. Similar to this, across the flame; see if you see this as I told you this is center, center line of the flame.

And from the center line the radial directions I try to plot the profiles of the quantities like say temperature, then mass fractions of say oxidizer, product etcetera. So, here fuel products oxidizer etcetera. I am trying to plot in a radial direction and two actual locations I have selected here across the flame.

So, for example, the flame sheet, this is $\Phi = 1$, what it indicates? The locations where fuel and oxidizer have mixed in stoichiometric proportions. So, $\Phi = 1$ line, contour line of $\Phi = 1$, this indicates the locus of all the points where the fuel and oxidizer has mixed in stoichiometric proportions and this will be the flame zone. How it is going to be flame, we will see.

So, now what we have shown in this figure is the structure of methane jet diffusion flame. So, methane is coming out of the nozzle. Here, it is the circular pipe of radius R. Now, this is numerically predicted profile and we have used a finite rate chemistry that means we have used some chemical kinetic mechanism.

So, this is $\Phi = 1$ contour, where the reaction zone may have only finite thickness, some finite thickness it will have. So, when the reaction rates are infinitely fast then the thickness of the flame will tend to 0, but here we have used finite rate chemistry that means, we have some thickness for the reaction zone that we have to keep in mind. So, I am emphasizing that point.

So, on the other hand instead of doing this numerical prediction using finite rate chemistry, I can also do the average reaction rate of a diffusion flame by simple chemical reacting system which we saw in the governing equations where we got rid of all the reaction rate terms by using conserved scalars. And we wrote the equation in terms of mixture fraction and we retrieved the variables back from calculation of the mixture fraction.

So, by using that we will get, but we assumed constant properties etcetera there and we got the structure. Here also we can get a structure and a reasonable value for the flame height.

So, these are the two things. Mainly, I am interested in the flame extents right, the height of the flame, and the radius of the flame at every axial location and the height of the flame. These are all flame extents which is what we are interested in. The flame height is very important and the flame radius is also important.

So, when you try to get this, we can either go for this type of finite rate chemistry prediction or without using chemistry go for SCRS, a simple chemical chemically reacting system.

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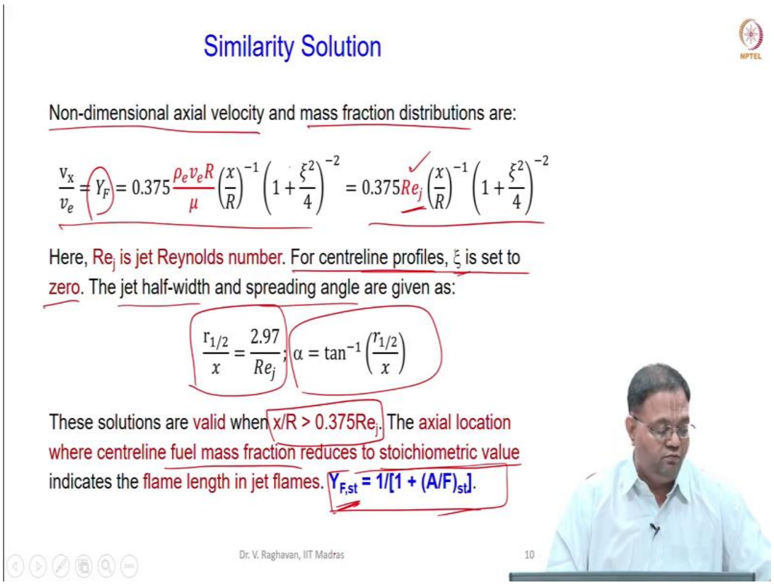

Similarity Solution

Non-dimensional axial velocity and mass fraction distributions are:

$$\frac{v_x}{v_e} = Y_F = 0.375\frac{\rho_e v_e R}{\mu}\left(\frac{x}{R}\right)^{-1}\left(1+\frac{\xi^2}{4}\right)^{-2} = 0.375Re_j\left(\frac{x}{R}\right)^{-1}\left(1+\frac{\xi^2}{4}\right)^{-2}$$

Here, Re_j is jet Reynolds number. For centreline profiles, ξ is set to zero. The jet half-width and spreading angle are given as:

$$\frac{r_{1/2}}{x} = \frac{2.97}{Re_j};\ \alpha = \tan^{-1}\left(\frac{r_{1/2}}{x}\right)$$

These solutions are valid when $x/R > 0.375Re_j$. The axial location where centreline fuel mass fraction reduces to stoichiometric value indicates the flame length in jet flames. $Y_{F,st} = 1/[1 + (A/F)_{st}]$.

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So, that we will use. Basically, if you see in our analysis of the non reactive jets we have got this profile for Y_F, profile Y_F is this. Now, I want to find the flame height. I will just set $\xi = 0$ there and find the location of x, where $Y_F = Y_{F,st}$. I will get the flame height.

Or if I take the radial profiles of Y_F everywhere and try to get the radial locations of $Y_F = Y_{F,st}$, then I can plot this $\Phi = 1$ contour. So, even by the non reactive flow also you can get this $\Phi = 1$ contour. So, there is no reaction at all. But that is not important for us because what we assume there is the process which is going to control the flame location is only the transport processes.

Like diffusion in the radial direction, convection in the axial direction plus when the fuel and oxidizer mix at stoichiometric proportions instantaneously reaction will occur. The reaction is infinitely fast; that means, the flame will be very thin zone. So, that is the way you can analyze this. There also you can get structures basically, what we have put here.

So, how will you calculate temperature from that? Again, use the mixture fraction type of approach to get the temperature. So, that is also possible. So, to just get the flame height and the flame radius I can just do the non reactive analysis.

The only thing is it should be non premixed flame that is the fuel alone comes out and air mixes wherever they mix in the stoichiometric proportion the combustion will be complete, instantaneously and we get the thin flame zone like this.

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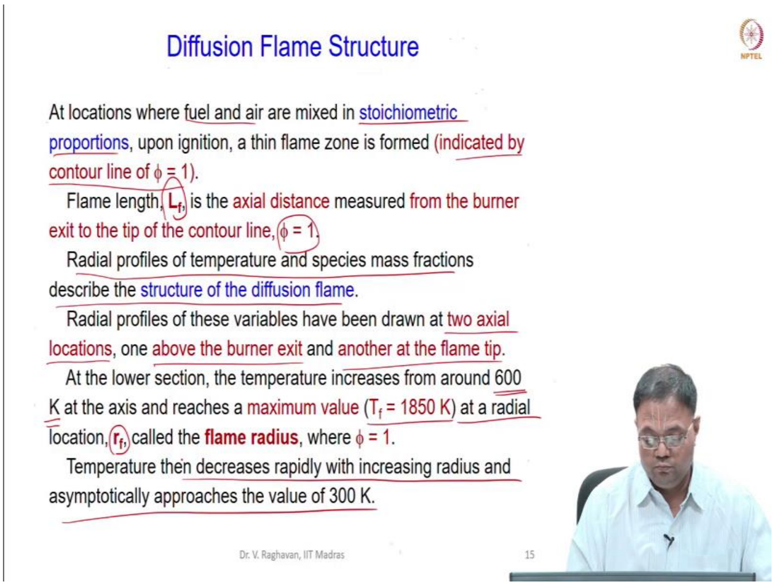

Diffusion Flame Structure

At locations where fuel and air are mixed in stoichiometric proportions, upon ignition, a thin flame zone is formed (indicated by contour line of $\phi = 1$).

Flame length, L_f, is the axial distance measured from the burner exit to the tip of the contour line, $\phi = 1$.

Radial profiles of temperature and species mass fractions describe the structure of the diffusion flame.

Radial profiles of these variables have been drawn at two axial locations, one above the burner exit and another at the flame tip.

At the lower section, the temperature increases from around 600 K at the axis and reaches a maximum value ($T_f = 1850$ K) at a radial location, r_f, called the **flame radius**, where $\phi = 1$.

Temperature then decreases rapidly with increasing radius and asymptotically approaches the value of 300 K.

Now, we will see some discussions on the structure of the flame. Now, as I told you, stoichiometric mixing between the fuel and air takes place. That is upon ignition, the flame zone forms there. So, that is indicated by the $\Phi = 1$, that is the stoichiometric contour line.

So, that is one of the important point we should understand. Then the flame length L_f is the axial distance measured from the burner exit to the tip of the contour line of $\Phi = 1$. So, going back from this point to this point, this will be the flame length.

So, that is the flame length. Now, flame radius also from $R = 0$ you can go to any location where $\Phi = 1$ is appearing. So, that will be flame radius that also varies with x like this. So, that also we can see.

So, radial profiles of temperature and species mass fraction describe the structure. Across the flame, radial profiles go across the flame. So, that will define the structure of the flame as I told you. So, now in this particular case we have plotted the radial profiles at two axial locations.

One slightly away from the burner exit or the nozzle exit which is there; $x = 1$, I will say x_1 and one more at $x = x_f$, I will say that is the end of the flame or flame length L_f, I will say L_f.

So, these are the two locations the structure is plotted. Please understand in the case of premixed flame only one structure is enough because uniform flame is there, unburnt side and burnt side. The unburnt gas comes from the left and burnt gas leave from the right and so on.

So, there we get only one profile, but here since it is actually a two-dimensional variation here, we can see that the profile will vary as per the location what we choose.

So, at the flame tip there is a difference in the profile. Anywhere inside the flame tip the magnitude of the maximum value and extent of the radial location etcetera may change, but the similarity will be still there within the flame, but at the flame tip we will get a different profile. So, we have chosen one location, axial location within the flame and one axial location which is at the flame tip.

So, we will discuss the structure in these two locations. So, radial profiles of these variables have been drawn at these two axial locations. One is within the flame, above the burner exit and another one at the flame tip. Now, at the lower section that is within the flame, we will see the description of how the profile varies. Temperature increases from around 600 K at the axis.

We can see temperature in this particular location is 600 K and it increases to a maximum of say around 2000 K at the flame location, then decreases asymptotically away. So, when I try to plot in this direction, I am getting this. So, you can see that here the temperature is 300 K and when you go up from the flame the heat is transferred to the axis.

So, you can see at the axis itself temperature has reached 600 K and from that it increases to the flame temperature which is say 1850 K, around 2000 K and then the location at which it attains this is the flame radius R_f.

So, this location at which now that will be the r_f/R, that is the location at which $\Phi = 1$. So, this is the location at which $\Phi = 1$ also. So, at the location of $\Phi = 1$, you get r_f/R and the maximum temperature is attained there which is very close to 2000 K.

And after that, the temperature decreases rapidly and with increasing radius asymptotically approaches ambient temperature. So, there is a decrease and also asymptotically approaches. So, there is a non-linear relation. So, rapid decrease and asymptotically reaching the ambient temperature further away. So, this is the typical profile.

Anywhere within the flame, you can plot this below the flame tip. Anywhere if you plot some type of this will be there. Maybe if you go to location, you will see a higher temperature at the center itself and at this, lower value of R you will get the peak, then it goes again.

But the similarity of the profile is still conserved. Like the values of the central line temperature, maximum temperature, radial location of the maximum temperature etcetera may change within the flame height wherever you try to plot.

But the similarity will be there. From a lower value at the axis it increases to the maximum value at the flame location which is indicated by $\Phi = 1$ and then it decreases rapidly and asymptotically reaches the ambient temperature that is the way the profile varies within the flame.

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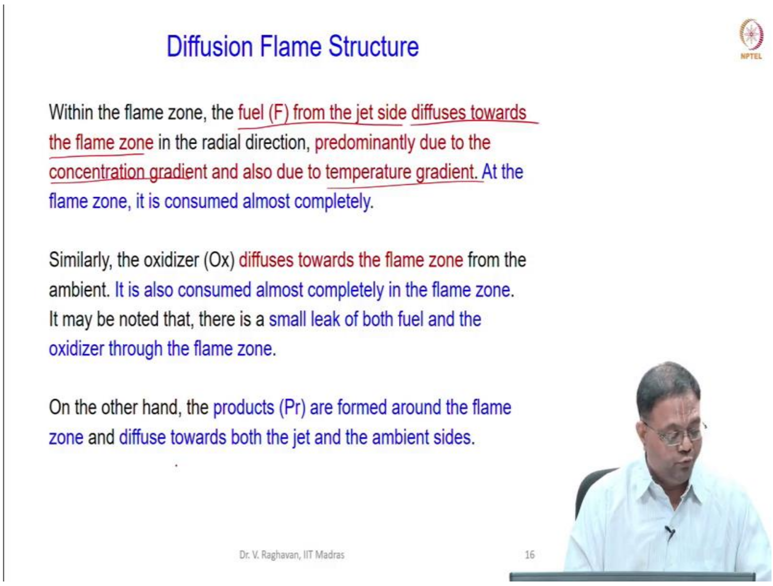

Diffusion Flame Structure

Within the flame zone, the fuel (F) from the jet side diffuses towards the flame zone in the radial direction, predominantly due to the concentration gradient and also due to temperature gradient. At the flame zone, it is consumed almost completely.

Similarly, the oxidizer (Ox) diffuses towards the flame zone from the ambient. It is also consumed almost completely in the flame zone. It may be noted that, there is a small leak of both fuel and the oxidizer through the flame zone.

On the other hand, the products (Pr) are formed around the flame zone and diffuse towards both the jet and the ambient sides.

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So, that is what is described here. Now, the other thing, let us take fuel. Fuel from the jet side that is the core of the jet, that is the axis side diffuses towards the flame zone in the radial direction.

So, predominantly due to diffusion only, there is no convection is there. So, predominantly it is due to diffusion and it is due to both concentration gradient and temperature gradient. In most of the cases we can neglect this, but whatever be the effect Soret diffusion also we can add into the species conservation.

So, when you do this, then you can see that here the inner zone, in the inner zone fuel is only present. When I say $\Phi > 1$, I indicated $\Phi > 1$ here, so, the fuel will be higher, because the rich mixture. So, from this point, when I say $\Phi > 1$, it is not actually Φ because you can see when the flame forms Y_F is still active in this. So, Y_F is going to be 0 only at the flame tip.

So, Y_F is there, but I cannot say Φ here because Y_F plus some products which are formed in the flame zone also will be there in the inner zone. So, the product plus fuel will be predominantly there, but not oxygen. So, here in this zone, where I indicated $\Phi > 1$, there product plus fuel will be present. Outside this flame, oxygen plus products will be present. Fuel will not cross the flame zone from the axis outside the flame radius. Similarly, oxygen from the ambient cannot cross inside this. Very small amount of leak can happen, but not this. This is controlled by the mixing there. So, wherever appropriate value of stoichiometric condition is reached, flame zone is formed there. That means, at the flame zone the oxygen from the ambient has to be consumed, fuel from the axis side has to be consumed. Then only this will be formed. So, when I say $\Phi > 1$ region, I say it is a mixture of product plus fuel. In the outer side you will have oxygen plus products. So, this is the way the things are distributed. So, fuel cannot go to the outer side or oxygen cannot come into the fuel side.

So, that is now given here. You can see that at the exit fuel mass fraction is 1, at the exit of this pipe or the port or the nozzle you will see the mass fraction will be 1, but I have taken a location which is away from this. So, there some decay has happened.

Now, the mass fraction is 0.55, from that it decreases sharply to a 0 value at the location here. This is the same location where the maximum temperature is attained. See 1, 2, 3, around 3R/R = 3, the fuel is completely consumed here. Fuel is completely consumed here and the maximum temperature is formed. You can see that the product is also maximum at that point. That means, products are formed at the flame zone. Now, after the products are formed at the flame zone, they diffuse in both directions; in this direction and also in this direction. Now, based upon the concentration already some products are formed at the base of the flame. So, these products are also convected away. So, the concentration of product at the axis is higher. So, this diffusion is lower. Basically, you can see at the axis the concentration of product is much higher when compared to 0. Concentration of the product in the tending to zero at $R \rightarrow R_\infty$ correct.

So, within the flame there is accumulation of product plus unburnt fuel and outside you can see it is going to infinity. So, asymptotically you can see this it is reaching the 0 value, products are formed at the location where the fuel is consumed. Oxygen from the ambient comes and is consumed here. So, at the location where the fuel and oxygen are consumed products are formed and the maximum value is reached there. The products diffuse both sides, the radial diffusion is dominated. Then I can see the maximum temperature is attained at that location. So, this is the typical structure of a diffusion flame. Anywhere within the flame height you can draw this, but maximum values and the locations etcetera where the maximum is got, those locations etcetera will be different, but the they will be similar.