

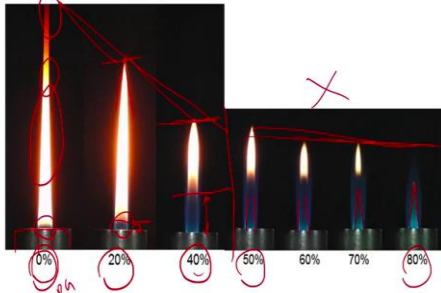
Fundamentals of Combustion
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Lecture – 47
Laminar Diffusion Flames - Part 7
Diffusion Flame Configurations
(coflow, crossflow and opposed flow flames)

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Effect of Partial Premixing

In order to control the combustion characteristics in such sooty flames, some amount of **primary air** may be added along with the fuel. LPG-air coming out of the core pipe is **not flammable** when the primary air content is less than ~40% of the stoichiometric value.



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Partial premixing, as I told you we will now try to add some amount of air in the fuel stream. Again, you can see this is the coflow burner basically, there is a core and annulus region. And this is the region where we are trying to now supply the jet fuel here. LPG is used, and some partial pre mixing we are doing.

Now, when I say 0%, there is no partial premixing, no primary air is supplied, only LPG is supplied at a given flow rate. The flow rate of LPG is kept constant in this. Now, we can see that smoke forms. Tip opens and the smoke forms.

You can see that the soot is not able to oxidize within this formation region or in this region, and the smoke forms here. So, we have selected a flow rate which is higher than the smoke point, and you can see that the flame will result in a smoky flame, tip will show some smoke coming out of that.

Now, I add 20% of primary air, you see that I am closing the flame, no smoke is there, so that is the effect. And two more effects are there basically. One effect is the flame height is very high here; we can see a rapid decrease in the flame height. Flame height is reduced tremendously. Also, the soot which is coming out as smoke in the earlier case here is now arrested, and there is no smoke coming out of the tip at all.

Now, increase it further to 40%. Now, you have to note that 40% is not flammable. If it is around 40%, less than or equal to 40%, this is not flammable, the mixture coming out of the port, fuel plus 40% primary air will not be flammable.

So, this is the limit. So, when you increase the primary air more than 40% approximately, then you get the flammable mixture.

So, you have to note that the LPG air coming out of the core pipe is not flammable when the primary air content is less than or around 40%. When I say around 40%, you can also take 40% into consideration, and this is not flammable. So, we can see that 20 to 40% there is a tremendous decrease in the flame height.

Second aspect is, you can see the blue region. Blue region here is very small because only at the base some air is available for it to burn. Now, due to the primary air, the blue region has extended to some height like this. When you say 40% air, flame height has reduced and the blue region has increased. Blue region height has increased. So, control of soot, control of extent, then better burning.

When I see more and more blue regions, we can see that more oxidation has taken place. It will make a premixed flame, and we will have more control over this. So, after this 50% onwards, it is flammable mixture. Please understand that. So, you can see that not much change in the flame height. So, from this to this, drastic reduction has taken place.

But after this when it enters the premixed combustion regime, you can see the flame length is not much affected. The flame is still and length is high here like this. So, flame length is not much affected. Because we can see that the laminar burning speed etcetera will be the characteristic, not the flame extent.

So, if you burn in the diffusion control regime, then the flame length will be the important characteristics. When you go towards the premixed regime, then the laminar flame speed will be the important characteristic. We can see that formation of triangular flame inside here; a premixed reaction zone is visible.

Also, when we go to about 80%, you can see the premixed cone. So, these are all the characteristics when you slightly add, but we will not do, so that is what this box is about. So, we will not consider this, because these are all flammable mixtures. So, these

are normally not considered. So, we go for primary aeration which will have the mixture not flammable.

Because if the flammable mixture exists out of the core flow, then there is problem of flashback. When you have a problem of flashback, then we have to restrict your flow rates. So, that means we cannot have the joy of operating the burner in a wide range of conditions which is the benefit what we gain from a diffusion control flame.

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Effect of Partial Premixing

Flame height decreases significantly with the addition of primary air.

Soot formation reduces and is oxidized within the flame.

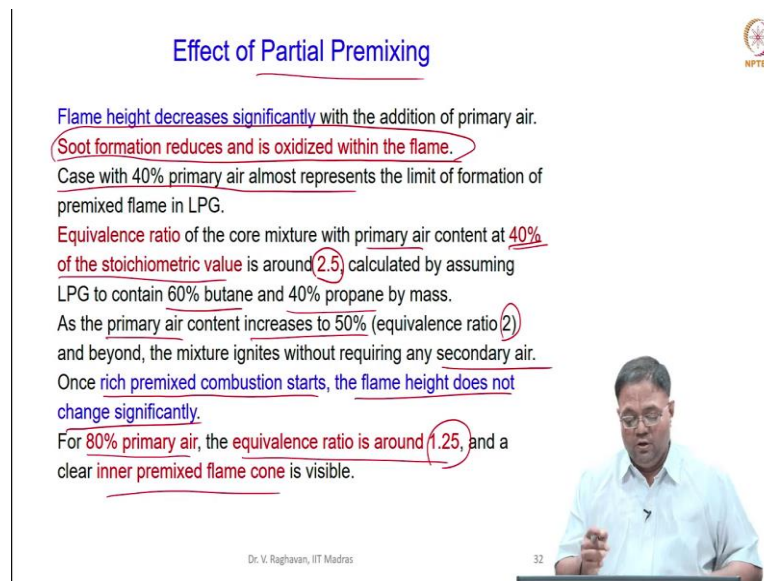
Case with 40% primary air almost represents the limit of formation of premixed flame in LPG.

Equivalence ratio of the core mixture with primary air content at 40% of the stoichiometric value is around 2.5, calculated by assuming LPG to contain 60% butane and 40% propane by mass.

As the primary air content increases to 50% (equivalence ratio 2) and beyond, the mixture ignites without requiring any secondary air.

Once rich premixed combustion starts, the flame height does not change significantly.

For 80% primary air, the equivalence ratio is around 1.25, and a clear inner premixed flame cone is visible.



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Now, let us see some aspects of effect of partial premixing. Basically, flame height decreases significantly that is what we have illustrated here. Clearly, flame height decreases significantly when you have a partial premixing. You can see that soot formation reduces and is oxidized within the flame, second aspect.

Now, when you increase this, third aspect is the blue region, the extent of blue region increases. So, here it is smaller, here it is smallest, then it increases and it increases considerably. Then, premixed flame forms. We do not really care about these positions, and I can see this. However, the main aspect is the reduction in soot. So, we do not have any soot formation at all, that is soot forms and oxidize within the flame.

Then as I told you, case of 40% air represent the limit of formation of premixed flame. So, just higher than 40%, you will get the get into the flammability limit. So, these are LPG flames. Considering LPG as a mixture of 60% butane and 40% propane by mass, if we calculate the equivalence ratio for 40% of the stoichiometric value, your equivalence ratio will be 2.5. So, that is the very rich limit.

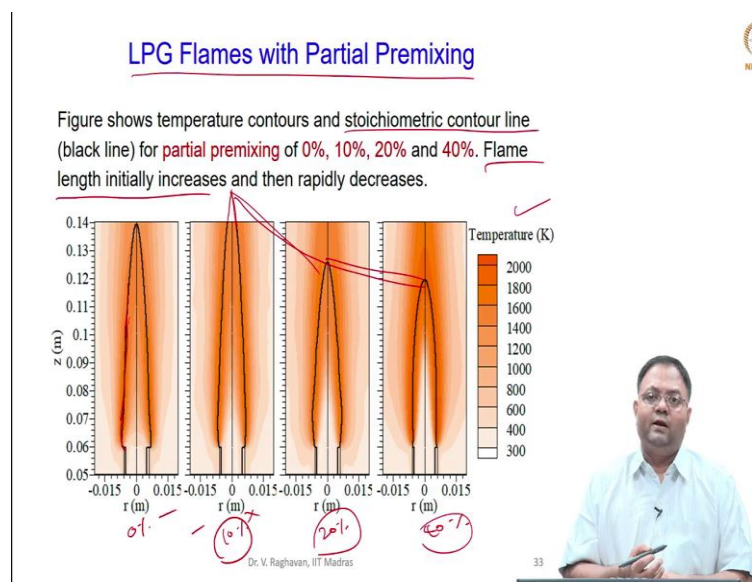
So, for this combination of propane and butane it will not be ignitable. If you slightly decrease the primary aeration, it will not ignite; slightly increase it will ignite. So, this is the rich limit of LPG for the primary fuel air mixture to be flammable.

Next, if the primary air content is increased to 50%, now equivalence ratio drops to 2, then you can see that the mixture will easily ignite without adding any more oxidiser. So, now what happens here? The secondary aeration is not required, it will burn. But anyway, if you see that rich mixture burns then more CO and even H₂ also will be present in the products. Anyway, you need additional air to burn it completely.

Now, rich premixed combustion starts, the flame height does not change that is what I have told here. Here, the drastic reduction in the flame height is not seen in this when you reach this. So, even here we have not supplied 100%. We have 50, 60, 70, 80% of the primary air supplied, that is not 100%. Even equivalence ratio is not 1 here, but you can see that the flame height does not change much.

At 80% primary air, the equivalence ratio is around 1.25, you can see clearly the inner flame cone. So, that is the transition from the diffusion to the premixed regimes. But we will now stop. As I told you when we want to operate the burner on diffusion mode, it is better to stop with this 40% which is the limit of the formation of a premixed flame.

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Now, again these are numerical results, numerically also we are seeing the same affects. You can see that here LPG flames are numerically predicted, the orange contour shows the temperature contours in Kelvin. The bright orange is 2000 K and white is about 300 K. Now, other than the temperature contours, it is also shown the dark line which represents the stoichiometric contour line.

So, stoichiometric contour line, that is the fuel plus the stoichiometric amount of oxygen required. You know the fuel mass fraction, and you know the mass fraction of the oxidizer. When they mix stoichiometrically in proportions what will be the locations where they mix like that? So, that locus is joined here and this contour line is got.

For example, this is 0% primary air, this is 10% primary air, 20% primary air and 40% primary air. And you can see this at 0%, you have a flame which is like a normal diffusion flame. But, when you initially add 10% of primary air, you get a higher length. You can see this; flame closes at a larger distance. So, flame length increases.

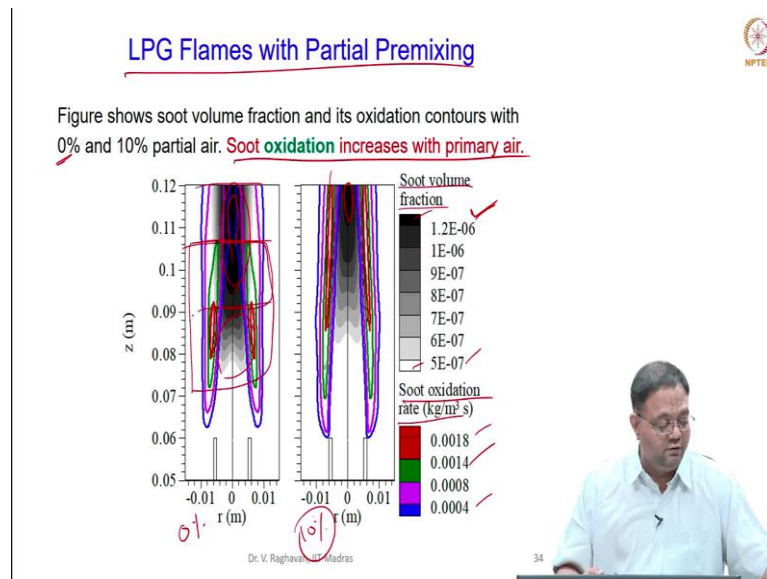
Initially, with 10% of the primary air, you will see that the volumetric flow rate of the mixture increases, so it is not able to burn faster. Because the oxygen or air is not enough to burn within this zone, since the flow rate is also increased. Due to the effect of increased flow rate and limited oxygen availability, the flame length slightly increases initially.

However, when you increase it to 20%, a drastic reduction happens in the flame height. At 40%, again there is a reduction in the flame height. So, this is the important thing we should understand about the characteristics of the flame.

And you can see that the flame radius is not much affected in all the cases almost the same flame radius is there. But the flame height initially slightly increases when you add air. So, this is not the correct premixing to do. Do 20%, you get good reduction in this and again 40%, it is reduced.

But let us see soot, the primary aeration, even though it slightly increases the flame length that is not a big problem for us. What it does to the soot is important? So, let us see that. Let us take these two cases first 0% then 10% and see how the soot behaves.

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For example, again numerically predicted soot contours are given here. Please understand that soot volume fraction is the quantification which we do for soot. In a given volume, what is the fraction of the volume which has soot that is soot volume fraction.

And this is given in grey scale contour, that is the black color will be the highest soot volume fraction value, and white will be the lowest soot volume fraction value. So, the volume fraction basically like mole fraction let us consider.

Then the lines coloured lines here are called soot oxidation rate $\text{kg/m}^3\text{s}$, soot oxidation rate. Again, you can see the variation, the red lines represent 0.0018, and the blue line which is the lowest is 0.0004. So, both are shown here. This is for 0% primary air and 10%. We have taken the first two cases to show and discuss here. In both, you can see that soot is formed in this range, very small amount of soot is there.

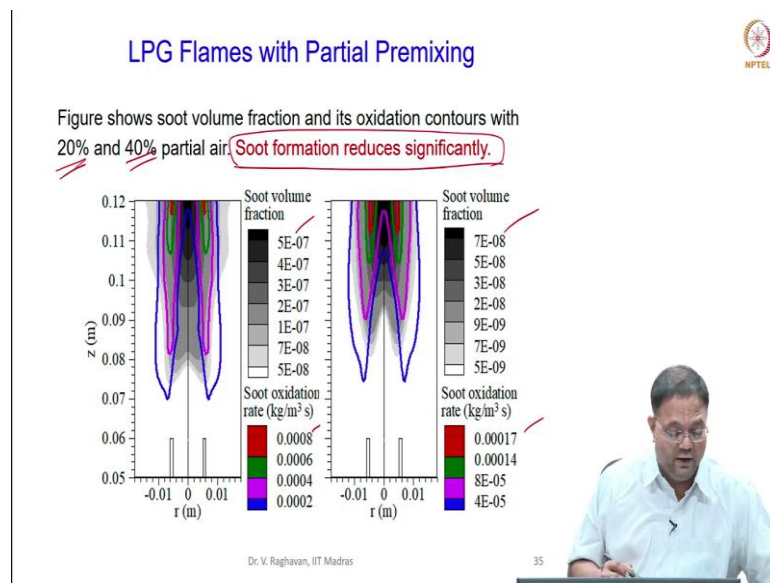
You can see that the soot forms here. You can see the maximum volume fraction of the soot in this area here. Soot oxidation, however, occurs only in this region where the red is there, maximum soot oxidation red and green let us take. So, in this region, the soot oxidation is maximum. After that now the temperature anything is not much favourable for soot oxidation to proceed.

So, what happens is the flame will leave some soot out. However, on the other hand, if you take 10% case, you see the soot oxidation. The soot oxidation in red lines is extending nicely. You can see the red lines and green lines were very short, this finishes here. In this regime, the red lines and green lines of soot oxidation are over there is no partial premixing.

But the 10% partial premixing slight increase in the flame length was found, but the soot oxidation green line and red line you can see now extends along the flame that means the soot is going to be less.

In fact, the soot actually reduces when you increase the primary aeration from 0 to 10%. But the maximum soot which is formed here, and here they have same value 1.2×10^{-6} . But there is a clear reduction in the soot because of increase in the soot oxidation rate with the primary air, so that we have to understand.

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Now, we will take the other two cases that is 20% primary air, and 40% primary air cases. Now, I need different scales to plot it. Because if you see 20% primary air, the maximum soot volume fraction is 5×10^{-7} . When I go to 40%, it is one order less in magnitude 7×10^{-8} . Similarly, you can see the soot oxidation rate which was 0.0008 for the case of 20% primary air, it has reduced significantly to 0.00017, more than 4 times it has reduced.

Now, we can see when compared to this 1.2×10^{-6} already for 20% one order of magnitude lesser. 40% again it is 1 order of magnitude lesser than the 20% case. The soot oxidation rate also you can see here it is 0.0018, reduces further to 0.00017. So, primary air is very important. And please understand till 40%, I do not have premixed mixture, that is it will not ignite.

So, by just adding 20% or 30% or 40% primary air, I can abate the soot formation completely, so that will give us good control. So, we have seen the reduction in the flame length, if we want to reduce the flame length we can go for primary aeration which will significantly reduce the flame length.

Then here the soot formation decreases, soot oxidation increases with little amount of primary air, 10% of the stoichiometric value, because of the tremendous increase in the soot oxidation.

Because of this increased soot oxidation, soot formation decreases significantly. So, 20% to 40% percent the soot goes almost to a very low value. So, when you slightly increase it to 40%, then you do not have any soot at all. It actually goes exponentially to a very low value.

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Cross-flow Diffusion Flames

Figure shows front and top views of LPG-air cross flow flame. LPG is sent from a horizontal injector vertically upwards and air is fed perpendicular to the LPG stream. A boundary layer type flame is formed. Proper mixing happens at the leading edge of the fuel injector, where the flame is bluish and relatively non-luminous. Flame becomes luminous downstream of the leading edge, contributed by factors such as soot radiation.

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Now, we go for cross flow diffusion flames. In cross flow diffusion flames, as I told you the fuel is supplied in a horizontal injector. And the air is supplied perpendicular to this fuel stream or parallel to the injector.

Now, again these two photographs are LPG-air cross flow flames. We can see that LPG is sent through horizontal injector. So, injector means, you can consider a honeycomb structure or a porous plate through which uniform injection of LPG is possible. So, the velocities will be uniform over this injection plate.

And this is top view of the flame, this is the front view of the flame. You can see that this is the injector. So, this injector position, again here also the injector. So, the flame is phenomenally 2-dimensional. From the top, you can see the flame covering the entire injector plate uniformly, and there are no side effects here no side effects. So, this is the phenomenal 2D flame.

And in this front view, you can see this. This is a boundary layer type flame. A boundary layer typically looks like that. So, it also assembles a boundary layer. So, boundary layer

type flame. So, this is the configuration. So, by adjusting the air flow rate and fuel flow rate, we can make the extent and burning rate higher and so on.

So, all sort of control is possible because whenever you have separate flow rates for oxidiser and fuel, we can have better control. So, as I told you horizontal injector is used to send in the LPG (Refer Time: 18:48), air is supplied perpendicular to the stream. So, again uniform flow of air comes in. And boundary layer type of flame is formed like this. Now, if you see the characteristic of this, you can see that in the front part blue region is present. Because of the incoming air, fresh oxygen is available and proper mixing takes place. A blue flame is formed here as shown by the front view and top view. So, flame is bluish in colour. Whenever you see bluish flame, proper mixing has happened in that, and it is relatively non-luminous.

When you go further downstream, you can see the luminous flames. You can see here bright radiation because of the soot formation and other things. Bright radiation is formed here.

Then based upon the air flow rate and fuel flow rate etcetera, we can see that the soot which is formed may be oxidized within the flame itself or it may come out as smoke and so on. But anyway, please understand that here the air supply is very nice, so more control is available in the crossflow flames.

But on the other hand, the stability of these crossflow flames is restricted. For example, the flame which is formed like this phenomenally 2D flame, it may separate from one end or both ends and so on forming some instabilities which I will demonstrate later. So, this is another type of configuration which is used to have better control of a diffusion flame. This is also a diffusion flame where cross flow reactants are injected.

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Opposed-flow Diffusion Flames

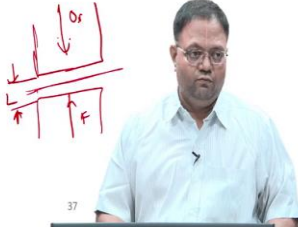
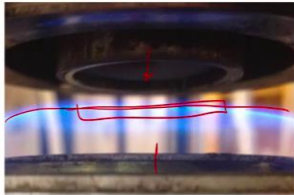
Counter flow diffusion flame

Figure shows CH_4 - air opposed flow flame.

Methane is sent from a bottom duct and air is fed opposing it from a co-axial duct at the top. An almost flat flame is formed.

Proper mixing happens and the flame is bluish in colour.

Based on the momenta of the jets the flame is positioned somewhere in between the ducts. If the flow rates are increased, the flame extinguishes due to an increased strain rate



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Now, the opposed flow or a counter flow flame. So, again please understand there are two ducts; one for fuel, and opposing that another duct for oxidizer. Now, a flame is formed somewhere here. So, when two ducts are kept opposed to each other, there will be stagnation zone. So, based upon the momentum of the fuel and momentum of the oxidizer, a stagnation zone may be formed.

Based upon this stagnation, the flame will be formed somewhere in between these two. The separation distance is say somewhere in between 0 to L, we will form a flame. And this flame is flat. So, this is the typical flame what you see here. The typical flame here is flat flame which is formed in between the ports. So, this is the duct which is supplying oxidizer, and this is the duct which is supplying fuel and so on.

So, almost a flat flame is got. Due to buoyancy, the flame may rise up towards the end wherever the stagnation zone, the stagnation plane is intact the flame will remain flat there.

So, away from the stagnation flame, you will see that the flame will rise up due to buoyancy or you can also take the hot gas, suck it down and take it through another port, so that is also possible. So, all together you are interested in the region here where the flame is flat and we can take measurements of temperature species etcetera.

Now, what is the advantage of this flame? This flame is extensively used in kinetic studies. So, when you want to do any chemical kinetics, this type of diffusion flame will be used.

So, the flame is normally blue in colour; methane itself is bluish in colour. Here due to the opposed flow, we have good amount of mixing happening between the fuel and the

oxidizer. So, due to thorough mixing a proper blue flame is seen. So, based upon the momentum of the fuel and oxygen oxidizer jets, we can position the flame anywhere.

So, if you increase the fuel flow rate, then the flame will go towards oxidiser side. On the other hand, if you increase the oxidizer flow rate, then the flame will come towards the fuel and so on. So, by controlling the flow rates we can position the flame anywhere. But if we increase the flow rates too much, the flame will not sustain. It will put off, it will extinguish because the flame is stretched too much. So, that is called strain rate.

The strain rate is increased beyond the limit, the flame will put off from the center and it will just blow off that is it. Again, that is important, so any extinction that is very important to understand and when you do careful experiments of fuel and with different fuel and oxidizer flow rates, with momenta we will calculate strain rate in a given manner.

And once you know the strain rate, we can know at what strain rate the flame is put off, and that will be termed as extinction strain rate. So, this is the configuration called opposed flow diffusion flames.

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Diffusion Flames from Condensed Fuels

When condensed fuels such as solid and liquid fuels burn, diffusion flames are formed over their surfaces. Examples are candle flame, a flame surrounds the wick attached to the candle, flame over a porous sphere, steadily supplied with a liquid fuel and a flame over a liquid fuel pool surface.

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Till now what we have seen is the gaseous fuel forming the diffusion flames. But when you have condensed fuels whether it is a solid or liquid fuel, when you try to ignite their surface, then you will get diffusion flames formed over the surface.

So, you can see the diffusion flames are formed over this. For example, if it is solid fuel it may paralyze to form vapours, gaseous fuel, and that gaseous fuel will mix with the oxidizer to form a flame. So, again you can see that there is no way to mix gaseous oxidizer in a liquid or a solid.

So, predominantly you will see diffusion flames are only formed. Some examples are given here, very important example is candle flame. So, candle, you have a wax which is the fuel. A wick is attached to this in its body. Then when you ignite it, what happens is the flame heats up the wax, creates a small cavity, and the molten wax is present there. The surface of the molten wax basically evaporates and the surface of the wick is also having this capillary. Though the capillary the molten wax will come to the wick surface, and that will be heated up by the flame and the vapours are formed, that vapour will travel from the wick surface. So, this is the wick of the candle, fuel vapours will form and traverse to the flame which is surrounding that. And oxidizer from the ambient will come towards this, and a flame is formed wherever these mix in the stoichiometric proportions. Now, the second example what is given here is called porous sphere flame. Now, I have an injector or maybe a needle in which a porous sphere is mounted. And this needle goes till the center of the porous sphere. So, now this is the porous sphere. Now, what happens? When you supply liquid fuel, the fuel goes to surface and keeps the surface saturated with the fuel liquid fuel. You can also have an air flow pass this. When you ignite what happens is a flame forms over the surface, which is shown here. And you can see that this fuel will vapourize and the heat from the flame will be transferred to the film which is formed over the porous sphere. And this film will evaporate. Once it evaporates, more liquid will come to the surface, but the vapour which is evaporated here goes to the flame and oxygen from the ambient comes from the atmosphere towards the flame and a diffusion flame is formed. So, this is the typical diffusion flame. Now, we have a liquid pool. For example, we have a liquid pool. Now, if we ignite it, a flame will be formed over this. So, this is what a typical flame is. It is a slot burner here. A slot having a liquid fuel. So, this surface is open to the atmosphere. When you try to ignite this, a flame will be formed. Please understand that for the flame to appear here the temperature of the liquid surface should reach the fire point. Once fire point is reached, a diffusion flame will sustain over the surface. And then you can see the rate at which it burns basically. A diffusion flame from forms over the surface here. You can see that fuel is transported from the surface to the flame, and oxygen is transported from the ambient to this, and the flame sustains like this. So, here is a long and low width slit or a slot burner where the fuel is fed at the rate which it is consumed. So, it is a steady flame. Please understand that these cases are steady flame cases where the fuel is fed at the rate at which it is consumed. So, we can also have transient flames and so on. So, these are the examples for diffusion flames which are attached over the condensed fuel surfaces.