Fundamentals of Combustion

Prof. V. Raghavan

Department of Mechanical Engineering

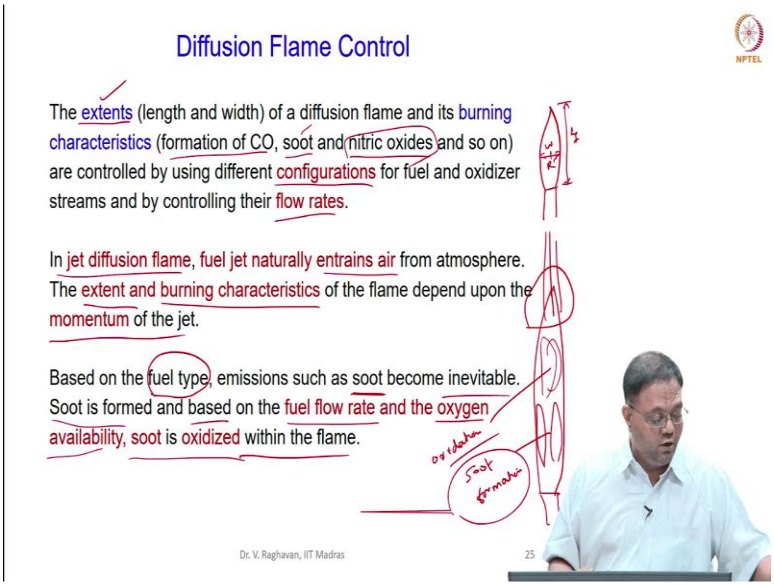
Indian Institute of Technology, Madras

Lecture - 46

Laminar Diffusion Flames - Part 6

Diffusion flame control

(Refer Slide Time: 00:14)



Diffusion Flame Control

The extents (length and width) of a diffusion flame and its burning characteristics (formation of CO, soot and nitric oxides and so on) are controlled by using different configurations for fuel and oxidizer streams and by controlling their flow rates.

In jet diffusion flame, fuel jet naturally entrains air from atmosphere. The extent and burning characteristics of the flame depend upon the momentum of the jet.

Based on the fuel type, emissions such as soot become inevitable. Soot is formed and based on the fuel flow rate and the oxygen availability, soot is oxidized within the flame.

Dr. V. Raghavan, IIT Madras

25

Now, let us see how to control a diffusion flame? As I told you, diffusion flame has a wide operating range when compared to a premixed flame. This is because you know basically when you increase the flow rate, the flame length increases and it completely burns wherever it finds the enough stoichiometric air.

So, that will define the boundary of this flame also. So, in that case it is very simple in nature but only thing is you will end up in some emissions. So, how to avoid those emissions. How to have better control of the combustion efficiency that we will see.

So, if you take this, the extent of a flame. See for example, if you have a same jet flame, when I say extent, I say the flame width or the flame height; the flame height is a very important aspect.

So, this flame radius. The flame radius or the flame width or flame height etcetera are called extents and this extent is one of the characteristic, burning characteristics; flame length is one of the important burning characteristic. Then formation of CO, soot, nitric oxides are other the burning characteristics.

So, this for example, when the diffusion-controlled fuel does not get enough oxidizer, it will end up in formation of CO. Then based upon the fuel type, soot formation can be there; based on flow rate and availability of oxygen etcetera, soot formation will be there. Similarly, nitric oxides are not much in the diffusion flames when compared to the premixed flame, in premixed flame nitric oxide emissions will be slightly higher.

So to control these, the main characteristic of the diffusion flame is the flame length, then the burning characteristics are formation of CO, soot, nitric oxide etcetera, we can go for several configurations. When I say configuration, the way in which the fuel and oxygen are supplied, that is the configuration. Similarly, I can control the flow rate of both fuel and oxidizer. See, if you take a jet diffusion flame only fuel is supplied in a force convection.

So, due to the momentum and viscous effects, you can see that the entrainment of air takes place. And in this case know there is no control; when you want to just control the flame length, only the volumetric flow rate of the fuel can be changed. But volumetric flow rate has to be supplied in a given ratio.

See for example, if I want to operate the burner in a fixed ratio of power, say maximum power to minimum power; then the flow rate also will correspond to that maximum and minimum values. So, how will you control the burning characteristics? If I say when I control, when I operate the burner in a minimum flow rate; there may not be much emission, even soot which is formed that may be oxidized within the flame itself.

However, when I go to the maximum limit of the burner operation; then I may get more CO which is not as per the standards, then I can also get more soot and so on. So, how to control this, that is the main thing? So, in this case basically the jet diffusion flame, the extent in the burning characteristics is dependent only on the momentum.

That means when I do not have any other control; then we will be in trouble. So, what to do? That is what I am adding some amount of diluents to the fuel stream, adding some primary air. So, these are the techniques which we will use.

Why we use it? we will come to that. So, based upon the fuel type; when I again stress the factor fuel type; that means every fuel is not so bad. For example, methane is a very nicely burning fuel; because it has only one carbon atom and 4 hydrogen atoms. So, its H/C ratio is 4 and it burns nicely.

However, when I go for say higher order hydrocarbon, heptane etcetera; you will see that the fuel has to pyrolyze to smaller hydrocarbons, and when it does, we also end up in unsaturated hydrocarbons like C_2H_2, C_2H_4 etcetera. So, those are the unsaturated hydrocarbons that can form soot. Even cyclic hydrocarbons, aromatics can also be generated.

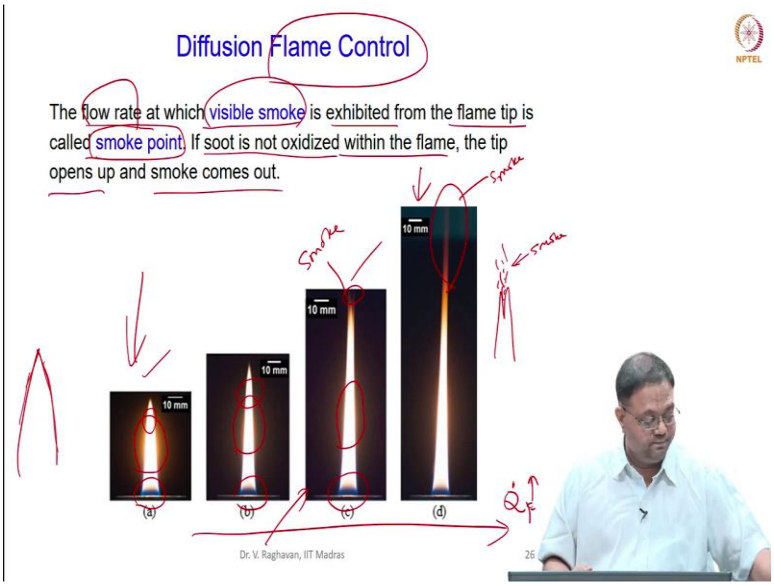
So, when you go for heavier and heavier hydrocarbon fuels, in such case what happens is, the soot formation becomes unavoidable; you cannot avoid soot formation. But, how to control the soot? Let it form, there is no harm in that; soot which is formed, if it is oxidized within the flame no issue.

For example, there is a flame and soot is formed at some location. But it is also oxidized in this region, so there is no soot in this position.

These are the hot products which are leaving; hot products are leaving here at the flame tip but there is no carbonaceous particle. Soot is nothing but a carbonaceous particle. Small particles which are grown to some size and are not leaving here. So, the soot formed and this is oxidation.

When the soot formed is oxidized within the flame there is no issue; but that will not occur for all the flow rates. Based upon the fuel flow rate and oxygen availability soot is oxidized within the flame, it is good if it is done. Or if it is not oxidized within the flame, the soot will leave along with other products CO_2, H_2O, some amount of CO, unburned hydrocarbons and so on. If that is the case, then that is taken as an emission. So, you will see smoke coming out.

(Refer Slide Time: 06:29)



Diffusion Flame Control

The flow rate at which visible smoke is exhibited from the flame tip is called smoke point. If soot is not oxidized within the flame, the tip opens up and smoke comes out.

Dr. V. Raghavan, IIT Madras

So, that is what this illustrated here. Let us take this, there are four cases given here; at low flow rate you can see that this is a typical jet diffusion flame. You can see there is a blue region here, where the fresh oxygen comes in and good premixing occurs.

As the flame height increases, you can see the bright emission that is due to this soot formation. Soot emits this bright emission here. But within the flame the soot is oxidized also. So, within some region here soot is also oxidized, so that nothing, no carbonaceous particles leave the flame.

Similarly, here also same regime, a bright regime and soot oxidizes here; no soot leaves the flame tip. So, flame tip is intact. So, when I say the flame tip is intact like this; but go to this figure. So, I am just increasing Q_F.

When the Q_F increases, I see the replication that; when Q_F increases, the flame height increases, also other characteristics changes. So, basically if you see these two flames; there is no difference in the characteristics. A bluish base, bright middle portion and the tip is nicely closed and so on.

Now, go to this higher flow rate, Q_{F3}, you see that this is again some bright emissions are there; but soot is not able to fully oxidize at this flow rate. What happens here? You can see the tip is open and now you can see some smoke coming out. So, this is the smoke which leaves. So, here you can see the same thing a tip opens and give good amount of smoke. Good amount of smoke leaves the flame.

So, please understand that the same fuel is used here, which is heavier hydrocarbon LPG flames. So, you can see that in the LPG flames at low flow rates, soot which is formed radiates. So, bright colour and the luminous radiation is due to soot. Soot is not able to oxidize.

In this first two cases, it is able to oxidize also; the flame tip is closed and the soot is fully oxidized. And when go to a critical flow rate, you will see the flame tip opens up and the carbon particles leave. So, this is we call as smoke.

So, this is visible smoke, here also you can see visible smoke. So, flow rate at which visible smoke is exhibited from the flame tip is called smoke point. So, this flow rate where the tip opens and visible smoke is seen that is called smoke point of this particular fuel. So, LPG at a given flow rate, you will see that smoke is formed.

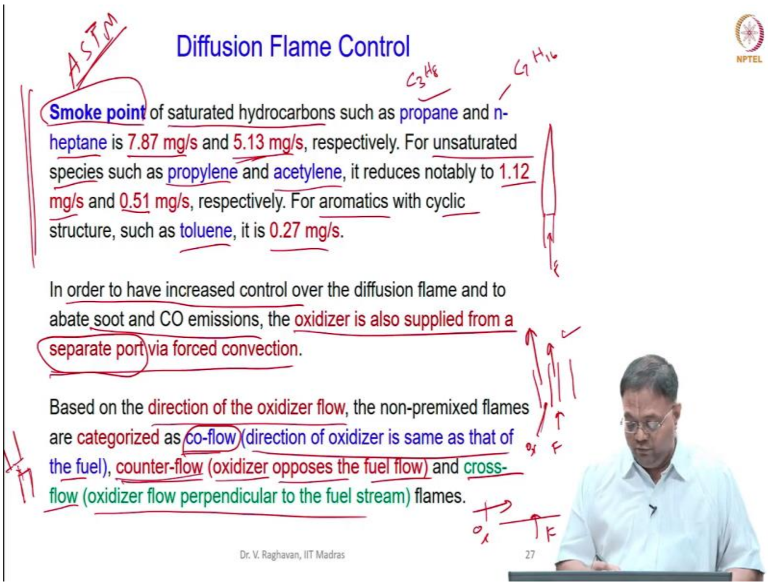
Till that no smoke is seen; because soot forms and oxidizes within the flame itself, so no soot is leaving the flame. So, these are well within the smoke point flow rates. So, flow rate at which visible smoke is exhibited that is called smoke point and that again depends on the type of fuel. So, type of fuel will do this.

So, in these cases, when the flow rate is less than the smoke point, the soot is oxidized within the flame; or else if soot is not oxidized within the flame, then the tip opens up and the smoke comes out. So, this is the illustration for that. So, please understand that, but I want to operate my burner. See this may be the lowest flow rate of my burner and this may be the highest flow rate of my burner.

But there is no problem when I operate in the lowest flow rate or low flow rates; but when I go to higher flow rates. Say, power equipment is higher. So, I want to increase the flow rate and operate my burner; I see that I do not satisfy the emission norms where I now throw out the smoke into the atmosphere.

So, some control has to be done in this to avoid the smoke which is released out or the soot which is unoxidized and leaving the flame tip. So, this has to be taken care. So, we need control for a diffusion flame in such scenarios. So, how to do this?

(Refer Slide Time: 11:20)



Diffusion Flame Control

Smoke point of saturated hydrocarbons such as propane and n-heptane is 7.87 mg/s and 5.13 mg/s, respectively. For unsaturated species such as propylene and acetylene, it reduces notably to 1.12 mg/s and 0.51 mg/s, respectively. For aromatics with cyclic structure, such as toluene, it is 0.27 mg/s.

In order to have increased control over the diffusion flame and to abate soot and CO emissions, the oxidizer is also supplied from a separate port via forced convection.

Based on the direction of the oxidizer flow, the non-premixed flames are categorized as co-flow (direction of oxidizer is same as that of the fuel), counter-flow (oxidizer opposes the fuel flow) and cross-flow (oxidizer flow perpendicular to the fuel stream) flames.

Dr. V. Raghavan, IIT Madras

27

Now, this is more about which type of fuel will form more smoke and so on?

So, for that smoke point experiments, standard ASTM experiments are there. So, ASTM standard experiments are done. So, basically it started with liquid fuels; for liquid fuels when they were burnt in pool. If you have a liquid fuel pool, it will burn with the diffusion flame. Based upon the diameter of the liquid fuel pool, you will see the smoke coming out.

So, the smoke point was judged like that. Further, it was actually extended to the gaseous fuels also. Smoke point basically as I told you it is the lowest flow rate at which you will see visible smoke coming out of the flame tip. Now, let us take saturated hydrocarbons say, propane heptane, this is n-heptane.

Now, saturated hydrocarbons, you need higher flow rates to form the smoke. So, 7.87 mg/s, 5.13 mg/s; so normally we have in small burners kg/h, so that is the flow rate here mg/s. So, that is given. So, this is somewhere higher; why I say this higher? Because relatively it is higher.

On the other hand, if I take unsaturated hydrocarbons like propylene, acetylene etcetera; you can see that the lower flow rate itself will produce smoke points, like 1.12 mg/s for propylene and 0.51 for acetylene. So, these are the fuels which will form more and more soot basically. Soot is not able to oxidize even for a very low flow rate like this. Say, if you compare to heptane, it is only at 10% of the flow rate; but you can see smoke point is reached, I am not able to control the soot oxidation, soot is not oxidized within the flame and the smoke comes out.

So, that is the problem. Go for aromatics, cyclic aromatic toluene; you see that still half of the acetylene, it has the smoke point flow rate. So, based upon the fuel type, if you have unsaturated hydrocarbon, cyclic with two bonds etcetera, then you will see that there will be tremendous potential to form smoke. That is the soot which is produced will be produced at a faster rate and it cannot be oxidized within the flame even for a very low flow rates like this, resulting in smoke leaving the flame tip.

So, for these fuels, understanding the fuel is called fuel characterization; understand the fuel and based upon the fuel characteristic, we need to control the diffusion flame or else we cannot operate in a wide range. The flame may be stable, but the emissions may be not under control.

So, that is the main thing which we will try to do. So, how to do this? So, if you take jet diffusion flame; these are all jet diffusion flame characteristics basically. I do not have any force flow for the oxidizer. Only fuel comes out and flame forms and based upon this, the tip opens or not, whether the flame is closed or not, it depends on the smoke points and so on.

But, how will I increase this? So, why this is happening because the rate at which oxygen is trying to enter the flame zone is not enough. The momentum of the jet is not able to entrain enough oxygen in order to oxidize the soot and so on. So, how to increase the oxygen availability for the fuel?

In order to have increased control, oxidizer is also supplied from a separate flow port via forced convection. Instead of allowing the oxygen only to naturally entrain into the flame; we will try to supply oxygen also in a force convection. Then convective mass transfers will be higher than a diffusive mass transfer. So, that will enable us faster mixing.

So, if you do so, we can try to control soot and CO emissions. That means we will have more control over the flow of the flame at higher flow rates also. So, that is the category we are going to address here. So, how to do this?

So, based upon the direction of the oxidizer flow, I now plan to supply oxygen forcefully, like in a force convection through another port. See obviously, we cannot supply oxygen in the same port; because they will become a premixed flame, partially we can add some oxygen or oxidizer to the fuel port that is called primary air only. But please understand that fuel plus primary air normally is kept out of the flammability limits.

For example, if you have only the primary air and the fuel coming out; you try to ignite it, it will not ignite, unless an additional air is provided to that. So, it will not have enough oxygen to burn. That will be the primary aeration which we do. If you have a mixture of fuel and primary air which is flammable, then flashback instability also will come into play; because the flame will ignite and can flash back when the flow rate of the fuel and the primary air is low.

So, in order to avoid that in industrial furnaces or domestic cookstoves especially, we will not allow the mixture to be flammable which is coming out of the fuel port; but additional ports will be engaged to supply oxidizer. So, separate ports will be engaged for oxidizer supply and that will be done through forced convection.

Now, based upon the direction of the oxidizer flo, we will categorize the configurations of the diffusion flame. Now, how will you categorize? First is co-flow. Now, fuel is supplied here oxygen is also supplied in the same direction as that of the fuel. So, that means I will have another port which is annular to this. And I supply oxygen here basically or air or oxidizer whatever. Now, you see fuel comes out of this port; oxygen is forcibly coming out of the annular region surrounding the core fuel port.

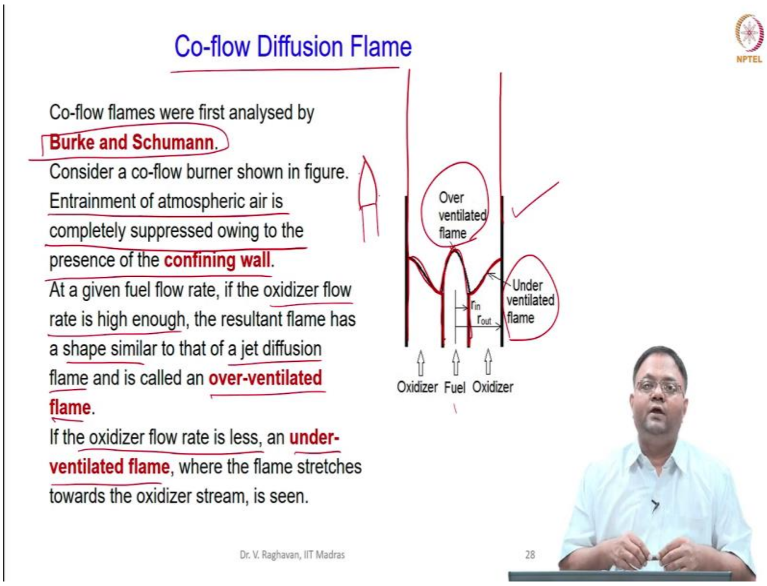
Now, this is called co-flow. So, the flow of oxidizer, the direction of the oxidizer and the direction of the fuel are the same. So, that is the co-flow, oxidizer co flows along with the fuel this is one configuration we have.

Second is counter flow, I can have a fuel coming out like this, oxidizer will come out in the opposing direction opposite to this. So, opposed flow also we can say, counter flow or oppose flow; oxidizer flows in the direction exactly opposite to the fuel flow direction.

Then another configuration is, I supply fuel in this direction and oxidizer in this direction. So, they will be orthogonal to each other. So, oxidizer flow perpendicular to the fuel stream. That will be the crossflow configuration. We can also do anything in between this. These are the configurations which we can use to build a burner, to have control over the dimensions of the burner etcetera.

So, we can also have other configurations. For example, some angle oxidizer can come in, instead of 90 degrees like this in cross flow. So, several configurations are available. These are the important configuration which people have used; co-flow is one of the very well-used configurations. What are the characteristics of these configurations?

(Refer Slide Time: 19:41)



Co-flow Diffusion Flame

Co-flow flames were first analysed by **Burke and Schumann**.

Consider a co-flow burner shown in figure.

Entrainment of atmospheric air is completely suppressed owing to the presence of the **confining wall**.

At a given fuel flow rate, if the oxidizer flow rate is high enough, the resultant flame has a shape similar to that of a jet diffusion flame and is called an **over-ventilated flame**.

If the oxidizer flow rate is less, an **under-ventilated flame**, where the flame stretches towards the oxidizer stream, is seen.

Dr. V. Raghavan, IIT Madras

28

So, co-flow configuration, as I told it has been done from several years, several researchers have been using this co-flow configuration started by Burke and Schumann. Burke and Schumann; this is a very important research paper which actually established theoretical solution for a configuration like this.

So, what is this configuration? There is a confinement like this and there is a flow of fuel in a central tube. Fuel is supplied and oxidizer air is supplied in an annular region.

And please understand that, this is a co-flow burner, Burke and Schumann used this and theoretically and experimentally they analyzed the flames. So, they saw two types of flames basically; one is called over ventilated flame which is like this and another one is like this which stretches towards the wall that is called under ventilated flame. So, that means I can have control of the flame by adjusting the fuel and oxidizer flow rates.

Now please understand that, entrainment of atmospheric air is completely suppressed owing to the presence of confining wall in this. So, the fuel should find the oxidizer only from the forced convective oxidizer flow, which is coflowing along with it.

Now, how the over ventilated flame is formed? At a given fuel flow rate, if the oxygen flow rate is high enough, so sufficient oxygen is supplied. Then what we get is a jet diffusion flame type of configuration. A flame which is like this is formed.

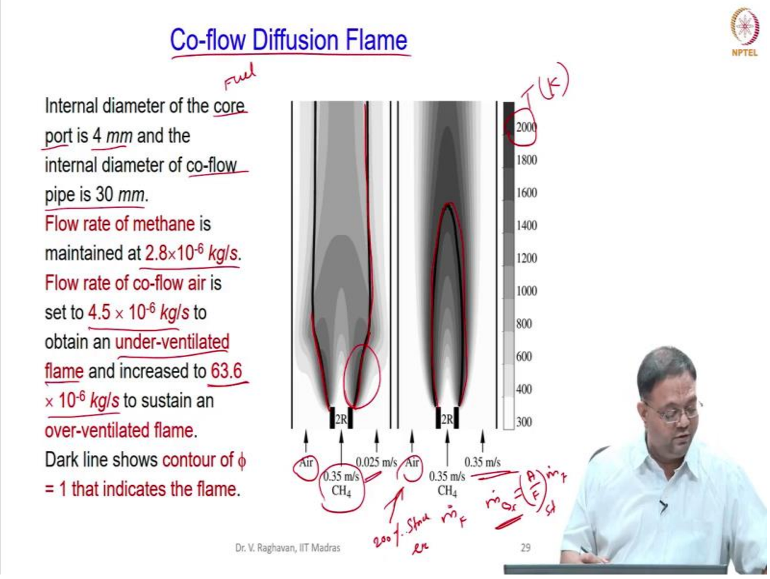
So, this is the flame which is formed; that means, enough oxidizer is coming there and it will entrain. So, oxidizer is actually entraining into the fuel jet and wherever they mix at stoichiometric proportions, a flame is formed. And it is similar to that of a jet diffusion flame that is called over ventilated flame.

On the other hand, if I do not supply enough oxidizer, the oxygen flow rate is less. Then the fuel steam will try to expand towards oxidizer and mix with this. Stoichiometric contour forms here, stoichiometric mixing happens in these locations where the flame is formed.

So, such a flame which stretches towards the wall is called under ventilated flame. So, this flame stretches towards the oxidizer side; it may not touch the wall. It may go towards oxidizer side. So, this is very important. By controlling the transport rate of the fuel and oxidizer, I can get different flame shapes.

So, that is the control we have here. So, we are supplying oxidizer in a forced convective manner plus we can control the shape of the flame by just controlling the flow of fuel and oxidizer.

(Refer Slide Time: 22:51)



Co-flow Diffusion Flame

Internal diameter of the core port is 4 *mm* and the internal diameter of co-flow pipe is 30 *mm*.

Flow rate of methane is maintained at 2.8×10^{-6} *kg/s*.

Flow rate of co-flow air is set to 4.5×10^{-6} *kg/s* to obtain an under-ventilated flame and increased to 63.6×10^{-6} *kg/s* to sustain an over-ventilated flame.

Dark line shows contour of $\phi = 1$ that indicates the flame.

Dr. V. Raghavan, IIT Madras

29

So, this is the numerical simulation of such a flame. Here, core port, that is a core fuel port of 4 mm inner diameter and some wall thickness may be there, say 1 mm. You can see the co-flow pipe diameter is 30 mm.

So, it will have some annular space. Within the annular space air is supplied and the flow rate of methane, in the core or the fuel pipe it has a velocity of 0.35 m/s. And now you have a velocity of the oxidizer side, very slow flow rate of oxidizer.

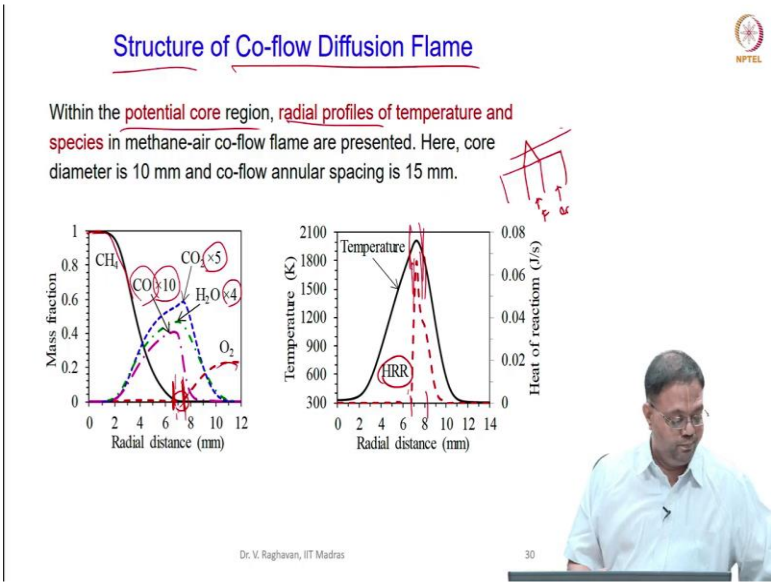
If you see the velocity is about 0.025 m/s, one order of magnitude less than that of the fuel; you can see the flame is formed as a stretching towards the oxidizer side, under ventilated flame. And please understand that the stoichiometric line is still open; the air is not enough for the entire fuel to burn; some combustion takes place in this zone. This is the temperature contour in Kelvin basically you can see that the dark regime is about higher temperature where the flame zone is formed.

Only after leaving the tube, it may find enough oxidizer; but we may require to reignite the flame there. So, based upon the flow rate of oxidizer, we can see that the flame actually stretches towards the oxidizer side and this is called under ventilated flame. So, the mass flow rate of methane is 2.8×10^{-6} kg/s and the flow rate of co-flow air is 4.5×10^{-6}; even though the air flow rate is higher, it is not even stoichiometric value.

But if you increase the velocity equivalent to that of the fuel in the annular port; then you can see that the oxidizer flow rate has now increased to 63.6×10^{-6} which is say for example, if this is 2.8×10^{-6}, this is 63.6×10^{-6}. So, we have enough amount of oxidizer supplied. So, we need 17 times know which is more than that.

So, if you do this, then you can see that you will get a flame which is exactly like a jet diffusion flame; but the control is if we can increase the oxygen flow rate, so that more oxygen can enter. So, basically what we have seen is, if you increase the oxygen flow rate in the co-flow flame then the soot which is formed actually reduces after a particular flow rate. It would not happen initially; you just have supply of stoichiometric flow rate here, see for example, if fuel flow rate is $\dot{m}_F$ and the oxidizer flow rate required for this will be equal to stoichiometric air fuel ratio × $\dot{m}_F$. Now, if the oxygen flow rate is say 100%, then you get same amount of soot what you get in the flame, jet diffusion flame. On the other hand, if you increase the mass flow rate of oxidizer; say to 200% of stoichiometric air and so on, you will get a reduction in the soot formation.

(Refer Slide Time: 26:45)



Structure of Co-flow Diffusion Flame

Within the potential core region, radial profiles of temperature and species in methane-air co-flow flame are presented. Here, core diameter is 10 mm and co-flow annular spacing is 15 mm.

Dr. V. Raghavan, IIT Madras

So, that means we have more control over the flames, the flame emitting characteristics basically; the flame height may not change much. The flame width may slightly reduce, flame height may not change much. However, the soot formation is actually reduced when you go for say this flow rate of air which will be say 200%.

So, when I say this co-flow air is 200% of stoichiometric air etcetera; then you get the reduction in the soot formation. So, this is the characteristic of co-flow diffusion flame and we will see the structure of the flame; structure of co-flow diffusion flame is given here. Again, numerical results you can see that radial profiles are used here and these radial profiles are extracted within the potential core region of the jet.

You can see for example, if this is the flow, this is the potential core region for the jet; this is fuel and these are oxidizer flow rates. Now, in this regime somewhere here the radial profiles are extracted and you can see the mass fraction of the methane is 1 here.

It actually reduces and consumed at the flame zone. So, this is the flame zone. Some finite thickness we have to give for the flame zone and you can see this is the position, so about 7 to 8. So, for the same regime you can see the heat release happening; in the same regime where the heat release peaks and the maximum temperature occurs.

So, when the fuel and oxidizer are consumed in some finite thickness; then you can see that the maximum temperature and maximum heat release occurs at that particular position and products are formed.

So, please understand that, here the product mass fractions are very low; so we have multiplied this with some amount, say some factors to show the trends properly. So, you can see that the water vapor, CO_2 etcetera are formed here. Some CO is also formed in this co-flow flame.

If you can increase the co flow velocity, you can also reduce this CO formation. So, that is the way we can have control. So, soot formation and CO formation can be reduced if you try to increase the co-flow air. So, just by making the air entry to the flame in a convective manner which is faster than the diffusion, we can achieve control.