Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 34
Flame Stabilisation

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So you have been looking at how this flame stabilisation happens and essentially what basically means is you have a linearly increasing velocity profile.

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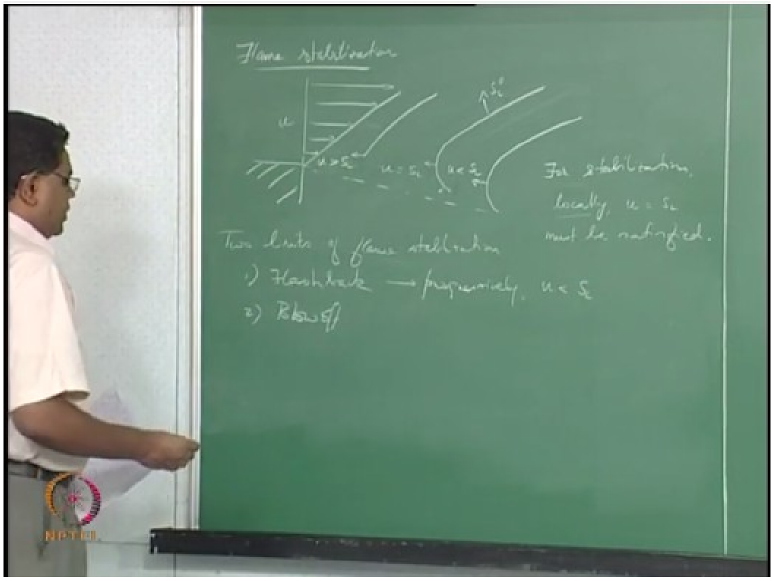

Flame stabilisation

For stabilisation, locally, $u = S_L$ must be satisfied.

Two limits of flame stabilisation
1) Flashback → progressively, $u < S_L$
2) Blowoff

But you also now have a flame speed that continues to decrease from the value of S_L^0 not and it decreases because of the heat loss to the burner as one of the effects and the other effect is the dilution from the ambient for like let us say we are looking the fuel rich sorry, I am sorry fuel in flame and therefore if you now have a air that is coming in and diluting this it is going to decrease the S_L further and you are to keep in mind that as you now get closer to the burner the decrease in the flame speed is going to be more because of the heat loss and less because of the dilution.

As you go further away from the burner if the flame goes further away from the burner the decrease in the S_L is going to be more due to dilution and less due to heat loss right, and that is actually the effect along this direction the other way to look at it is also the radial direction as you now go closer to the as the flame strands closer to the burner the heat loss is more and the mixing field is actually quite narrow between the premix make reactants and the diluting ambient gas where us as you go further out you can now actually have the premix mixture going further out into the intermixing zone and the flame can actually establish itself further and further out.

And what we are basically looking for is like a leading edge of the flame which is having a slow perpendicular to the flow where the S_L has to match the velocity literately, and what we are basically looking for is a condition where the S_L has to the local S_L has to match the local u, since the u is also increasing linearly what we should be looking for is a condition where the local S_L matches the local u and so the flame stabilisation condition is locally we need to have this matching which we satisfied.

Then what we look for is to two occurrences what happens when this condition cannot be satisfied in two ways, one if you now progressively keep on decreasing your flow velocity right, or progressively keep on increasing the reactivity maybe by changing the mixture stoichiometry towards the stoichiometric mixture so that the flame speed keeps increasing for the same flow velocity.

So in one case what we are looking for is a relative decrease of flow velocity with respect to the flame speed or relative increase of the flame speed with respect to the flow velocity. In which case the flame has a progressive tendency towards establishing itself closer to the burner and ultimately you are going to get your situation where it cannot be held at the burner anymore it wants to propagate even further in and that is actually situation corresponding to flashback.

The second situation is where we now do the opposite we just we now try to progressively increase the velocity relative to the flame speed or progressively decrease the flame speed by maybe going to linear leader mixtures for the same flow velocity and that is going to have a tendency for the flame to actually get established further and further out stabilized get further and further out and at some point it cannot be stabilized anymore and then it starts blowing off, right.

So you have two such limits of flame stabilisation two limits of flame stabilisation or one is flashback the other one is blow off, right. So here what is happening is progressively we see progressively for a reason that I will explain soon S_L becomes a less than U_L.

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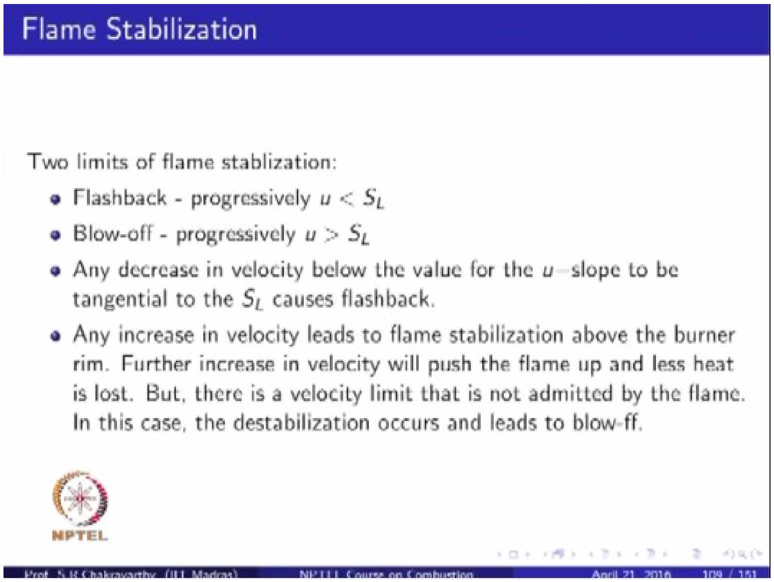

Flame Stabilization

Two limits of flame stablization:

- Flashback - progressively $u < S_L$
- Blow-off - progressively $u > S_L$
- Any decrease in velocity below the value for the $u-$slope to be tangential to the S_L causes flashback.
- Any increase in velocity leads to flame stabilization above the burner rim. Further increase in velocity will push the flame up and less heat is lost. But, there is a velocity limit that is not admitted by the flame. In this case, the destabilization occurs and leads to blow-ff.

And here progressively u becomes greater than S_L right.

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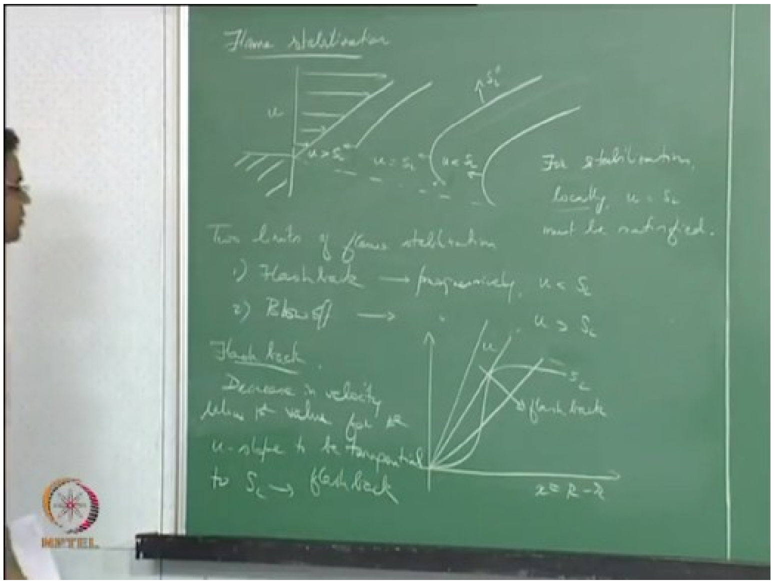
Flame stabilisation

For stabilisation, locally, $u = S_L$ must be satisfied.

Two limits of flame stabilisation
1) Flashback → progressively $u < S_L$
2) Blow off → $u > S_L$

Flash back.
Decrease in velocity below the value for the u-slope to be tangential to S_L → flash back

So let us look at the flashback situation, so what we are saying here is let us suppose that you had a velocity contour that is a velocity profile that is going like this with respect to x which is R-r that is the x coordinate that is measured radially inward from the burner rim and what we want to think about is a match between a limit match between u so this is u, and S_L so the S_L basically you see what is going on the u increases linearly and the S_L for most part of the radius of the burner is nearly constant at S_L^0.

And then it drastically decreases within a short region and then goes to 0 ultimately, when you are leading when you are reaching the what is called as a flame edge right, so we are looking for a match that would give rise to a situation when we now have u that is at the most equal to S_L. Now what happens is if you know if you now try to decrease your velocity you are now going to not be able to actually satisfy this match anymore and you now going to have a condition where let us to this S_L you are now going to have a condition where the u decreases and that leads to your flashback, right.

On the other hand if you now try to actually have a higher velocity then this is actually the condition for flame stabilisation at the rim at the most and any decrease in velocity is now going to actually induce a flashback. But if you now try to increase the velocity further it is not going to progressively starting to have a flame stabilisation a little bit away from the flame from the burner right, and so increase so decrease in velocity below the value for the u slope to be tangential to S_L leads to flashback any increase in velocity.

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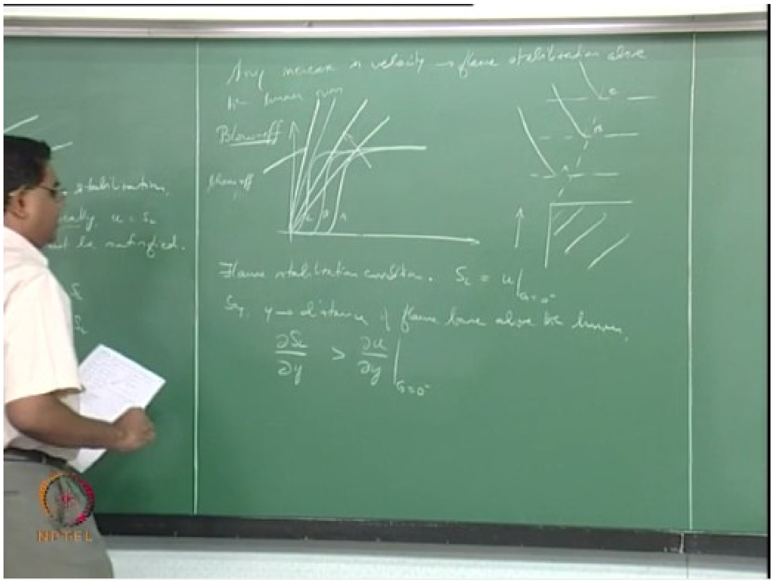

Any increase in velocity → flame stabilisation above the burner rim

Flame stabilisation condition. $S_L = u|_{y=0}$

Say, y → distance of flame base above the burner,

$$\frac{\partial S_L}{\partial y} > \frac{\partial u}{\partial y}\Big|_{y=0}$$

On the other hand leads to a flame stabilisation about the burner rim that means to say at this particular collision the flame is stabilized at the rim and that the most you can do to prevent flashback. Then what happens if you keep on increasing the velocity further and further right, if you keep on increasing the velocity further and further we have seen what is likely to happen there is the flame shapes itself in a way to adjust to the increasing velocity situation alright.

We have found that with a artificially simplified condition that ζ=0 at r=R you can now say that the flame is going to be a conical shape of any angle depending upon the S_L/u ratio so for a fairly wide range of use given a certain S_L you can actually have a flame that is hell pretty much near the rim without worrying about the details of how it is attached to the rim. If you have to worry about it then you start seeing that it starts moving a little bit further away the edge of the flame starts moving away from the rim a little bit and progressively so how does it really adjust.

So if you now think about the situation there so this is your u so and this is like the z boundary and let us suppose that we now look at three locations where the flame is stabilized progressively so you can say flame is stabilized here, here and here of course when you go further and further the flame gets curve like the way we are talking about but what you talk what you are basically saying is let us look at these three conditions the way the adjustment happens is at a lower location you now have intense heat loss so the flame edge is actually more towards the center when compared to the other way.

When you now have a less heat loss and further location the flame can be privileged to the rim when I mean radially when compared to if it is much closer to the rim axially. Therefore what happens is for the condition a your S_L actually is 0 for quite, so quite a while and then increases and then you now have a flame stabilisation condition that matches this.

If you now try to increase your velocity to a let us say a higher value the linearly increasing profile would increase this way and the flame now begins to actually so the flame speed now begins to increase in such a way that you now have the match happening over here, what this basically means is of course looking at how this curve looks like maybe you should have drawn it with a slightly greater slope then what or less of slope then what I have done.

But essentially what this means is when you now increase the velocity the flame is getting pushed up there for the heat loss is less so what it basically means is if you now think about a distance going a little bit away from the rim right, you can see that the flame speed is beginning to rise sooner than in the previous case and the reason for that was a decreased heat loss situation alright.

And then you could still continue to have that happen if you now think about another velocity we are now increased but then you are really getting pushed to the corner beyond a point as you know get the flame speed to increase because of less heat loss you are progressively so this is actually a this is b this is c progressively you are going further and further away and then the other mechanism of the dilution trying to decrease the flame speed is going to come in so the rate of increase of this flame cannot actually happen so soon from the rim and there is a cap on how much it can increase that is the S_L^0.

So beyond this point you cannot really have a further increase in velocity admitted by the flame right, and this is a mechanism of de-stabilisation of the flame leading to a blow off conditioner right. So effectively the flame speed because of these two mechanisms of heat loss and dilution they combine together to adjust in order to match the flow speed locally as it is being increased over a fairly wide range but not beyond a point right, and that is when you are going to have a blow-off.

So in effect the flame stabilisation condition is that you need to have a S_L=u at G=0^- that is to say just a frame of the flame the notation used previously and if you use now let us say why is the distance, the distance of the flame base above the burner then partial S_L over ∂u sorry, ∂y now should be greater than ∂u/∂y G=0^- again just upstream right.

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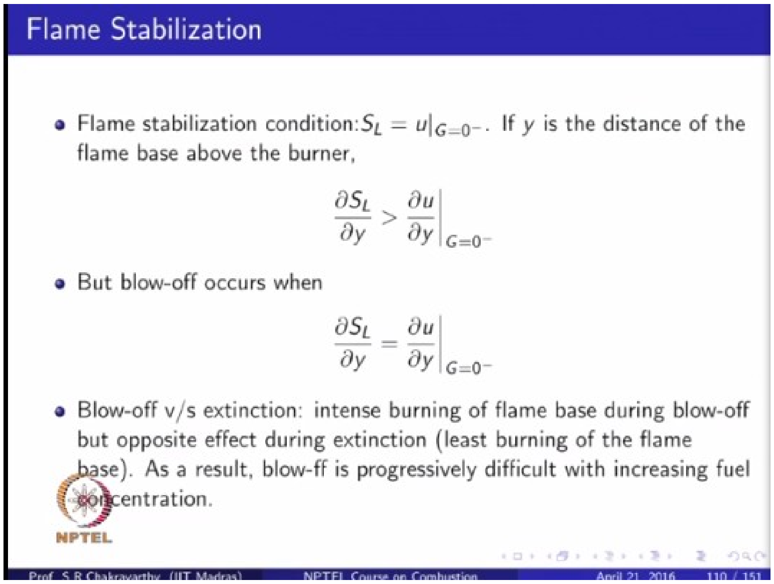

Flame Stabilization

- Flame stabilization condition: $S_L = u|_{G=0^-}$. If y is the distance of the flame base above the burner,

$$\frac{\partial S_L}{\partial y} > \left.\frac{\partial u}{\partial y}\right|_{G=0^-}$$

- But blow-off occurs when

$$\frac{\partial S_L}{\partial y} = \left.\frac{\partial u}{\partial y}\right|_{G=0^-}$$

- Blow-off v/s extinction: intense burning of flame base during blow-off but opposite effect during extinction (least burning of the flame base). As a result, blow-ff is progressively difficult with increasing fuel concentration.

Prof. S.R Chakravarthy (IIT Madras) NPTEL Course on Combustion April 21, 2016 110 / 151

So this is typically the condition that we are looking for when we when we have an equal equality.

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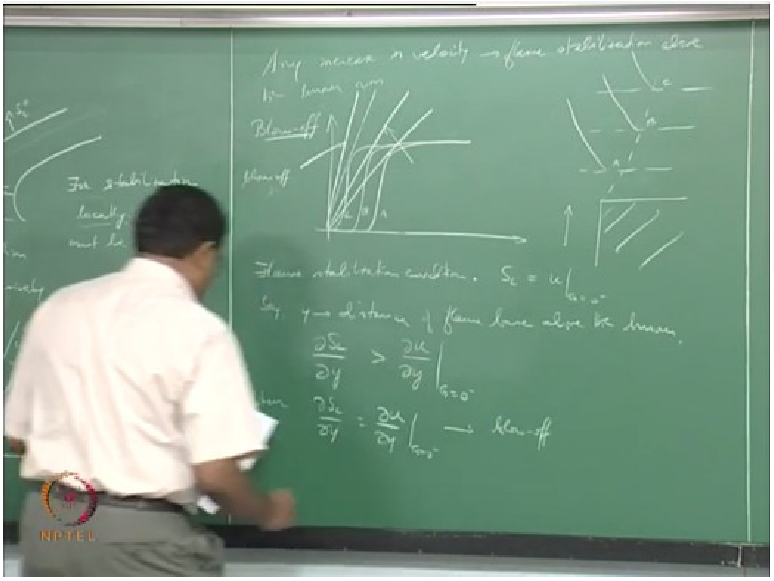

Any increase in velocity → flame stabilization above the burner rim

Flame stabilization condition. $S_L = u|_{G=0^-}$

Say y → distance of flame base above the burner.

$$\frac{\partial S_L}{\partial y} > \frac{\partial u}{\partial y}\Big|_{G=0^-}$$

when $\frac{\partial S_L}{\partial y} = \frac{\partial u}{\partial y}\Big|_{G=0^-}$ → blow-off

So when $\partial SL/\partial y=\partial u/\partial y$ $G=0^-$ this leads to a blow off right, what I would like to point out is one thing here blow off is not the same as extinction of the flame okay.

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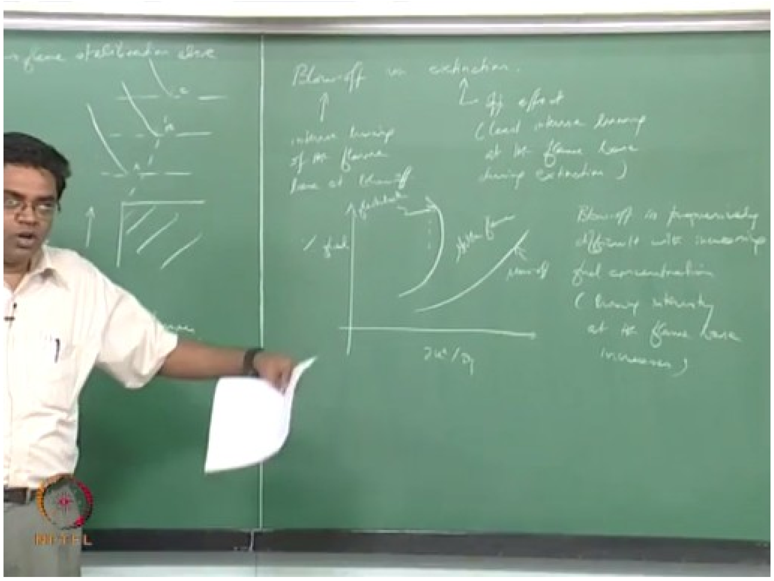

Let us see what is going on when you are when you are having a blow-off, when you are having a blow-off the S_L is actually more quickly rising to its high value closer to the flame base okay, so the frame base is shifted over to this point and the S_L as we now go from the flame base sorry, burner rim you are now having a more drastic increase in the S_L this basically shows that when you are now getting closer to a blow-off condition which is corresponding to the curve c the S_L is actually pretty high and you are having a fairly intense burning of the flame base at blow off okay.

So blow-off is a situation of intense burning of the flame base at blow off, extinction is the opposite of this extinction is where you are progressively starving the flame of reactant mixture right. So effectively the reactivity is coming down further and further and since you now have a heat loss situation and the dilution situation that further decreases layers at the flame base so the flame base is the place where you are going to actually have the biggest hit on the intensity of burning for a extinction situation where on the whole the flame is being starved of reactants and the reactivity is coming down the burning intensity is coming down it is going to actually be the worst at the flame base because of the heat loss the dilution, so burning so I should use the right word, so opposite effect least intense flame base during extinction, so putting these two together what we can see is there is a role for the velocity gradient in this flame stabilisation.

So one way of looking at this is I look at it in both ways one is to actually look at the velocity itself because you have a condition here and another way is to actually look at the velocity gradient you can look at it in both ways they give you slightly different pictures but not very different okay, so they can be the same idea. One you have a limit like this is this percentage fuel and let us suppose that this is $\partial u^*/\partial y$ or $\partial y^*/\partial y$ corresponds to velocity gradient what at a flashback or blow off.

And so obviously you are looking at two limits one for flashback and another for blow off, so this is the flashback curve right, and this is the blow-off curve and in between the two you are going to have a stable flame right, and see what is happening here the flashback curve is non-monotonic so it is it is increasing and then going back again that means you should now be able to actually look at two points for the same gradient and this is now a different percentage feel at these two points right, that simply means that you could re-stabilized the flame from a flashback situation either by going towards this region or that region.

Flashback is all about having a higher flame speed when compared to the flow, so if you now or in a below a certain velocity gradient for the flow then if you are now within the stoichiometric range you are going to have a higher flame speed and therefore you are going to flashback so you now enter a unstable region. So you now can re-stabilize by either going in the direction of fuel rich or fuel in because on both sides the flame speed is going to come down right. So it is possible for us to re-stabilize either by going the fuel rich direction or the fuel in direction that is not the case with blow off.

The blow-off does not look like a non-monotonic curve it does not really curve back right, so it is keeps increasing what that basically means is as you are going richer and richer the flame is going to be relatively indefinitely stable against blow off that means it is not going to blow off, it is only the lean flames there are actually susceptible to this, why is it the case naturally because of what we pointed out last in the last time the delusion from the oxidizing ambience. If you now have a few rich flame and the flame is getting further and further lifted away from the rim because of a higher and higher velocity and a higher and higher velocity gradient consequently then you are going to have a mixing coming from the oxidizing ambience which is going to cost a locally toward stoichiometric kind of mixture.

And therefore the flame the burning is going to be more and more intense and therefore it is not really going to try to blow off you see so what this means is blow off is progressively difficult with the increasing fuel concentration, right. And because burning intensity increases should particularly say at the flame base at the flame base increases, there is another way of looking at this of course the question that you have to ask immediately is what if I actually burn this in an inert environment is I tokay if I now have like let us say a nitrogen Indians in which I have a reactant mixture that is coming out through the burner right what happens then.

I am going to allow for nitrogen to dilute through the sides regardless of whether it is fuel rich a fuel lean should I expect the blow off to actually be happening for fuel rich mixtures as well yes, sure enough correct. So there is a different way by which we can look at that which is a broader stability map.

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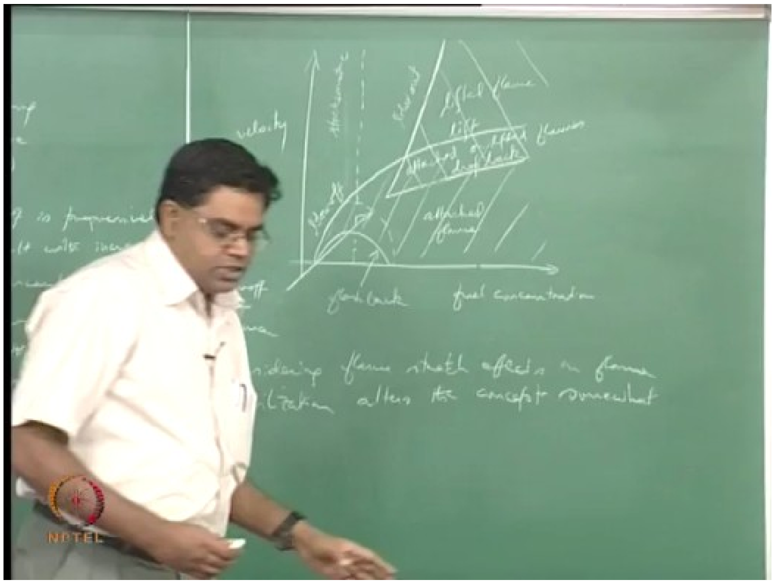

So to speak so here we just look at it in terms of velocity directly instead of velocity gradient the picture does not change significantly at least in a quantitative way, so if you now plot flow field concentration on the x axis or the horizontal axis as opposed to the vertical axis the period earlier, then let us now say we are somewhere in the stoichiometric somewhere here right, that means all this is fuel rich. Then our flashback curve would be somewhere there right, and maybe I should locate this a little bit further out relative to this curve and then you have a blow-off curve that keeps going like that that is for then adding its or an oxidizing ambience.

But if you had an inert ambient you will have a curve that goes back like this so this is a blow-off in keynote ambience, so it is sort of like reproducing this picture but then I would like to point out one more thing which is favor which is beginning to look very interesting for us now and I would imagine you should stop thinking about it right away we are now beginning to look at a space which is significantly fuel rich right, so if you are some are there what you should be looking at is your now having like a lot of field that is coming in and only a little bit of oxidizer that is coming along with it right, in an oxidizing ambience, right.

What if I did not have any oxidizer at all here it is highly fuel rich to the point of being only fuel in an oxidizing ambient what would I get, right. I am now progressively departing from a premix flame so it is not a pre-mixed flame anymore it is actually now beginning to look like closer to a diffusion flame, alright. So what was happening all the while when you still had some oxidizer and we really had a premix fuel rich mixture okay, it could be flammable we are not talking about getting positive flammability limit even right.

So it could have a fuel rich pre-mixed flame alright but what are the products going to be, the products are going to be fueled rich right, they are still going to have some field that is remaining which would which can mix with the air downstream of the flame not just at the base not only at the base but not only through the gap between the base and the burner rim, what we have been talking about is this mixing effect that is happening between the flame base and the rim so as to focus on the flame stabilisation. But on the whole you are going to have an excess fuel that is coming out of the flame which would mix with the ambient and form a diffusion flame envelope that is around the pre-mis flame this is typical.

And so long as you have this diffusion flame envelope it is lot harder to destabilize this flame, because diffusion flame is going to actually be there with the fuel and oxidizer or the excess fuel and oxidizer mixing all the time and it does not really have to propagate against flowing mixture a flowing reactant mixture, therefore the stability seems to be significantly protected for us in the case of fuel rich flames that is that is what essentially is happening, right.

However, there is another interesting to think that begins to happen which is you now have to worry about something called a lifted fling so somewhere and here you now have another envelope that is coming up in the stability diagram where you now have a lifted flame as opposed to which what we have been talking about so far in this region as well as here is what is called as an attached plane, that is to say whatever we have been talking about as aflame standoff here is still corresponding to what is called as an attached flame.

We are magnifying the region in the vicinity of the burner rim corner particularly and trying to decipher this standoff but this is still an attached flame, what we mean by a diluted flame is when now the flame gets significantly lifted away from the burner because now it can get very, very reactive as you now have a fuel rich mixture that is coming in and mixing with the ambient the flame can actually get significantly reactive right.

So it can get stabilized further out of a completely away from the rim not even not anywhere near the vicinity of the rim, so that is actually a lifted flame and it has its envelope as well and this is actually the blow out of the blow out of the lifted flame this means this is an edge where the lifted flame also blows out so that is distinguished between blow off and blow out blow off say terminology that is used for a attached flame and blow out is for the lifted flame to just go out okay.

And this curve then becomes basically the lift transition from an attached flame to a lifted flame this curve becomes like a transition that that causes the lifting that means if you know or fixing your field concentration and kept on increasing a velocity you should now lift at this particular point, right. And interestingly this curve corresponds to what is now called to say drop off or drop back what does that mean if you now have a difference between these two right.

What that basically tells you is if I now have a burner and I keep on increasing my velocity and I now have the attached flame trying to desperately hold on to the burner by giving way it is kind of like elastic thing right, so the flame is trying to actually get pushed a little bit further and further but still attached and then it lifts, okay.

And then it is actually burning there and you are like oops let me just bring back the velocity so that it can attach now it would not, it would stay lift it until you decrease the velocity significantly lower than the point when you cause this lifting to happen, that is what is called as a hysteresis right. So what is going to happen now at that velocity is not going to actually cause a drop back right there we need to come down to a much lower velocity for the drop back to happen.

Because now the flame has found a new home where it has got stabilized and it is beginning to get comfortable there it is going to stay there even if the velocity were lower and would allow a attached flame to happen. So the question of whether you are going to have a lifted flame or an attached flame now begins to depend on which way are you approaching in your velocity direction for example, right. If you are now going in the increasing direction of velocity you would stay attached until you even there if you had a lifted flame to start with at a very high velocity and you keep on decreasing you will stay lifted until you get to the drawback limit.

So this is a region corresponding to both lifted and attached flames so attached or lifted right, and so if you want to actually shade this somewhat you see this region is now going to take shadings from both and is a common point for both. I would like to point out one thing that we have not talked in detail at all or the other matter of fact not considered when we did the tip right, we talked about flame stretch effects which is to take in account the flame curvature and flow divergence effects. When we talked about the flame base where the stabilisation happens we have not really bothered about that at all okay.

So considering flame stretch effects on flame stabilisation alters the concept somewhat so we could do this, we could do this we know how the S_L changes with flame curvature and flow divergence as we have seen yesterday and we could take into account a diluting environment and they progressively changing a field concentration or reactant concentration effect on S_L so you can you can take an account a spatially varying S_L because of spatially varying concentrations of reactants and all these things can be taken into account in like a computation right, in a way you want to calculate this and take this into account and that changes things somewhat.

The other thing that I would like to point out is what we are being primarily talking about is a flame stabilisation over a burner rim right, but in general we could be talking about flame propagation in a duct. So for example, then you know think about like a flashback you will say okay, fine so let the flash back and see what happens, right. So how does the flame propagate further down into the duct? So there are some things that I would like to just say about playing propagation through the duct before we get to the next step.

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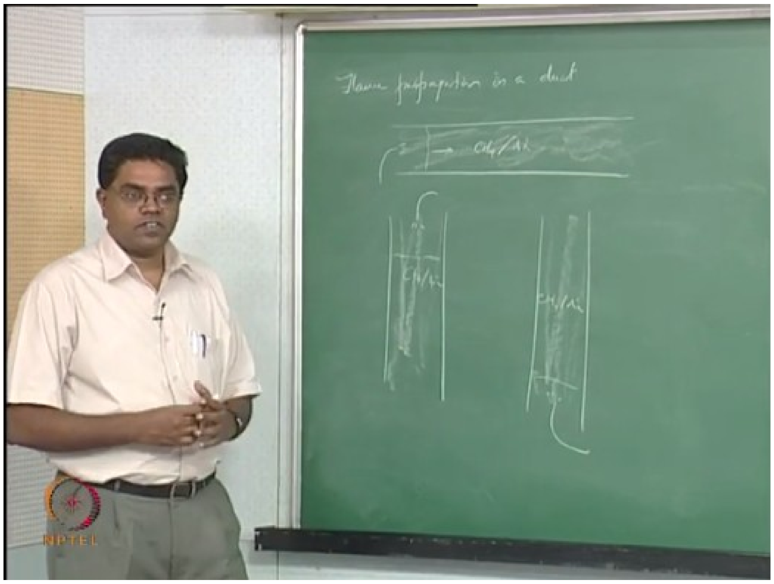

Right, now here what we have to think about is how is the duct okay, so far we have been thinking about like a Bunsen burner where typically we are looking at a Bunsen burner that is vertical and I now have a flame that is stabilized about the rim of the Bunsen burner and then the products go out up right. Now implicitly in our minds we have been adopting a gravitational field that is acting on these things and therefore there is a effect of buoyancy on these gases where the lighter gases would actually go up and the and the denser gases would stay down and the lighter gases are made lighter because of a higher temperature mainly for the products when compared to the colder gases being the reactants and therefore denser.

And so long as you now have aflame that is demarcating denser gas is being down here and the lighter gas is being above that is where they belong so nothing is difficult or different right. So what we would like to think about is a horizontal duct for example, and you now may fill this with a reactant mixture let us opposed methane and methane air right, keep it open on both sides for your safety you do not want to have transition to detonation here right, so you now ignite from one end and now allow for the flame to propagate alright.

Of course there are lots of nice interesting studies about flame propagations and tubes that are progressively of smaller dimensions and then you will find how the flame convolutes and so on right, and you see that the gas gases became have to flow away from the flame for a deflagration and then they begin to actually have a velocity profile there is a propagates and all those things okay, so but that is because the no slip boundary condition oh that is very interesting.

So now talk about flame propagation and a duct rather than being stabilized on the other rim of a rim outside a duck that is vertical, so far what we have been imagining is like having a burner and then having a flame that is stabilized about it but implicitly in our minds we have a gravitational field that is acting on this and you see what is going on you have a gravitational field that is acting downwards and you now have a flame reactants are coming up here and products are going up there.

And this gravitational field is now going to actually impose a buoyancy effect in which the lighter gases are going to go upwards and the denser gases are going to stay downwards and lighter gases are made lighter because of a higher temperature which is mainly for the products and denser gases are actually for the cold reactants and in a flame that we have that is stabilized the cold reactants are below and the hot products are above and then you have a fairly stationary flame.

But that is not necessarily the case all the time, so the way to actually think about this to begin with is start looking at flame propagation in a duct which is horizontal. So we now consider a duct which is horizontal and fix it up and fill it up with a reactant mixture let us say methane and air and you now ignited it in one end and keep the duct ends open so that you do not get into transition to detonation and those kinds of issues.

Then you expect a flame propagation to happen right, and there are lots of nice studies about how this flame propagation happens in this tube and for progressively smaller tubes how the flame actually curves because the flow curves the flow attains velocity profile because of the no slip boundary condition and this is actually the flow that is moving away from the flame and so on those are all nice studies that we will not really get into. The question that you are asking now is if I ignited it at this n you have a flame propagation from left to right if I ignited it from the other end would the scenario be different except that the flame propagation is going to be from right to left.

In a gravitational field that is acting only way we do not expect a change. On the other hand if you now consider a vertical duct and you know fill it up with a methane air mixture and you now ignited at the top and you now have a flame propagation that is happening downward from the top you see you have a cold reactant mixture at the bottom and the hot products are going to be at the top and they are going to go they are going to flow up right, conductively they are they are flowing up the buoyancy driving is also going to make them flow up, right.

And then you now have a propagation that happens further down and you get a certain flame speed. But what happens when you now have the same vertical duck you take the same mixture that is in it but ignite it from the bottom you now begin to have a flame that is actually beginning to propagate upward the reactants are cold and they are above and the products are hot and buoyancy is actually trying to drive them to go up against the deflagration expecting deflagration causing an expansion that is making it from flow down, right.

So if you now look at it is momentum balance the product gas is now going to have a tendency to flow through the flame upwards and contaminate or dilute your reactant gases, and therefore you are now going sorry yeah that is right, therefore the flame speed that you are going to get is different. On top of this we will also have to factor in the fate of the thermal diffuse of instability that is like perturbation to a planar flame and how much heat that is going to get conducted versus how much reactant gases are going to get diffused right, versus now product diffusion as well and so on.

On the one hand and also the hydrodynamic instability of what is the fate of a plane a flame that is perturbed from a planar condition with hot gases on one side and cold gases on the other side with the density jump across this you now have an instability because of that all these things eventually lead to the formation of things like cellular flames that means you do not really notice no longer have a flat flame at all the flame gets highly wrinkled okay, and then you get into what is called a cellular instabilities these are things that are not going to be covered at all.

But I wanted to point out a very interesting phenomenon here where you just have to take a duck and then hold it horizontally and ignited at either end or hold it vertically and ignited it either in you are going to get significantly different results. Point out something about the flammability limits is again like an information thing rather than an analytical thing.

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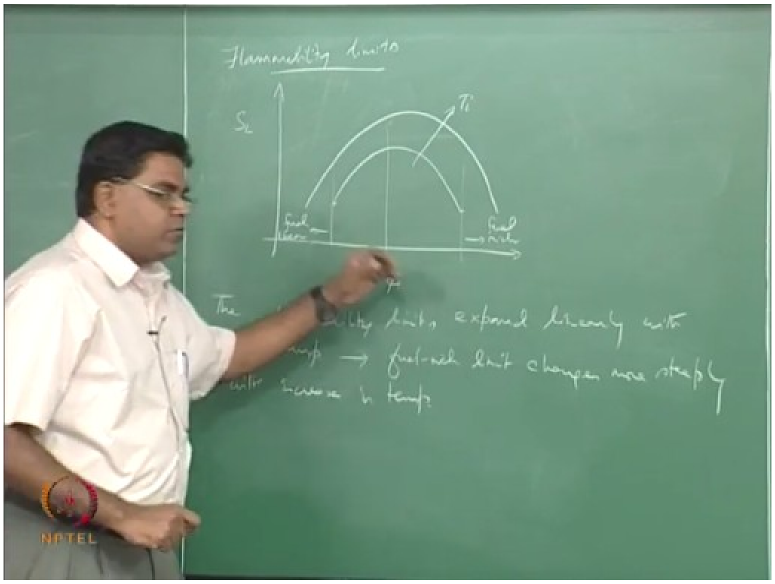

So we had this kind of a curve right at the beginning to look at the dependence of S_L on physical and chemical parameters and what we found was the flame speed actually increases and decreases about a point of ϕ=1 the equivalence ratio one slightly picking towards field ridge side and in fact this is actually a something that could be obtained by doing measurements on a Bunsen burner or the shoulder of the flame to look at what it is angle s with respect to the incoming flow or you could actually look at a glass tube apparatus the measure would set up like this and then ignited at this end and then see what happens or you could also have a spherically propagating flame.

There are many apparatus that are used for measuring flame speed and each of them has its own uncertainties because of additional effects that are not considered typically in the flame speed expert. For example in a spherical flame you have a flame curvature effect that is coming into picture that is altering the flame speed measurement and so on.

Now what we are talking about here in the context of flammability limits is something that we found the other day that is we have the flame speed decrease on either side from the maximum and then stop that means this does not really go to 0 you do not have any flame at all propagating on either side here and this is wait this is what is called as a fuel lean limit and the this what is called the fuel rich limit.

And add these limits you have a significant role for chemical kinetics coming in what is the effect of chemical what are the set of reactions that are happening and you are now starving the system of one set of reactants right or one reactant to start with and then corresponding set of radicals that are there okay. So the chemistry can significantly play a role play a role over here and for this reason the flammability limits are somewhat empirical I mean the knowledge on flame speed limits is quite empirical even to this day you have to significantly work on the theory to be able to explain this correctly.

There are some theories which do a good job like for example a heat loss theory where you now basically say that there is a lot of heat loss to the surroundings when you are now looking at these limits and so on, and keep in mind what I meant by heat loss today which is heat loss to non-participating reactants, right.

So you could have that situation but we are not going to get into all those details I am just going to factually state that you have these limits and what does it depend on, so effectively the controls that we have in an inning any experiment or the temperature and pressure. The pressure is kept constant and we are talking about reactant temperatures how do we actually change these with the reactant temperatures.

The effect of temperature is lot more straightforward you typically have a increase in the envelope of the flammability when you now increase your initial temperature Ti and the flammability limits are expand linearly expand linearly with the initial temperature and this linear so that means you can think about like a coefficient in the sense what is the rate at which the fuel lean limit expands as you increase the temperature and how does the fuel rich limit expander the increase the temperature per unit degree for example, right.

So what you will find is the slope if you now try to actually look at how the slope of the limit change is with temperature you will find that the coefficient or the slope for this relationship is higher for the fuel rich limit that means the field rich limit changes more steeply with increase in temperature right, so that is to say basically you know that this gap should be quite less when compared to that gap although this picture does not reflect that significantly okay.

And keep in mind when we say expand we expect the fuel lean limit to decrease and the fuel rich limit to increase in ϕ the corresponding ϕ should actually decrease for lean and increase for rich okay, so if you are asked to do some kind of calculations given what is this linear dependence you should factor in that lean is going to decrease in which is going to increase it to the pressure dependence.

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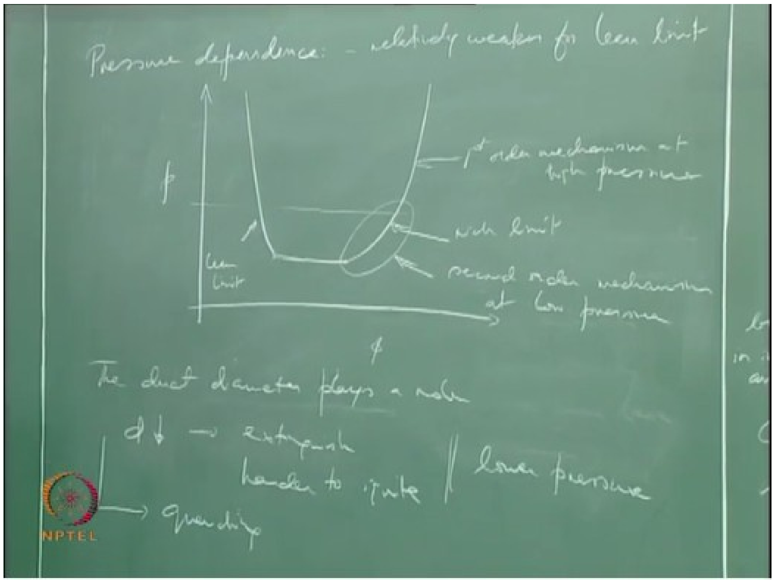

Pressure dependence: - relatively weaker for lean limit

The duct diameter plays a role

d ↓ → extinguish
harder to ignite || lower pressure
→ quenching

So pressure dependence is more significant than the temperature dependence usually you find a dependence that sort of looks like this if you now have a P verses let us say ϕ you have a relatively weaker dependence relatively weaker for the rich for the lean limit I am sorry, still it is sort of linear okay, so over a range of pressures its weekly linear and then almost remains constant over a smaller range if you think about it and then flattens out beyond a certain low pressure beyond which you just have no flammability at all.

But then it is more sensitive at the rich limit so this is the rich limit and this is the lean limit. If you now look at how this works this is actually controlled by like a second order mechanism at low pressure and this is controlled by a first order mechanism at high pressure, high pressure or low pressure could be success essentially on either side of atmospheric right, so we are now looking at tens of bars over here there is a sub atmospheric pressure over here okay.

And one more thing I would like to point out in these kinds of things is the duct diameter plays a role in determining the familiarity limits typically for small ducks, so if you now look at small ducks as you now as this diameter actually decreases then you have you get into two problems one you could actually extinguish rapidly or at a, or within the limit of what was actually deduced with a higher diameter or harder to ignite as you know go to smaller and smaller diameters may not be even be able to ignite the mixture, right.

And this is typically true at lower and lower pressures, so you now have a fairly good sensitivity of the flammability limits the duct diameter at lower pressure essentially because of the difficulty the ignite or even if you ignite you could have an extinction happen within a narrow range of equivalence ratios or giving a fairly narrow range of flammability limits correspondingly. And I would like to point out that this leads to something called quenching which we will discuss next.

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