Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 33
Bunsen Burner

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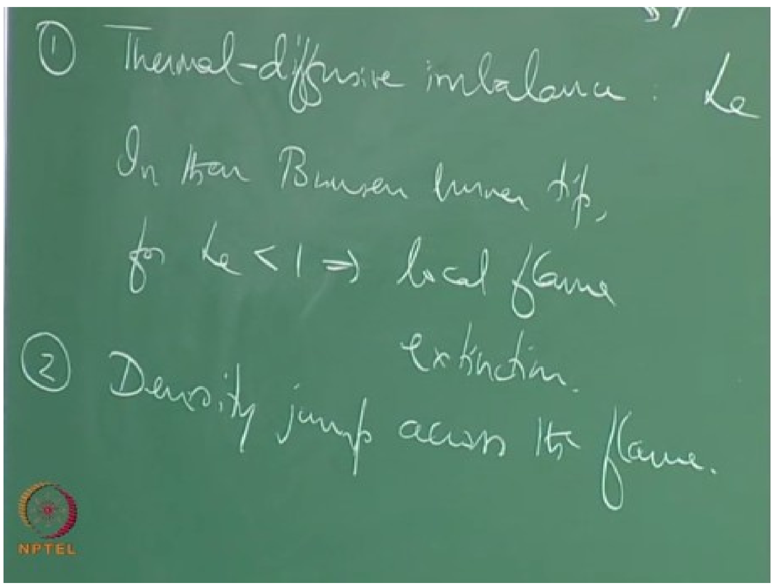

So we were talking about what happens to the Bunsen burner at the tip because what we found about the flame the flame stabilization was largely speaking we are now talking about like the shoulder of the flame where you have the normal component of the flow velocity tries to balance the flame speed that is normal to the flame itself and therefore the flame shapes itself corresponding to that, but that is true for most of the shoulder of the flame but if you now think about what happens to the tip.

No matter what the flame speed flow velocity balance is the tip also always has to actually propagate purple against the flow directly right, so which means no matter what the flow speed is and how the flame speed is able to balance that the tip always has to adjust itself to match the flow speed to the extent it can right, so question is how does that happen right, so what we find is we now have to think about think about a locally highly curved flame there and then see what happens.

When you now have a flame that is so curved of their therefore what we want to do is think about Flame curvature and also another aspect of it that we need to worry about called the flow divergence effect in the context of a small perturbation theory of plane fling, so if you now begin to think about a nominally plane flame that is propagating against a propagating with a flame velocity S_L superscript not all right which means in a flame fixed coordinate system you have your reactants un burnt reactants coming in into the flame at S_L superscript not then.

Let us now think about what happens when you now perturb the flame about this point okay and this particular picture here shows a couple of things one is you have one part of the flame that is curved convex against the incoming flow and the other part of the flame is curved concave relative to the incoming flow we need to think about what happens to these two parts separately but we should probably come to the same conclusion either way, so typically in a classroom if you explain what is happening to the concave convex.

Part and the exam you can you can expect a question of what happens the concave part right, so you should be able to think about this just as well what we want to talk about here is actually a to process to two different kinds of processes that are that that come about when you have this kind of curvature one is a thermal so one is the thermal diffusive imbalance or balance or imbalance depending upon what really happens so one of the things that happens is when you now have aflame that is curved let us now take the concave part this is a little bit more intuitive.

And it is also kind of like what is happening in the buns and flame tip, so this is pretty instructive when you are not thinking about a curvature which is now beginning to be off the order off not exactly equal to but off the order of which means still a little greater than the flame thickness okay now, so keep in mind what is meant by flame thickness the flame thickness includes a preheat zone and the reaction zone and the preheat zone is where the upstream heat conduction and downstream species diffusion happens.

Along with convection superposed on for both the species mass as well as z and therapy what we are now beginning to see is, if you now have a curvature like this then beyond what is being heated up when 20 for the cold reactants you now have a focused effect of heating the reactants s So this conduction, now becomes multi-dimensional the heat conduction becomes multi-dimensional and therefore you are now actually heating the reactants significantly more than if the flame or planar this should actually give rise to a tendency for the frame speed to increase all right.

Now on the other hand look at what is happening to the species diffusion the species diffusion now is going to actually go radially outward, so typically when you are looking at something like a fuel inflame for example then the diffusion species says deficient reactant is fuel in a few lean situation and when you are now trying to have this speak that, so that it is more critical to think about the deficient reactant, so the deficient reactant now spreads thinner occur in a radially outward manner.

So instead of actually feeding the planar flame straight it is actually spreading itself thin that means the flame is running out of the deficient reactant more than in the case of a planar flame if you have a concave curvature relative to the upstream right, so this has a tendency to decrease the flames p alright so you now have a possible balance between these two these two effects that will tell you whether the curvature is going to stay or grow or decay so when you now have to think about a balance.

Between heat conduction and species diffusion what comes to our minds is a lowest number right so we have to think about what the lowest number is and depending upon what the lowest number is okay, so if you now have a lowest number that is greater than one right, so if you now have allies number that is greater than 1 that means the heat conduction upstream right is more than the mass diffusion bounce free right that means the species depletion effect is not going to be as significant.

As the focused heat conduction which means that the flame is actually going to propagate no vigorously or there is going to be a net effect of increase in the flame speed all right, so if you not think about what is happening at the tip of the flame for a greater than unity lowest number right, we expect a no intense burning an increased frame speed that can try to match the flow speed they are all right for a greater than Lewis the greater than unity lowest number, but if you now have a four in the bulls in burner tip right.

The Bunsen burner tip for early less than one you now have a greater extent of deficient species depletion that is happening when compared to the extent of upstream heat conduction, so the flame is essentially running out of reactant even if it is trying hard to conduct heat upstream to heat up whatever is remaining of the reactants, so this leads to this could lead k so could lead to a local claimed extinction alright, now many times I should not say many times sometimes you do see flames.

Which have a hole in the middle so the Bunsen you now have a flame that keeps going up like this instead of turning around it actually goes up like that and see that I am actually drawing it with the lighter line that is simply because the faint fades as it goes along that that indicates like a lesser burning intensity progressively and the extinction there all right, so you now have a hole in the flame it is not as if like it you need to have le less than 14 for this hole in the flame there is also one more thing that we have to think about.

So the first thing that we talked about was a thermal diffusive imbalance tell most hyphen diffusive imbalance the second thing that we have to worry about is the density jump okay, so density the density jump across a flame, so what is the consequence of having a decrease in density for the products relative to the reactants where the flow gets past the flame right any ideas here what is going to happen if the flow now tries to go pass we try to still go through go through the same idea.

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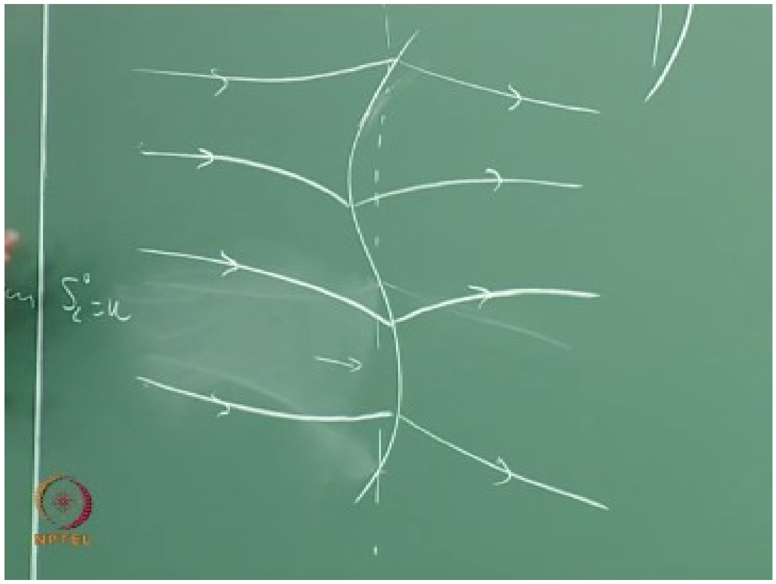

That is you now have a nominally flat frame with a S_L not but then now you are beginning to think about the fact that the density of the products is going to be less than the density of the reactants and perturb the flame to be non planar alright, so as a consequence of the density difference local mass balance dictates that the velocity should compensate for it alright, so if you now think about a point here a long along a curved flame what we are basically saying is you now have a let us suppose that you are this is your U_0 and.

What you want to do is try to decompose this as parallel and perpendicular to the flame right so this is U_0 and this is U_T not and what happens is when you try to have a flow that is going past the flame it is mainly the normal component that suffers the expansion because that is how we are normally thinking about a flame, so if you had a unperturbed flame with a with a with a flat a profile then what you are basically saying is the normal component of the flow is going to actually expand right.

So what we then what we then have to expect is we need to have the normal component increase significantly this is significant because what we are talking about is a constant pressure more or less a constant pressure system alright, and you have to think about what is the density change because if the density changes because of the temperature change, so the temperature rises therefore the density falls right so what is the temperature rise like if you take like a 300k over here.

And let us say it is reasonable to expect something like a 2400 k there right so that is about a temperature rise of about 8 fold can be 2100, 2400, 2700 k think in terms of factors of 3 or 300 for the sake of simplicity right, or three thousand so you are now talking about a factor that somewhere between 7 to 10 times more all right, so this has to be significant and then so the density corresponding is decreases right, so p = ρt and as T increases ρ has to decrease and then ρ_0 U_0 = ∞ U ∞ or more specifically in this case.

$\rho_{0\ Un0}$ un not it should be equal to ρ ∞ Un_0 ∞ / ρ_0 ∞ s going to be about a factor of 7 or 8 or 9 then U_N ∞ is going to be that much higher when compared to UN_0 right, so it would be okay if we extended this line even more like this particular vector in the right room it is only about three times, so this let us just exaggerated a little bit more each other it is still not an exaggeration and so this should actually be your U_T sorry un ∞ right and the U_T not gets preserved as such when you now want to locate your U_T∞.

Because that does not really suffer any expansion and then so what happens to the resultant so the resultant, now obviously gets tilted more towards the normal of the flame all right so this is basically then your U∞ this is the picture you would like to see, so what is it what essentially is happening it essentially means that if you now have a stream line that is coming like this it is going to get compressed right.

So if you have a streamline that layer that that goes like here is going to go together well obviously streamlines cannot hit it either right, they try to turn and in trying to turn and accommodate each other they try to disturb the streamline setup that are approaching the flame as well okay, so you now get into a situation where your stream lines should actually turn out to be in reality somewhat like this it starts bending outward in anticipation of having to converge again further downright.

And correspondingly if you now look at this kind of a curvature which is what is pertinent for us in a Bunsen burner tip right, so we expect that the flame should actually increase sorry the flow should actually increase or diverge and then converge back again I am sorry I made a mistake right, so look at what is going on here you have a situation where you are thinking that you want to have a flame that is stabilized at S_L not right, now this is what is equal = u locally here that means you always.

This is very important I think I mentioned this earlier the way you always want to think about flames and I will re iterate this when we are dealing with triple flames after doing diffusion flames the way we always want to think about a flame propagation speed is always relative to the flow speed far upstream of the flame that means you do not want to worry about all this mess you have to say it all depends on it all boils down to how much do you have to open the valves for my flow to actually sit in.

So that the flame is approximately stabilized what has been by approximately the stationary there I can actually have a flame fixed coordinate system what it is doing within the frame fixed coordinate system is not of concern to me so long as it is their right, and what is the flow speed at which it is there is what is the flames feet is what I would like to think about right, so if I want to now say that this is what it is then what is the problem that it is happening near the flame you now find that the flow is locally accelerated.

When you now have a flame that is curved concave relative to the far upstream reactants all right so the waters essentially happened is the flame has now induced the flow to go faster at it when it when it when it tries to have a concave curvature right, and this means the flame needs to actually try to compensate for a higher level of increase in flame speed which should be by a mechanism that we talked about here if it has to survive if not it is going to actually cause a local extinction right.

So we see this actually happening in a in a in a Bunsen burner for example when you now talk about a streamlined path that is approaching the flame you now know that know for a fact that you now have a streamlined part that goes like this so you do have a flow that is actually getting diverged for most part and then that continues to happen over here, but locally it tries to actually squeeze in and then diverge so effectively what happens is you need to have to take into account the effect of flow divergence.

On the planar flame speed so if you want to think about this effect you want to try to actually bring this into modifying the planar flame speed such that all this is like a black box and if you now had a planar flame speed how is it going to be modified in a way that will take into account the local slow deceleration or acceleration all right, so there is a way by which we can do this I am not going to derive this or this little bits quite beyond the scope of this particular course.

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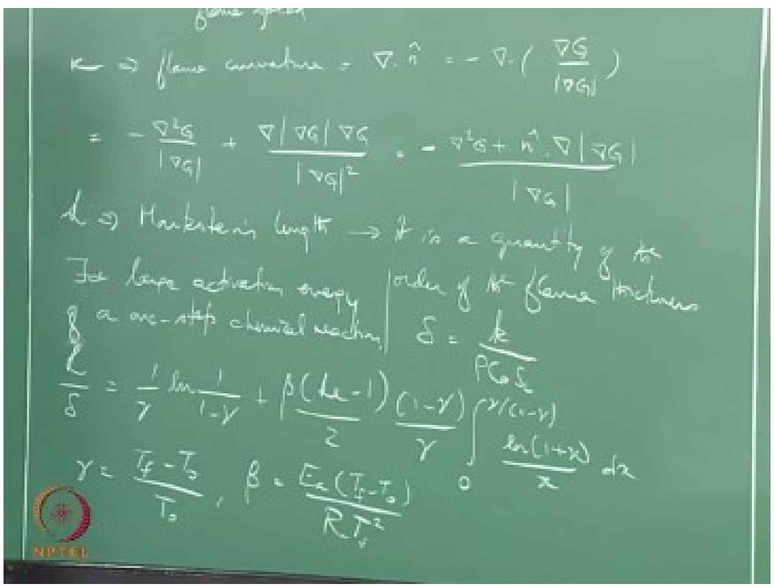

But we will just take these things so if you now assume constant properties constant properties the fleeing speed is modified as $S_L = SL_0 – SL_0$ LK+ L n^ dot divergence.

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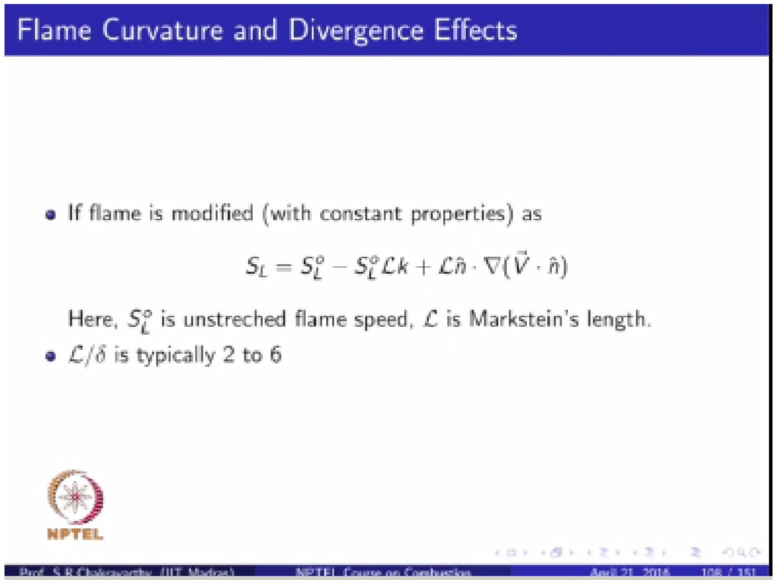

Or n^ dot gradient v vector dot inhale so here the S_L^0 not is basically the un stretched fleeing it does not suffer from the flame curvature and flow divergence effects okay, but S_L is actually the frame speed that you would that you would have to use for a flame that is curved and also induces a flow divergence correspondingly and therefore alters the flame speed as well right so here Kappa then is the flame curvature right, so that is equal to divergence of n^ hat which is nothing but negative of divergence of ∇G / mod ∇G.

In the framework of the G equation and so of course you can now try to do a chain role differentiation here, so this is ∇^2d / mod ∇G + ∇ mod ∇G times ∇G / by mod ∇G^2 which is minus ∇^2 G + n^ dot ∇ mod ∇G / mod ∇G keep in mind we are actually trying to find the flame shape okay and the flame shape is now contained in the flame frame speed okay, so previously you are trying to find the flame shape based on the un stretched flame speed right, but now we have to use a stretched flames speed.

Which depends on the shape and the shape depends on the speed so you will have to do a literate of solution of this it is possible and there are there a resolutions it can be made available for these things l here the script l is what is called as a mark strains length and recall I kept talking about a length scale that is of the order of the flame thickness but not exactly equal, so it is somewhat greater gates is a little bit greater than the flame thickness because, if you now have a frame curvature the heating effect is going to be felt.

A little bit further upstream than the original un stretched flame thickness okay, so previously the un stretched flame thickness contained the preheat zone, but now if you curve like let us say concave the heating is going to be felt further out right, so that is kind of like the mock scenes length we are talking about, so it is a quantity of the order of the flame thickness flame thickness and of course we know that the flame thickness δ depends on the flames p this we did long ago right.

So the first time we started talking about the structure of the premix flame the mass balance in the preheat zone resulted in something like this okay but here keep in mind this δ is actually for the stretched flame thickness the S_L is actually the stretched flame speed okay and what we are now saying is this depends on L okay and so how does l depend on the δ so there is a derivation for this again which we would be three would not go through but I will just state for large activation energy.

Of a one-step chemical reaction right so within the framework of assuming a one-step chemical reaction with the large activation energy for it l over δ script l over δ is one over γ natural logarithm 1 - sorry 1 / 1 - γ + β lowest number - 1/2 1 - γ / γ integral 0 γ / 1 –γ natural logarithm 1 + x/ x dx not a evidently x is a dummy variable of integration from 0 to γ /1 – γ is now not the ratio of specific heats that you are used to in gas dynamics this is actually the ratio of temperatures.

Which is basically a temperature difference divided by the initial temperature and ß is our Zelda which number, so it is E_A x times $T_F – T_0 / RT^2$ so you can see that the γ is actually embedded in here you could say TF – T_0 / T_0 is γ, so ye over r UT are you TF times γ would be your ß.

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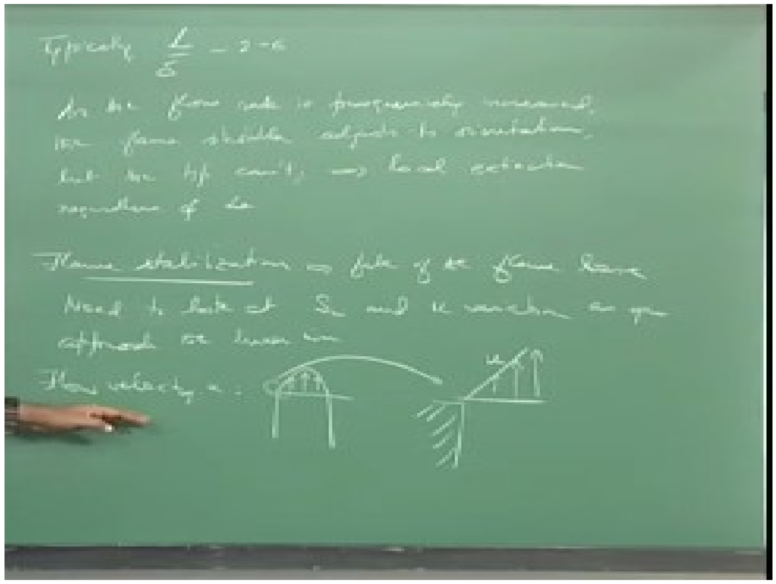

Now typically it is found that the typically L / δ is 226 so there are analysis so what would you what you will see is now, if you want to try to actually find a curved flame shape it is quite difficult it is more getting more involved your mark change length depends on the flame thickness the flame thickness depends on the flame speed the flame speed depends on the mock strains length and so on, so there is like a loop within a loop that is going on here which we have to solve iteratively there are analysis where we would just assume a constant mock stains length.

Let us not worry about so you pick a number between this because it is about a variable that varies within this range, so let us not worry about it is the attitude for those analysis so then what happens as I said you see as the flame speed increases, if you now go back to the tip of the emulsion burner that that is what we were concerned with if you now keep on increasing the flow speed right as it is the flame speed in this case the flame speed for the un stretched flame is less.

Than the flow speed okay and the flow speed or put another way the flow speed is actually greater than the un stretched flame speed and at the tip because we now have a concave curvature the flow tends to actually, converge and actually increase faster the flow faster that means the flame speed has to increase much more to counter that and that would be through the thermal diffusive imbalance all right and that is obviously possible mainly when you have a lowest number greater than 1.

But still since this effect is countering that even when you have a lowest number greater than 1 you could have conditions of local extinction right, so as the as the flow rate is progressively increased right the flame shoulder adjusts its orientation, but with the tip con the tip all this has to stay as the tip it cannot adjust the adjust its orientation to the flow velocity therefore does this results in a local extinction regardless of any whether it is whether it is greater than 1 or less than 1 and so on.

Fine what next we talked about the Bunsen burner we realize that at the shoulder of the frame the flow normal component of the flow velocity should match the flame speed for the flame propagating perpendicular to itself then we realized that that is not as simple a situation at the tip so we went through what we needed to go through to think about the tip and it we found that it is not, so straightforward you have to worry about these effects to effects mainly the thermal diffusive imbalance.

And the density variation effect density change with temperature effect, so all these things are involved in explaining what is going on with the tip, but what about the base right so what is going on at the base when we did the G equation we made an assumption that over ζ should be equal to 0 at $r = R$ that was like a boundary condition that we had adopted okay basically saying that the flame is touching the rim of the burner of course within the framework of the G equation we do not bring into effect the thickness of the flame all right.

So it is as if like the flame is having a thickness and we are basically saying that the S_L is a constant it does not change and therefore we do not have to also worry about a varying thickness of the flame near the near the base and or r a varying flame speed as we approach the base right but none of these things is true, so we need to now focus a little bit more on what is happening near the base and see what is the fate of the flame speed as we approach the base as well as the flow is not uniform either right.

So we tend to think that you have a uniform flow that is approaching the flame and you have a uniform flame a constant flame speed with which the flame is trying to attack the reactant flow and therefore you have a shape but that was not the case for the flow as well the flow was not uniform there it is coming out of a burner and it has to satisfy no slip boundary condition that means the flow velocity has to start from zero right, so we tell you anything wait a minute if you are going to have a zero flow velocity there that means of flame should be able to propagate.

Against the flow right there along the walls and never really be stabilized about the above the burner on the one hand it looks like the frame has to actually not be held at the burner at all and maybe get pushed up by the flow, but if you now look at the flow right it looks like the frame has to go deep in what's going on right, so let us does this idea of having to look at the base of the flame takes us to what the issue of what is called as frame stabilization flame stabilization.

So this is just refers to the fate of the flame bass playing bass or flame anchor point frame stabilization can also be referred to as flame anchoring because the base is the one that is actually holding the flame, so corresponding you can also use the term flame holding right so flame holding flame anchoring flame stabilization all these things refer to pretty much the same and it deals with the fate of the flame base because the base is where the flame is held right.

So we need to look at so what we what we just said was we need to look at S_L and U variation as U approach the burner rim approach the burner rim right, so let us look at the flow velocity variation that is simpler, so flow velocity U okay so what we expect is if you now have a burner big we have a no slip boundary condition all right and of course you could quibble saying we do not know exactly how the flow was formed in where and how is it developing as it reached a fully developed profile do we have an entrance length of associated.

With it and so on those things are not very relevant okay so even in the in a worse case where you assume like a fully developed flow that is emerging out of the of the tube right and we are talking and talking about laminar flames, so we are looking at a laminar flow lam the fully developed flow that is coming out of the tube we expect a parabolic velocity profile right, but what matters to us is what is happening here right so this basically means that we are looking at now what we drew as a line has suddenly.

Become not a thick block I am even exaggerating and going further into saying that this is almost like a semi infinite solid filling one quadrant and will be the corner here corresponding to that burner rim and the flow velocity is locally linear that is your U, so when we said that we wanted to look at the flame speed and the flow velocity variation as you approach the burner rim we pick the flow velocity because the flow velocity is always going to be somewhat linearly increasing from the rim inwards.

Towards the center of the tube so that is more like a monotonic variation you increase the flow speed the slope is going to increase if you decrease the flow speed if the slope is going to decrease the top right, so there is no there are no counter effects or competing effects here but that is not the problem that is not the case with the really flame speed there are competing effects that we have to worry about for how the flame speed changes as it approaches the rim so it is not so straight forward so we consider that next.

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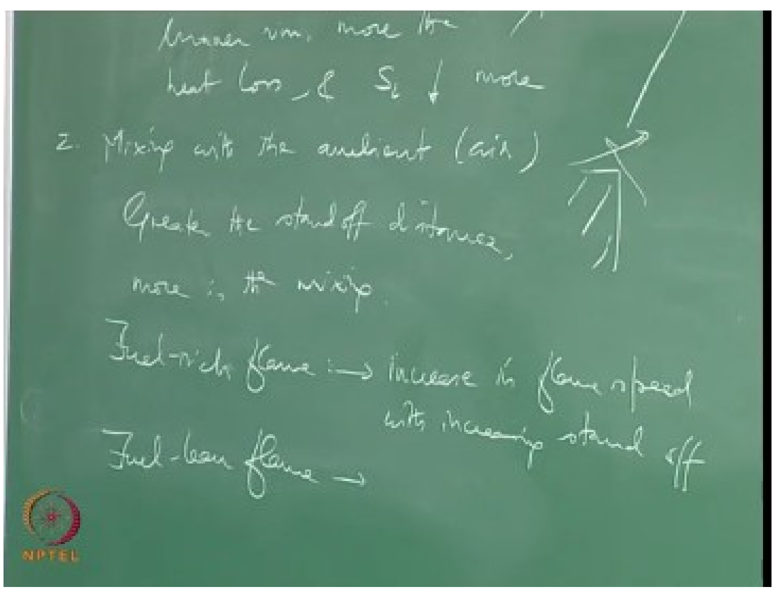

So how does the flame speed behave right there are two factors in fact 22 contravening factors that we have to think about one first and foremost as a matter of fact is the heat loss to the burner heat loss to the burner, so when you now have a flame that is approaching the burner so think about what is happening if you now have a burner rims let us look looking like this when you are now trying to zoom in into the burner so much right you cannot simply draw a flame like a single line anymore pretending.

That is going to now consume contain both your preheat zone and the reaction zone and all those things right you now have to worry about how does the preheat zone look like how does the reaction zone look like what I know for a fact is far away from this burner rim I am going to have a certain thickness for the flame and the preheat zone is going to be thicker than the reaction zone larger the activation energy okay.

But what happens as you now progressively come closer to the rim is keep in mind that this is actually the region where the temperature actually rises from the initial temperature to the flame temperature as we go along and this is the region where most of the conduction is happening, but as you now come down to the flame with the burner rim you now have a heat conduction that is going on inside the rim as well, so it is suddenly like the burner rim intruded into the preheat zone.

Because the preheat zone essentially is part of where the conduction happens right but the preheat zone was supposed to actually heat up preheat right, so preheat means it is supposed to heat up the reactants to react, so there is no point in heating up the burner rim because the burner rim is not hopefully going to react right it is kind of like the joke about whether look how does the how does a combustor work the combustor burns it is not good news because the combustor burns means the converse is not going to be there.

So similarly you do not want to have the burner be part of the reactions right, so what this what then happens is you know essentially you are thinking about a thick progressively thickening preheat zone and the fact that we are talking about a heat loss is because the reactants are not the only ones that are getting heated up okay in an adiabatic flame there is a heat transfer going on it is not as if like there is no heat transfer going on in an adiabatic flame, but it is kind of like you know the father gives us money to the son.

And the son gives the money to the grandson and so on it is different the money is kept within the family right it is not going and going away, so it is like the reactants or are the ones that are actually getting the heat and reacting in the flame, so long as the reactance of the ones that are going to get all the heat and then react in the flame to release that heat it is an adiabatic system but the moment the reactants are not the ones that are going to get heated up anymore that is not an adiabatic system.

So obviously then the local frame speed should decrease right, so the flame essentially becomes a lot thicker and the flow the flame speed progressively decreases to towards heat or z as if flame is held closer and closer is essentially the heat loss to the burner basically means that closer the flame base is located to the burner rim right more the heat loss and S_L decreases more right the decrease in the S_L is more what we are basically thinking is as you now have a burner and you are now trying to increase the flame.

Speed we are beginning to imagine that the base is not exactly touching the rim anymore the base of the flame is now going to go up a little bit and try to adjust its position why would it adjust is something that we are going to see pretty soon right, but when at the moment we now begin to think that the flame is not going to be at the rim and can move up or down relative to the rim what we are basically saying is closer it is to the rim more is the heat loss and therefore the flame speed near the rim is going to be progressively less.

So this is say a contribution that is going to decrease the flame speed okay the second decrease the flame speed more move when you are the frame is closer to the rim second is the mixing with the ambient mixing with the Indian right, now for the purpose of what we are talking about let us fix the ambient as air right, air as in what we find on earth here right that means you do not have the oxidizing ambient right and then think about what happens as you as you now allow for mixing to happen.

So essentially what this means is you now have more standoff of the flame let us say the flame is now further out okay, so if you now have a flame that is progressively further out and for this purpose it is sufficient for us to just draw a line to represent the flame, let us not worry about its thickness right, it is thicker and so on, that is fine but what you are looking at is this distance more this distance greater is the mixing of the reactants with the ambient right what is the consequence of this for the flame speed.

That is really the question that we would ask that depends on whether the flame is a few rich flame or a few lean flame right, so if it were a fuel rich flame right so great so let us just record this greater the standoff distance right more is the mixing and the question is that mixing going to be increasing the flame speed or decreasing the flame speed right, so that depends on whether the flame is going to be fuel rich of your lean.

So few rich fleeing in oxidizing ambience what happens now this region actually becomes closer to stoichiometric right because it is fully you will reach flame and then you are now sending in more oxygen from the side and therefore, it becomes closer to s stoichiometric, so this leads to an increase inflame speed right with increasing standoff right, and this goes in the same direction as what the heat loss effect was in the case of the heat loss what we understood was the close of the flame is to the burner lesser.

It is less than it is it lesser is its flame speed or conversely the farther it is from the burner it is going to have a higher flame speed because of less heat loss is exactly what we are saying here increase in the same flame standoff means a increase in the flame speed because it is filled rich, so in this case this is a little bit more complicated and we will talk about this later on what is important for us to is to look at a competing effect that means an opposing effect right and that is presented in the case of a fuel lean flame.

So in the case of a few lean flame you are already fuel lean and a greater mixing with the ambient is going to dilute the flame further and further, right at the beans of flame speed is going to decrease as the flame standoff distance increases the heat loss was less, so the frame speed does not have to decrease that much more but it is going to decrease because of the dilution right so dilution decreases S_L within crease in standoff right with these two we should now be able to tell how the flame is stabilized we will do this now and we will worry about pushing the limits on this to lead to a flash back or a blow-off later.

So essentially what happens is if you now have a first-round put these two together that means originally, if you now had a flow velocity that was locally in linear right and I am let me, now consider the flame the flow like this right that is a flow velocity you what we are looking for is if you now have a flame that is like this.

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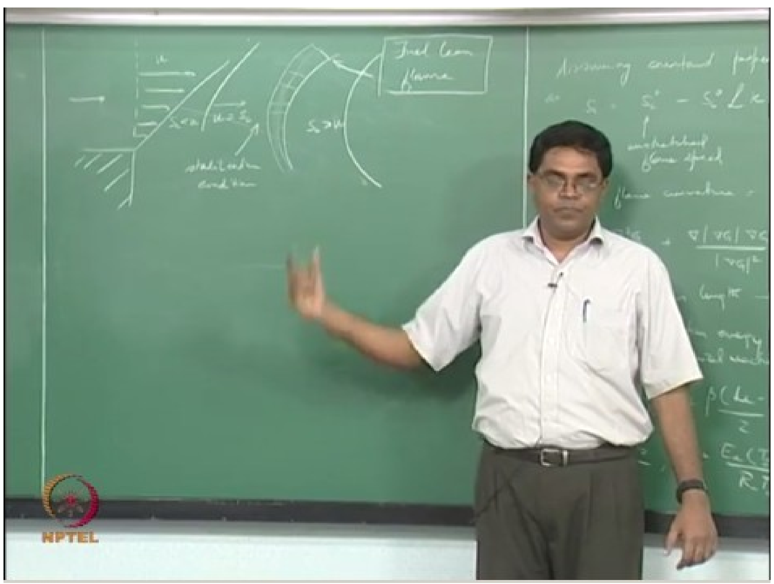

Let us look at how its flame speed is going to be right as it is over here with respect to like the free stream velocity the flame speed is low, but the flow speed is actually decreasing linearly and the flame speed is decreasing because of heat loss on the one hand as its proximity to the burner is determined and because of the mixing and we are now considering a fuel line case right the fuel in case it is a more straight forward for us to think about, so there is a position there is there is a condition.

When maybe the scales are in good here so let us consider the scale it look like that, so there is a condition when the local velocity and the local flame speed match exactly where you have this curvature facing the flow right, so this is where you now have a $U_0 = S_L$ I am not saying u bar equals S_L not for you not equals S_L not okay I am saying u is equal to S_L, so this is the stabilization condition right now what happens when you now try to actually have a flame that is perturbed inward.

Is it now gets closer to the flame right so it is S_L actually becomes less than you because of a greater heat loss effect all right but the mixing is not much, so it is not trying to decrease the S_L a lot but the heat loss is actually trying to decrease the S_L and therefore the flame gets pushed backwards to this point, but if you now try to actually have a flame that is pushed further out it now becomes lot more extended you can see how you how I am drawing these pictures you now see that it is actually stopping somewhere, here it is stopping here can extend further because you are mixing fan is more.

You now have this reactance reaching a greater distance laterally outward right so you can you can have aflame over here but in this case the S_L actually now becomes greater than you because you do not cover too much of a heat loss effect and therefore it has a tendency to move upstream you now have a larger flame because the reactants have actually found out and they have less heat loss and they have a tendency to move against a linearly decreasing velocity.

Until you reach a matching point okay so effectively it now becomes a local match between a varying flame speed and a varying velocity, the flame speed is not uniformly varying the velocity is linearly varying and this match is what is going to actually dictate how the flame is stabilized locally there and therefore correspondingly a flame standoff distance stop here.

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