**Indian Institute of Technology Madras**

**NPTEL**

**National Programme on Technology Enhanced Learning**

# COMBUSTION

## Lecture 32
## Bunsen Burner

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So we were looking at the G equation which is written back here again.

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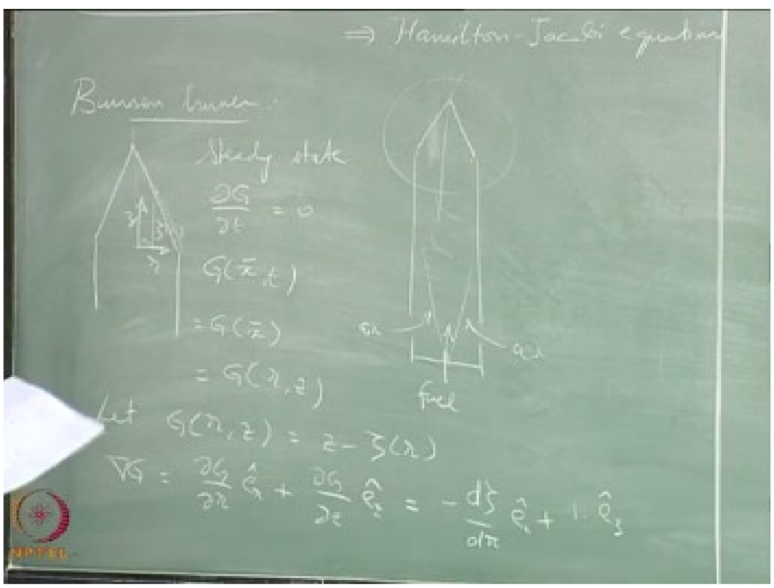


This is typically belonging to your class of what is called us Hamilton Jacobi equations well it is not exactly this but we will look at a specific form of this pretty soon which could be looked at as a Hamilton Jacobi equation, but the reason why I am mentioning this is yesterday we were talking about the possibility of solving the G equation as if it is a scalar field everywhere in the domain with the G varying from a value that is less than 0 to a value that is greater than 0 through a very thin region.

Where it directed where it drastically increases from - 0 2 + 0 sorry less than 0 to greater than 0 through 0 and wherever you have this iso- surface of G equals 0 will form the flame, flame sheet is what we were saying but it is possible also to solve this equation directly without having to actually assume that is a scalar field, so you do not have to actually solve for this everywhere in the flow field it is possible for you to solve for this directly and the only problem there is you will find that.

You require you have to make sure that you are not creating any spurious numerical oscillations if you are trying to solve this numerically because you are looking at something like a very thin sheet and it is very difficult to resolve this therefore typically numerical solutions will have errors that accrue and try to cause oscillations, so there are these what is called is essentially non oscillatory oscillating solutions that are two schemes that are employed like typically the more advanced versions are like weighted.

Essentially non oscillatory schemes and also for the time marching in an unsteady case you should look at something like total variation diminishing schemes and so on, so there are some special ways by which you can solve this numerically directly instead of having to think about it as a feed, so having said that let us now try to see if we can work with this in the classroom on a simple problem right so we do not have to do heavy duty numeric’s and have to learn a lot of advanced schemes and so on.

So the simplest example for us is the Bunsen burner right, so the Bunsen burner Bunsen by the way is a German he was working in Heidelberg, so that there is if you go to the Heidelberg town square you will find a statue of Bunsen right across kerkoff's house and apparently Bunsen divides the burner for crack off to do spectroscopy with it so the Bunsen burner is a simple idea here you have a you have a fuel flow through an surface and you now allow for air to get entrained.

In this jet of fuel that is coming out so you have like locally sub atmospheric pressure over here and then the air and feel mix with each day over here, and then issue out as a pre-mixed mixture and you now light up the flame in the at the rim and then you now have a almost like a conical flame that is established a conical blue flame that is established for most typical fuels, so this is this is a pre-mixed in fact most of our kitchen staffs work on the same principle, so you do have a orifice at the bottom.

And you can enters the air and so on so let us, now try to see if you can come up with a simple version of how this will this can be done, so let us just enlarge this picture right there, so this is the burner rim and of course what we first do is to fix your coordinate system so you can have all z coordinate system and you now have a flame and for simplicity well I should not say this at this stage.

Let us assume that it is say axis -symmetric flame that is fine and then what we should actually be able to show that show is this is the conical flame, and then of course it is not a perfect cone you have some deviations from a cone at the tip and a database as well, but let us not worry about all those things at this change what we should be interested in is to get the shape of bulk of the flame right which is what color the shoulder of the flame, so let us aim to do that and so we are now looking at a steady state.

This is reasonable in fact many times area now light up a Bunsen burner view the flame hardly shakes, so you do not even know if there is any time dependence at all so you have a very good steady state situation in a laminar Bunsen burner so that means the unsteady term in the G equation goes to 0 right, and therefore if you now have the steady state then G of let us say x vector , t excess the position vector just being becomes G of x vector alone which in our case.

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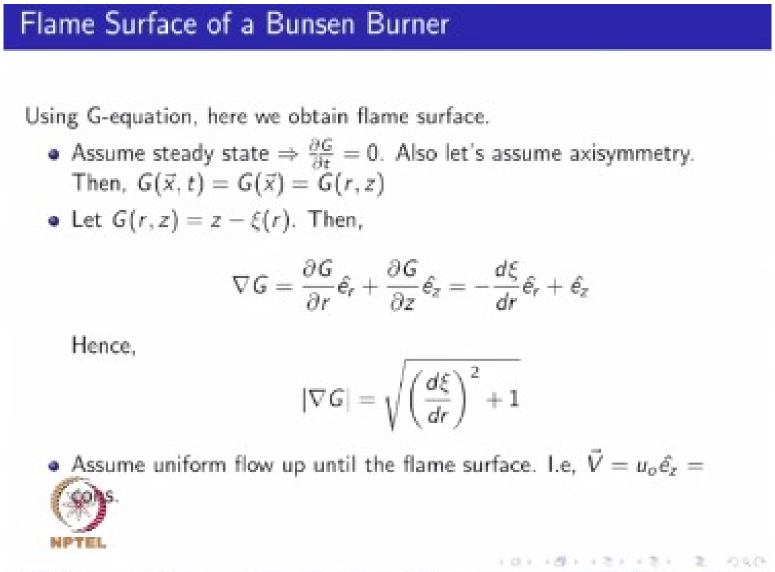


H as to be G of r , z because it is x axis symmetric that means it is not even depending upon the azimuthal angle θ, so it bear depends only on or answered so you want to keep this a bit simple so you do not want to actually have a G equation that is GG expression that is so general so rather what we want to do is let G of r, z be written as z – ζr what does that mean we want to have G = 0 at the flame right, so if you now set this equal to 0 you are going to get a the flame shape as z = ζ of r.

That is what we are looking for okay so this is a two dimensional picture graph in which you would not have the flame shape and a two dimensional function in an xy plane would be like y equals f of x that is what you are used to but because it is a what we call cylindrical polar coordinate system we are using a z or plane in which we are now going to assume the flame shape to be of the form z = 0 of r right, so if z = ζ of r at the flame then sub ζ of or should be equal to zero or the flame.

So that should be your G right so what does it essentially means is any location on the flame is measured by a vertical distance ζ along z okay, so this is 0 for a given r okay the moment you now have your G written out like this then, we can we can write this as ∇G right so ∇G is ∂G / ∂

r P or cap + ∂G / ∂z e is a cap and this is going to be, so ∂G/ ∂r is going to be a negative d ζ / dr e or cap + you just have z over here, to they take a partial derivative with respect to.

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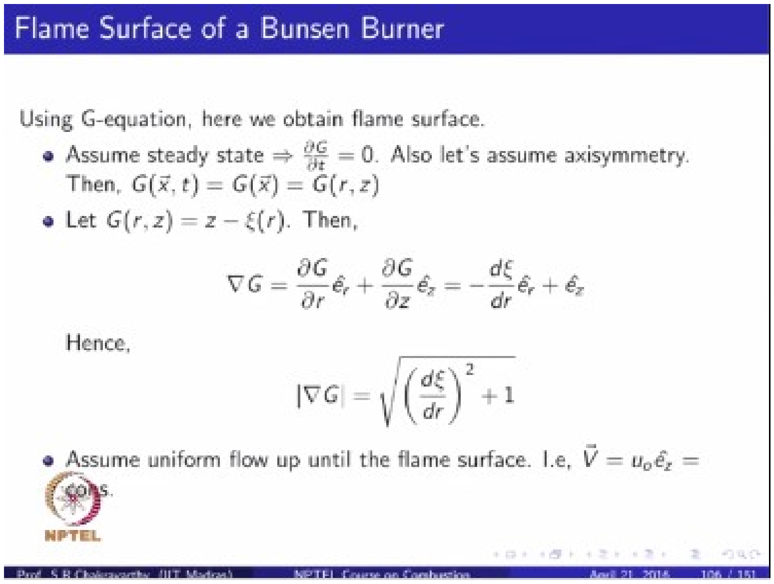


So that is going to contribute to 1 times e is a cap and ∇g Therefore.

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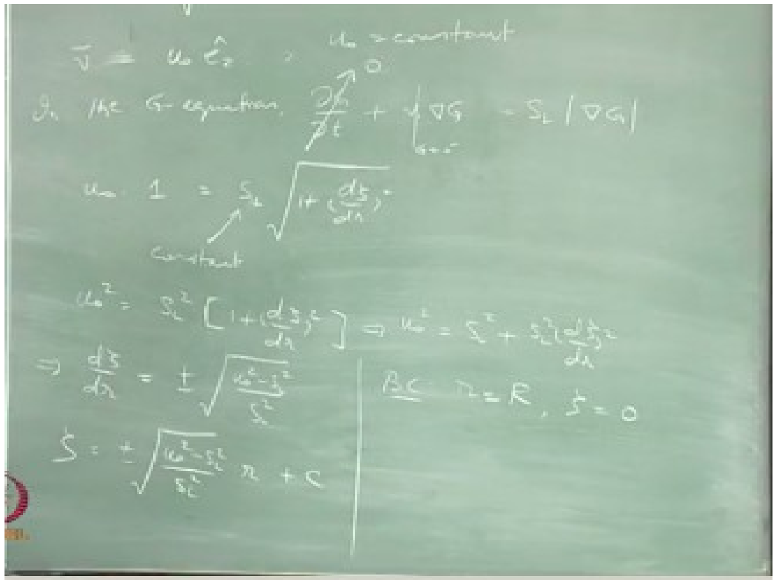


Is simply going to be √ 1 + dζ / dr or the whole square right so what we have done is to find out what this is find out what this is, and we now have to look at what the V is the V is now assume is now going to be basically a $u_0$ or if you can say $u_0$ typically the subscript 0 gives you a mental picture of something like a steady state okay, I just or you could have used u bar also but I wanted to avoid bar because you have this lower bar representing an arrow for the vector so essentially what we are saying is V vector is nothing but.

You not easy cap right U okay so what happens then is you know plug in these things, so this does this term so in the G equation V dot ∇G this is of course you measure that ∇ G = 0 - = $S_L$ ∇G this goes to 0 and we are assuming a uniform velocity everywhere up to the flame okay, we are not saying that the entire flow field is uniform the flow could actually do whatever it wants beyond the flame what we care about is the V that is just a free just upstream of the flame right so we have to worry about.

How what the velocity is as you look from the flame upstream right and we now suppose this is something that we suppose, now that the flow is uniform up until the flame and then let it do whatever it wants it we do not worry about a fate of the flow beyond that as far as this analysis is concerned right, now we will start worrying about a little later but not yet so we should now say that V is uniform so U is not as a constant of course it is strictly not a constant okay we will have to think also about the velocity profile.

Because we have this pipe and you know think about like a fully developed flow or whatever it is these are things for little later not yet okay well at the moment say it is just a uniform constant flow, so then what happens is because you have to take a dot product of V with respect to ∇G and you know UV has only a z component which is $U_0$ all you have to do is worry about only the z component here right, so you get a $U_0$ x1 = $S_L$ times √ 1 + d ζ.

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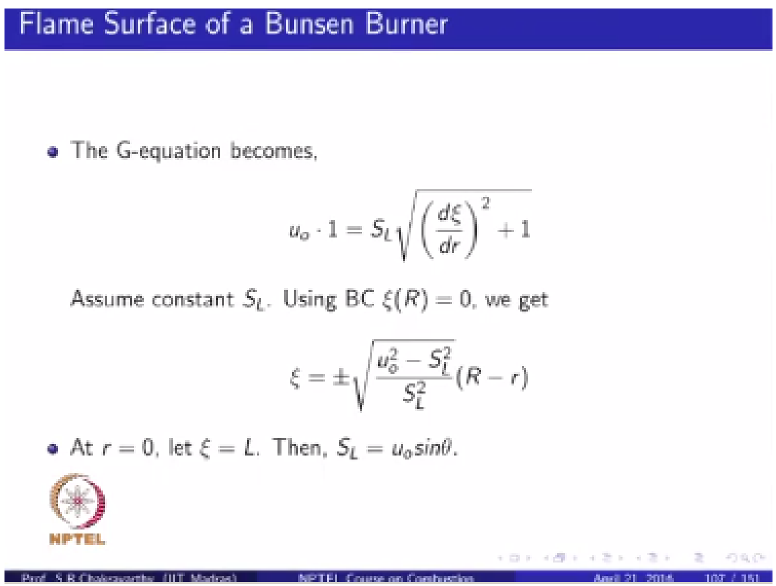


The whole square now we assume the $S_L$ to be a constant for this particular analysis at this cage there is really no reason to expect it to vary, because we are not going to worry about how the step is going to be formed at this stage we are not going to worry about what happens at the base we are looking at pretty much like a constant slope for a bulk of the flame and in the shoulder and we suppose that the mixture is uniformly mixed before there are no concentration variations anywhere.

And the temperature is uniform upstream and so on so lots of reasons to believe that the $S_L$ is more or less going to be a constant right, for a given mixture of a big of a given stoichiometric pressure temperature etc. So this is assumed to be a constant $U_0$ is also a constant as I mentioned therefore we can just do the manipulation, so you just take a square of the entire equation $U_0$ squared equals $S_L^2$ x 1 + d ζ/ dr the whole square and so this is going to give you.

So you open up the brackets $U_0 2 = SL^2 + SL^2$ dζ d the body or the whole square so from here we can now get your dζ / dr + or - √ of $Q_0^2$ d – $1^2$ / too difficult for you to figure out, so we now we have to choose between + or - at this stage we will do this in a moment, so we can now integrate so what we find is that $U_0$ as a constant $S_L$ as a constant so square root of $V_0^2$ - square is a constant right so all you have to do is integrate this so ζ = + or - √ of $U_0^2 – x^2 / SL^2$ times R plus a constant integration constant that means we have to supply a boundary condition right.

Infact when you now supply G is equal to z times z – ζ of r and then plug it in here with the unsteady term kept in there right so if you now keep this time dependent then the time dependence is now going to go ζ r or ζ r, t, so you will have a partial derivative of ζ with respect to t and then you can you can, so you will have a $U_0$ times 1 all right or yeah and then if you know plug in this grad so √ 1 + d ζ / dr the whole squared that would be actually the Hamilton Jacobi equation.

That you can solve for ζ numerically if you want to but what you we got past that point and we now have to any way supply a boundary condition, so that is what I was beginning to say so in any case you need to have a boundary condition what I wanted to point out is this is this is roughly first order in space okay, so this is like square root of √1 + $^2$ of the first order so it is a basically a first order in space equation if you now also have a time dependence in a cunt steady term.

You may have a first order in time but this is this is an equation which requires either an initial condition or a boundary condition it is not this is this is sort of similar to the hyperbolic class of equations where you do not necessarily have to supply everything unlike in parabolic or elliptic equations therefore we know choose to actually supply a boundary condition here in the steady state problem because you now have the variable or showing up, so the boundary condition here is we now say at R = R all right ζ = 0.

Okay the visa flame is coming and he getting held firmly at the rim of the burner right, now this is a bit questionable if you now look at the base quite closely you will find that there is hardly any flame at all this little gap there okay, but we are looking at like bulk of the fame it is always like this is very big it most of all is typically very small for lamb of things but when compared to the length of the flame it could be maybe a mini a senior year or two okay what is this small when compared to the power we are talking about is still much smaller right.

So we for this for this purpose now we know that the particular part labor but if you do not begin to take think about that you are going about variable $S_L$ and soon she gained a lot of trouble the moment to do that, so you now say if the flame is firmly anchored at the rim.

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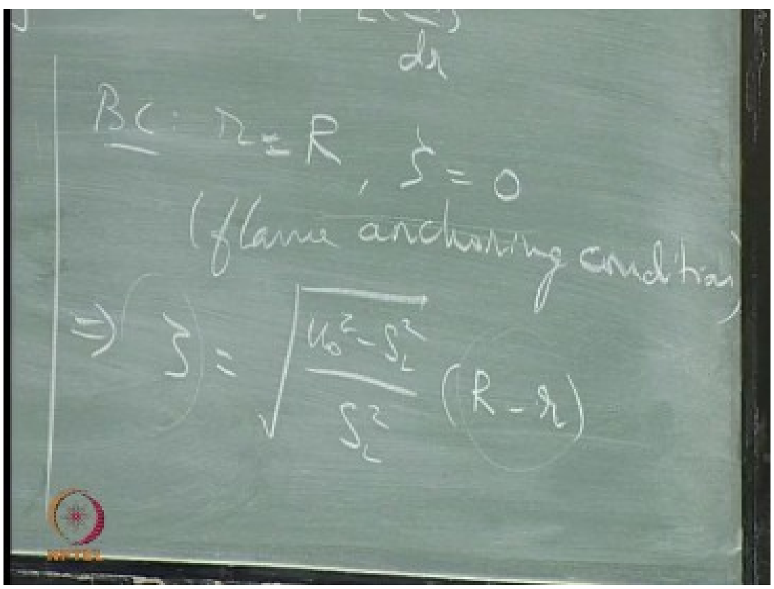


So this is basically what is called as a flame anchoring condition or flame at anchoring condition again you can talk this is lee in many ways, so this is like playing like anchoring condition if you do this then what happens you see if you now plug in R = R & 0 = 0 c becomes the negative of this with a capital law on the side in how now take a step so that certainly means that ζ should be written as 0 should simply be written as √ of $U_0^2 - SL^2$ / $SL^2$ times R – R, so I did choose the positive sign in the end because.

I am sorry because I guess I totally listen so if I know to this negative sign and plug cap articles capital or get this C equals positive this is actually negative the reason is we want to have 0 to be positive right, we want to have the flame looking like that you are looking at the end rotation where the flame is actually inside the tube, so this is what we get and all minus all along is positive because the maximum value that small orders want to take its capital off right okay what do we get out of this what we what we think is well two things one first of all we find that ζ.

Is linear in r okay that was that was obtained from right here when we found that d ζ/ dr is a constant right, so ζ then becomes linear in or so we first retrieve the fact that you are going to have like a straight line for the description of the flame and we the second thing we find a ζ is actually going as something times capital or minus small or so the slope of this straight line is negative okay so you are now looking for a flame that is going like that in the 0 to R 0 to R domain for the for the smaller .

So as a small or goes from 0 to capital R the flame has to start from a peak value and then go to 0 at the rim right, so this of course the axis symmetric assumption you now have a volume of revolution or a surface of revolution bother in this case you should now get a conical flame so this basically represents a cone okay, so once we understand that then we start thinking about it more like a cone rather than like in a coordinate geometry kind of thing, so many times you do chord in geometry you forget geometry but strictly speaking you should be able to think about the problem in both ways simultaneously so let us try to do that.

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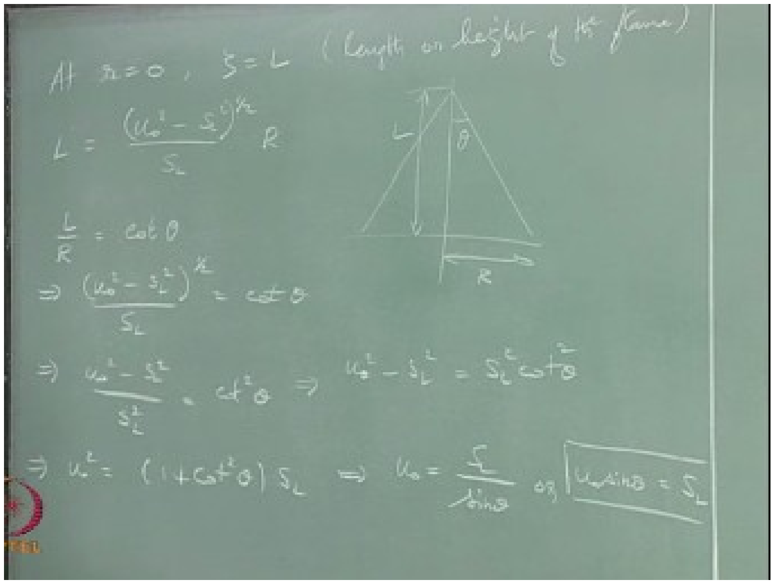

So we note that at x = sorry r = 0 at r = 0 there is at the center line right the flame has its highest location right, so that is actually the height of the flame so $\zeta = L$ let us say so L is like the length of the flame length or height whichever way you want to call this, so length or height of the flame now of course we can try to find that here we can we can find that L = so you can plug in r = 0 then you can find out what the $\zeta$ is which is which is now denoted as L $U_0^2 - S_L^2 / S_L$ or numerator alone can be written as power whole power ½ times r okay now let us look at some trigonometry.

So if you now have a triangle with a apex angle $\theta$ and what we are saying is this is L and this is R right, so L / R should actually be cot $\theta$ cotangent $\theta$ so this implies that $U_0^2$ - $SL^2$ the whole to the ½ / SL = cot $\theta$ and from here we get $U_0^2 - SL^2 / SL^2 = \cot^2 \theta$ a couple of more steps $SL^2 = SL^2$ cot square $\theta$ so $U_0^2 = 1 + \cot^2 \theta \, S_L$, so $\cot^2$ is cosine divided by Sine so get the Sign up here and keep it in the denominator as well so $\text{Sine}^2 \theta$ is 1 right, so you get a $1 / \text{Sin}^2 \theta$ right so this is going to give you $U_0$.

So again you can forget about the square root and do not worry about the + or - just keep it as + because everything is positive here, so $S_L$ / Sin $\theta$ or $U_0$ Sin $\theta$ = $S_L$ right that is what you are trying to get now what does this tell us what it tells us, is if you now have a $U_0$ that is coming up here what we should be looking for is its component perpendicular to the flame right, as so if you now look at this as the component perpendicular to the flame that is the one that is along the flame I hope I got my oops sorry.

Right so this is my you knot Sine θ the one that was along the flame was you not Cosine θ, so the $U_0$ Sine θ is the one that is actually trying to balance the propagation of the flame perpendicular to itself at any point with a frame speed $S_L$ that is what this basically says right now if you knew anything about Bunsen burners this is what is going on okay and whatever we have done, so far is a vindication did this vindicates set okay what we originally said was we wanted to come up with a general flame surface.

G of r vector, 0 or x vector, 0 sorry expect x, t which is equal to 0 and we wanted to say that represents the flame surface and then we now want to want to have this frame surface be placed in a flow field to compete with the flow field by propagating with a flame speed normal to its local sorry frame speed in the direction along the local normal to the surface.

Against the reactants that are flowing in so there is like a flame flow balance that is going on with the help of Lagrangian and conversions and all that stuff that we did we came up with an equation okay if that was not convincing you know try to apply this to a simple case of a steady Bunsen flame right and then do all the mathematics and then finally come to the moment of truth that we are familiar with which is the component of the flow locally normal to the flame has to balance the flame speed right.

So this is basically what the G equation gives you when you are trying to do the Jake we buns and Bunsen burner, so from here we can actually get your L so L then is essentially or cot θ, so that that comes from here and you can you can easily see what θ is θ is now defined so θ is nothing but Sine inverse SL over $U_0$ so when you now say sine inverse $S_L$ over $U_0$ then $S_L$ is supposed to be less than $U_0$ okay if $S_L$ is less is less than $U_0$ then the flame so essentially what It means is the flame is trying to heat into the reactants.

And the flow is trying to blow it away okay so it is sort of like the flame cannot propagate just as fast as the flow, so the flame sort of like tries to give way to the flow as much as it as a flow wants but it starts heating into the reactants that are coming as fast from the side, so it kind of like instead of actually trying to propagate exactly this way it now says okay you want to go fast let me give you away but then as a ghost it sits on the side and then starts eating into this and survives right.

Why does it turn like that because it is anchored at the base right so the flame is not going anyway going any far it is just trying to give way to the flow or so it seems, but it is eating from the side eating the reactants from the side because it knows that it is actually anchored at the base right, so this is a condition where clearly the frame speed is less than the flow speed that is one you are going to get a flame that is inclined otherwise it going to progressively try to become flatter so that it is normal as in the direction of the velocity so that you do not have to worry about a component of the velocity the actual velocity itself suffice.

Then the catch is what is happening at the base because the base is where it is actually being held and from there you can now get this flame to tilt that means there is this dynamics, so long as the flame is anchored the dynamics is always between $S_L$ and $U_0$ that dictates the orientation of the flame or the shape of the flame so you can call us in there several ways shape of the flame you can say is conical but what we refer to is the angle what is the length of the flame how tall is the cone and so on.

So lower the $S_L$ when compared to you not taller the cone alright so this takes us to what we were doing the other day with trying to tinker with $S_L$ know if you now say where I am going to send an air which is a mixture of nitrogen and oxygen and you have a certain flame angle now what if I actually progressively remove the nitrogen, then sent in an organ right so if the $S_L$ now begins to increase then the flame is going to become shorter and then if I now progressively withdraw my organ and send in nitrogen sorry helium right.

The $S_L$ is going to still get it get higher and therefore the flame is going to get still shorter and so on, so there is a point when the flame speed could exceed the flow speed so one of the easier easiest ways of doing that is to try to shut down the flow without putting off the flame right so typically new graduate students who do not really care about safety yeah they would just try to shut down the air first before sharing door shutting down the field all right then what happens you might have been working.

Fuel lean you shut down the air first you are actually progressing towards stoichiometric right, so if you now progress towards stoichiometric the flame speed is increasing and the flow speed is decreasing because you are shutting down the air, so this is a very good combination for what is called as a flashback to happen that means $S_L$ increases the you not decreases the flame begins very becomes progressively shorter and becomes normal to the flow and then it can begin to propagate inside and that is a bit dangerous right.

So if you now have allow for the flame to propagate inside it can go all the way up to the point where the pre-mixing happens in the case of a Bunsen burner it is not very serious because the pre mixing is happening just upstream a little bit and it cannot go beyond that but the flame can actually get attached here as a diffusion flame and so on, okay if it can but this is actually a fairly high velocity but in typical experimental apparatus you are trying to mix with in a controlled manner.

Because you want to meter your air as well as the oxygen as well as fuel so you cannot just let Aarontrain from atmosphere in an uncontrolled fashion, so you do all these things and then you have like a mixing chamber in which this makes us and so on so the flame goes back with the mixing chamber in a confined region it can link your detonation right and typically grad students blow up a couple of mixing chambers before they start doing here experiments properly, but it is very dangerous so this is where premix flames are somewhat unsafe to deal with.

You have to be very careful because of this reason on the other hand if you now had a flame which was already fairly elongated and you now do things that will actually decrease their self further and further right all increase the $U_0$ further and further right, it progressively becomes steeper and steeper and at some point it blows off so in the one hand we talked about a flashback and the other one on the other hand you talk about a blow off in both these cases the anchoring is lost okay.

So long as the flame can get anchored it will now try to adjust its angle in such a way that the flow balance the flame balances the normal component of the flow all right, so this is what is going on, now this is a very simple idea so for example if you now think about something like a ramjet combustor.

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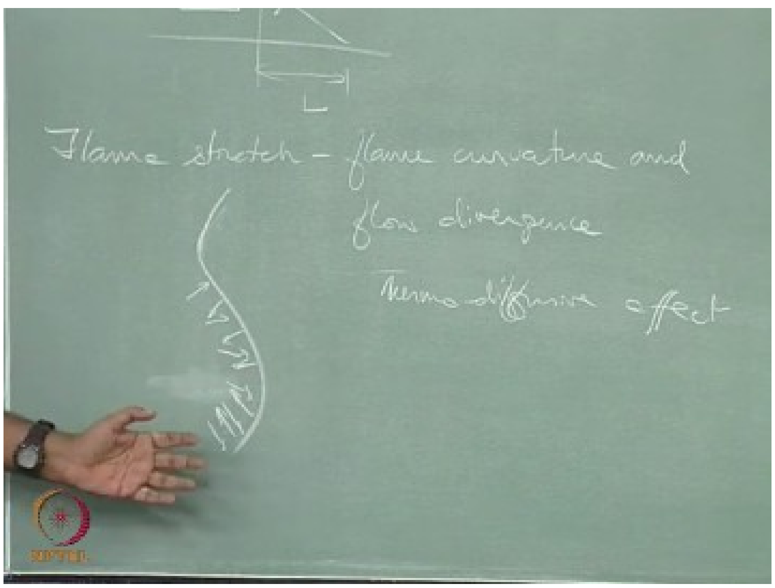


Or a afterburner combustor alright so what do you what do you expect you know typically the combustor is like you now have a fuel injection manifold ring which is essentially a circular tube of circular cross-section right, so you have like a circular tube which is now coiled like a circle and then pass holes to inject fuel and this is typically liquid fuel but it vaporizes with it within some distance and that you have what is called as a V gutter so the V gutter is again like a ring but if its cross-section is a V.

And the flame is actually stabilized or anchored at the edges of this V and it is now going to actually begin to look like that I am of course drawing it in the wiggle for two reasons one is to tell the flame of from distinguish the flame from the rest of the drawing the other thing is it is actually a turbulent flow okay, so here what is going on is the plane is trying to propagate normal to itself and the flow is coming very fast so these velocities that we are talking about are of the order of 100 m/s.

Or so right so you are having a fairly high speed flow and the flame is quite turbulent as well so in these cases you cannot use FL for the frame speed you have to use a $S_T$ that is that sounds very simple although all you have to do is change the letter of the alphabet fro to get from laminar to turbulent huh well it is not so easy but it is not very difficult either okay, so as a quick rule of thumb for you to estimate what the combustor length should be if you are now trying to design a combustor.

Based on this you see all you have to do is look at a turbulent flame speed as a factor of so I should say fact as a multiple of the laminar flame stream, so what happens when you have a turbulent flame speed the turbulent flame speed is a lot faster when compared to a laminar flame speed I am not going to go into details about how this happens, but effectively you can it is essentially an order of magnitude more faster okay it is not as fast as it a nation's detonations are about three orders for three to four orders magnitude faster right we are still talking about deflagration right.

And this is about an order of magnitude faster than a laminar flame so if you are now going to use like a rule of thumb on how to get your $S_T$ or like use in order of magnitude appropriately for the for the turbulent flame speed then you can simply use this kind of approach and try to get a length estimate on where the flame is going to hit the wall right or where the same is going to merge from these two points near the center line either of these could be longer right, depending upon whichever is longer.

You need to have a combustion chamber that is that that much longer or more than that can throw in a factor of safety to make it longer you will typically find if you go around after burners or ramjets the combustor is just a long pipe half beyond the fuel injection unfold and the we got or just to give room for this right, and how did you arrive at the length exactly the same is what you would do with the Bunsen burner is not that kind of funny right so the same idea essentially works in these cases.

So bottom line the flame tries to propagate against see against the flow so we can do a little bit more on the flame speed now because what we have to further think about this a question this is approximation of the assumption is $S_L$ really a constant okay, so why would $U_0$ get a sharp tip over there and yesterday we pointed out that we do not really have a so we assume that the flame shape is smooth right and it does not really have any kinks and soon so indeed you will find it at the tip you have like a curvature okay.

And many conditions I will discuss conditions when there are exceptions okay but many conditions we have to actually think about why you have a little curvature a day at the tip very much near the tip okay later on we will talk about diffusion flames which are much smoother if you want to think about that in your mind right, now you ought to think about a candle flame okay the candle flame is not really a sharp as a pre-mixed flame cone of course it may it is made sharper in a gravitational field.

Because of buoyancy effects that that cause the flame to shape itself that way but it is not because of because of the convection diffusion reaction processes right the convection diffusion reaction processes that we have encountered so far gives rise to a finally sharp call a cone except near the tip, for the for the flame for the for the prim explain on the most conditions and then we ask the question if it is going to be locally like that, if I now zoom in and see the flame is actually coming like there.

And then becoming like this it is flat at the top but if it is flat at the top that means it is propagating against the flow right that means the flame speed should have somehow increased over there to match the flow speed is that right, is it what is going on or is the flow speed really that uniform is it possible that the flow would have actually slowed down because of the flame right, so how does the flow know that it is actually approaching a flame so that it can change its velocity.

And how if that is a case so on the one hand we have to worry about the flame and the other hand we have to worry about the flow is it possible that the frame would have changed its frame speed is it possible that the flow would have changed its low speed locally there right, so in effect what we should worry about is to contributes to contributions to what is called as a frame stretch what is going on there is that the flame is actually getting stretched effectively when you are thinking about a increased flame speed over there.

Your thickness of the flame is actually decreasing so if you had a let us say I think about a thickness, so if you had a thick flame as you know go towards the end you have to actually tin it so for example in a and then a PhD qualifying exams question of something feel asked about thickness of the flame make sure that you are not drawing it uniformly thick near the tip as along the shoulders that is pretty important.

That is what they are looking for free for you would appreciate right so the foam stretch effect has two contributions one is what is called as a frame curvature and the other one is called fluid divergence the flame is curveball right, and therefore is in it there is an effect of the flame curvature on the flame speed and then there is a flow divergence that that is caused by the flame curvature that also slows down the flow against the frame speed right now there is a very interesting point that I would like to make.

What is meant by flames fee okay flame speed is that flow speed for which the flavor stationary all right, so how would I measure my flames feed like the way we were treating beginning to think about flame speed right in the beginning was you now try to actually have a flame fixed coordinate system and then allow for the flow to come in come in here right, so me now said wherever is the flow velocity that is approaching the flame should be the flame speed because if this were still the flame would propagated.

That is at the traitor now we have a seriously think about this what happens is if you now have a flame that is not exactly flat we have been thinking about a flat flame all the time right, so if you now think about a flame that is somewhat curved okay, you just do not worry about why we are thinking like that at the moment the suppose that it is somewhat curve and maybe because of this and we will explain this soon maybe because of this as the flow comes in it tries to now get diverged.

Or converge or something of that sort but all that stuff is happening locally near the flame right and because of this what the actual flames sees is a different flow than far upstream but just like how we said the entire flame thickness consists of a pre heat zone and are action zone for the flame thickness and anything for the flow is upstream of that okay anything for the reactants that we considered like the flow velocity and so on, is all upstream of that this is the flame on the whole.

With the preheat zone and soon here what we have to think about is okay you had richer and all those things and the flow changed its local velocity here and soon because of which it will look like the frame can propagate against Earth's lower velocity but still for an experimental point of view I would measure the flow speed here you see, so if it is possible for me to actually handle a higher flow with a curved flame so that locally the flow slowed down to accommodate the flame it will look formally apparently.

That the flame speed is higher because it could handle a higher flow well in fact in some sense this is exactly what is happening in wrinkle turbulent flames if the flame can actually get so wrinkled at a very high flow rate right, and then stay there very wrinkled I am now begin to say that is a turbulent flame and its flame speed is much faster, but locally it is it is probably trying to have a flow that is much slower when it is trying to heat into it there because of it changed the flow.

Therefore the effect of the flame on the flow basically comes back at it as a change in the frame speed because of the way we think about and measure flame speed because this is relative to the far upstream velocity not what happens in the vicinity of the flame right, so effectively these two effects are actually going to change the flame speed that is what we are looking for right so if it is possible for us to think about a modified flame speed that that takes into account these two effects.

Then we now can go back and say where when we put that $S_L$ here and still work with the constant velocity because follow up frame their velocity is constant is he said how to worry about the details, what is the point in working with $S_L$ we did not have to worry about the details of preheat zone and if you reaction zone and all those things in these lines it is all there inside it is all like a package right we are now trying to further everything that the flow goes through right into the flame speed.

So that we can now use a modified flame speed against a uniform flow right, so what you are essentially talking about here is, if you now think about a curved flame for some reason let us say it is a perturbation right and I am a little bit hesitant to use the word perturbation because that gives us into stability on whether this perturbation is going to the Voyager or converge and so on will hold on for some time not thinking about that but essentially what I am saying is let us think about like a slightly curved claim for some reason.

I would like to talk about two things when you now have this situation one is a thermo diffusive effect that is if you know for example take this part of the flame you can argue the same thing on the other part of the flame, so typically what I do is in the classroom I just discuss this and I on the exam I ask you to work on that right, so you know look at a flame that is actually having a concave curvature with respect to doctrine flow right.

What is happening is this is now actually heating the reactants this way the conduction is happening radially inward, so the reactants that are coming in or not just getting heated up right here right but it is also getting heated up from there you got to be a bit careful when I draw a frame like this it is assuming that the preheat zone and all those things are within this and we should be looking at only the reactants that are going locally normal to that point and then getting heated up there until then it is not supposed to get heated up.

So we are actually blowing this image up to a length scale that is comparable to but maybe a bit like higher than the flame thickness right, and when what I really have to think about that if I have to go to a that is so small there we are talking about a curvature which is of the order of the flame thickness all right sounder these circumstances, we will now find that the heating is not one-dimensional the heating is now multi-dimensional so you have now an increased heating that tends to increase the same speed.

As we see from far upstream okay but there is another effect the reactants will have to get spread out then this is particularly critical for the diffusion reactant, let us say if you are now looking at it off stoichiometric condition right say a few lean mixture the means of fuel is deficient right and that particularly is now going to actually spread out radially and it is going to feed the flame less but the lesser concentration then if it were to feed a straight flame or a flat plane right that weakens the flame.

So what you would expect is we are now beginning to talk about like the fuel diffusion versus thermal conduction upstream, so fuel diffusion downstream versus thermal conduction upstream right, what comes to what comes into our minds conduction versus diffusion lowest number right so louse like a god of combustion you cannot forget him, so the lowest number has to be has to come into picture there is no you are to begin to think about what happens as a function of Louise number okay let us stop here.

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