Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 35
Flame Stabilisation

Prof. S R Chakravarthy
Dept. of Aerospace Engineering IIT Madras

Play let us look at a few more aspects on premix combustion.

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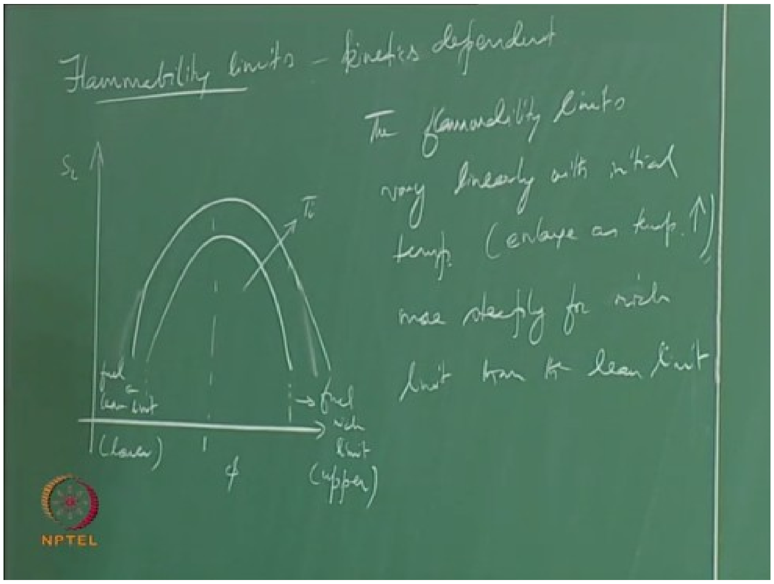

Flammability limits – kinetics dependent

The flammability limits vary linearly with initial temp. (enlarge as temp. ↑) more steeply for rich limit than the lean limit

We will primarily be looking at flammability limits and this would lead to looking at quenching and ignition so these are things that we will start looking at, we will try to do this as quickly as possible because we just do not have too much time to involve into these the second thing is you can understand that these are typically unsteady phenomena right, we are talking about the flame quenching near the flammability limit because it runs out of one of the reactants or it gets quenched because of thermal heat loss or the ignition again is a transient phenomenon and these are things that are not very well understood and it is heavily kinetics dependent.

So it is not amenable to simplified analysis that works we are quite well except for in a qualitative sense so this kinetic dependent, so what are we talking about as far as flammability limits is concerned. We know for example that if you now try to plot the laminar flame speed versus the equivalence ratio you have a curve that is having a maximum somewhere in the middle a little bit past equivalence ratio one and then it falls down and then it stops at some point the means it is not really going all the way to down to 0 it is stopping there which means that you now have a few lean limit and a fuel rich limit right.

So this is a fuel lean limit and this is the fuel rich limit this is typical of most fuels the question then is what happens as we try to increase so to let me go back and say this is sometimes called referred to as the lower limit and this is sometimes referred to as the upper limit lower and upper meaning different values the low value of Φ and then higher value of Φ or lower value of fuel, fuel or ratio fuel oxidizer ratio versus higher value fuel or fuel oxidizer ratio.

Now what we are interested in is trying to find out what these limits depend on and mostly what we are talking the mixture ratio obviously is a question so the control parameters in any pre-mixed flame or the mixture ratio the temperature and the pressure. So the question here is what is the lean mixture ratio, lean limit mixture ratio or the rich limit mixture ratio depend on that means you need to be looking at what is the dependence on temperature and pressure.

So the answer to the initial temperature of the reactant mixture how it is going to affect the fuel lean or fuel rich limit is typically linear, so the flammability limits vary I am saying very instead of saying increase or decrease we are because one of them increases the other one decreases are very linearly with initial temperature right, that is enlarged as temperature increases right so a large as in you can now expect as you increase the temperature the curve to go like that in a linear fashion.

And since this curve is not necessarily symmetric about ϕ=1 this gap is not the same as this right, so typically this linearity is more steep with fuel rich limit so more steeply for rich limit in fact that this particular picture is a little bit wrong in that sense you need to have a larger increase in the upper limit and compared to a decrease in the lower limit. So that is what I meant by saying very as in they were the upper limit increases further and the lower limit decreases further, so more steeply for the rich limit then the lean limit.

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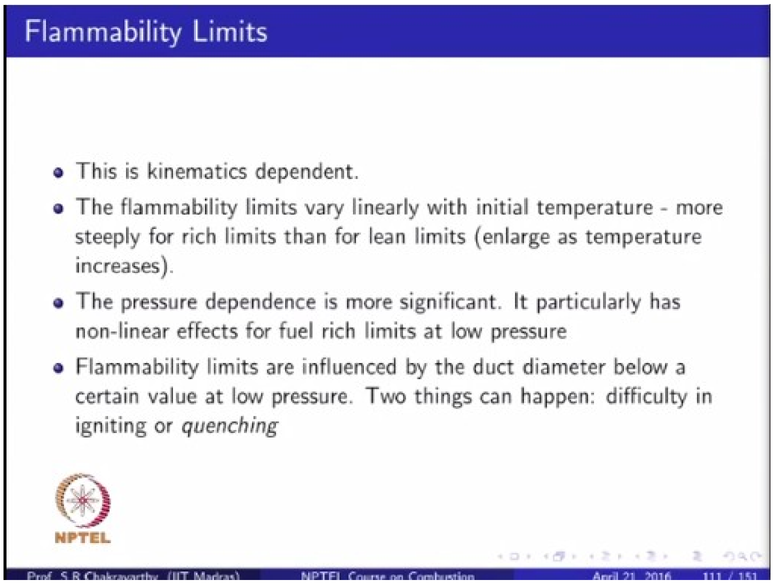

Flammability Limits

- This is kinematics dependent.
- The flammability limits vary linearly with initial temperature - more steeply for rich limits than for lean limits (enlarge as temperature increases).
- The pressure dependence is more significant. It particularly has non-linear effects for fuel rich limits at low pressure
- Flammability limits are influenced by the duct diameter below a certain value at low pressure. Two things can happen: difficulty in igniting or *quenching*

So what we are talking about as limit is again do you emphasize it is the equivalence ratio or the fuel air ratio, fuel mass ratio so if you now think about a linear variation so it should be able to now estimate like for example at 300 k if you have a lean limit like this and I know how this variation is in terms of like what is the slope of the line that is connecting the temperature with the lean limit I should be able to predict what the lean limit should be as you now advance your initial temperature to let us say 400 k right, how it should decrease and so on okay. Now the more interesting thing is the pressure, the pressure dependence okay.

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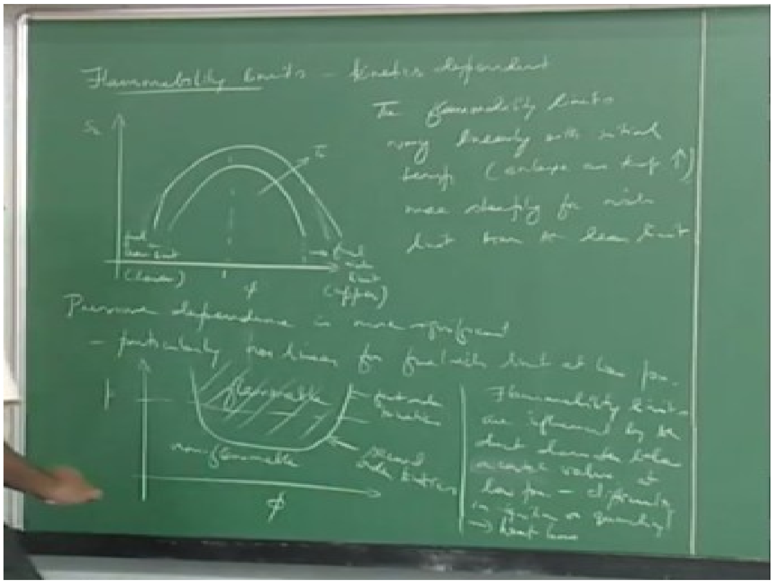

So the pressure dependence is more significant the sense it is not so straightforward and non-linear in some regimes and insensitive and some of the regimes so particularly non linear for feel rich limit at low pressures, so it is sort of like where we are all in the pressure equivalence ratio graph. So if you now look at pressure and equivalence ratio you go to get a curve that is somewhat so you have a less sensitive variation with on the lean limit with pressure that means for a wide range of pressures you pretty much get about the same limit here or a mile variation.

And that is not really the case in with the rich limit so here we are talking about φ and then there is like a wide variation where if you now go to a pressure that is below this limit it does not matter what your equivalence ratio is it is going to be like a flat curve, so this is your flammable region and this is your non-flammable region you have got to be careful in reading texts on this for example I think the conventional British English is if you now say inflammable that means it burns it is not a non burning thing, right.

The reason why we use the word non-flammable rather than inflammable, inflammable actually means it burnt so that means which should be we should write that here so to avoid the controversy just gives flammable and non-flammable. So now this is actually this is again as I said you know it is kinetics dependent so here we could show I am not going to get into this now this is actually a because of second order kind of takes at low pressures and now it becomes linear so here it is a nonlinear part and then you now have it first order at higher pressures again what are we talking about for the range.

So somewhere and here we are looking at atmospheric pressure okay, so we are looking at above and below atmosphere and many times for this part of the graph we would probably look at more like a linear scale whereas that part of the graph you would look in the logarithmic scale because you could strictly speaking even think about like pressures that are going up to 100 bar or even more for practical applications right.

And somewhat mysterious like between not exactly 0 you do not go to 0 pressure but it lets a point 0.00012 up to 1 atmosphere so he could go over there then the race of atmospheric range. Of course what we are talking about this is for typical hydrocarbons keep that in mind the other thing that that is going to lead us to the next topic that we want to talk about is the determination of the flammability limit is going to depend on the duct diameter okay, so one of the things that we were talking about is having a duct in which you allow for the flame to propagate.

But you now progressively make the fuel the mixture leaner and leaner and linear or richer and richer and richer and then see at what point the flame refuses to propagate right, and then you now obtain the limit but this experiment will also depend on the diameter of the duct beyond below a certain value of the diameter, right. So above a certain value of the diameter then the flammability limits that you determine become insensitive to the diameter of the duct, but now we have to think about the with the effect of the diameter of the duct.

So flammability limits are influenced by duct diameter, duct diameter at low pressure I should say below a certain value right, at low pressure so this, so what this begins to mean is the duct diameter below which you are going to have a flammability limit being sensitive to the duct diameter is going to depend on pressure that means lower the pressure higher would be the duct diameter below which the flammability limit begins to become sensitive to the diameter, right.

So this is a this typically at low pressure there are two things that can happen one is the difficulty in ignition or quenching right, or quenching that means if you could ignite it would quench or you would have difficulty in igniting to begin with right, so you get into that regime where you have this problem and this is typically both in both the cases difficulty in ignition or propensity for quenching this is because of heat loss to the duct, so we will consider this a little bit more detail next. First let us consider quenching it is a little easier to deal with when compared ignition quenching.

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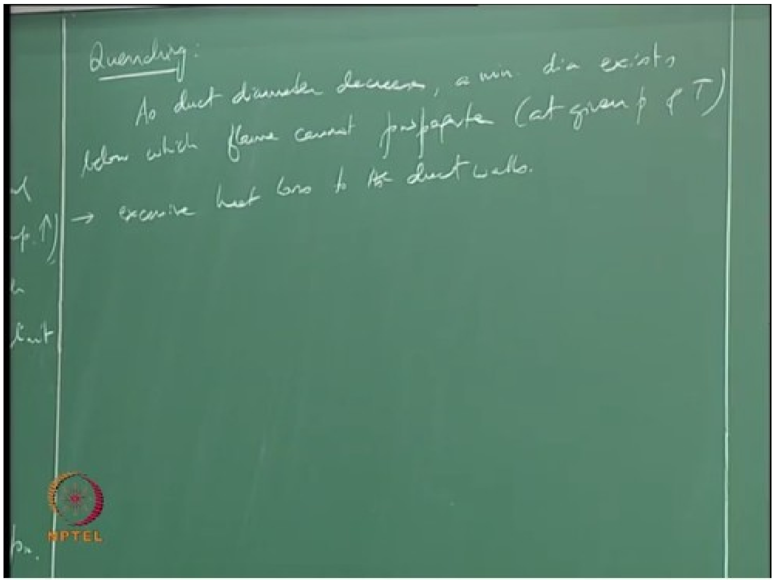

Quenching:

As duct diameter decreases, a min. dia exists below which flame cannot propagate (at given p & T)

→ excessive heat loss to the duct walls.

So as the duct diameter decreases right, a minimum diameter exists below which flame cannot propagate at given pressure and temperature right, so this is mainly due to excessive heat loss to the duct walls.

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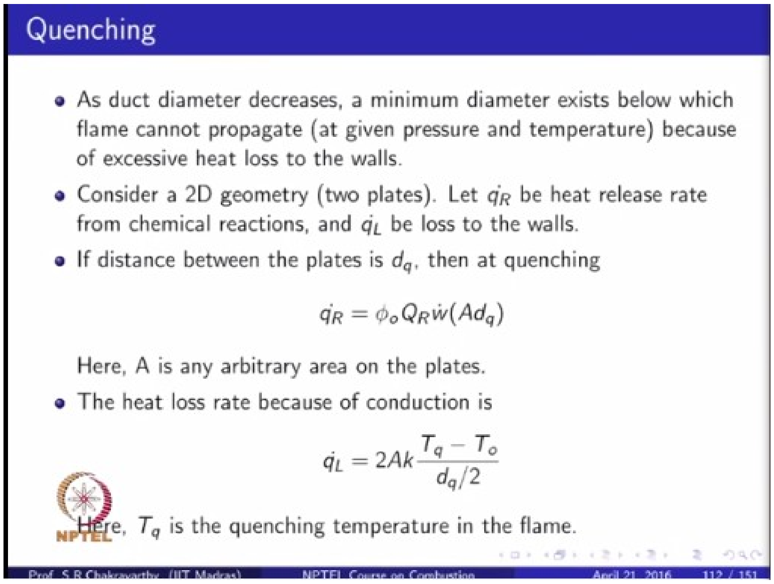

Quenching

- As duct diameter decreases, a minimum diameter exists below which flame cannot propagate (at given pressure and temperature) because of excessive heat loss to the walls.
- Consider a 2D geometry (two plates). Let $\dot{q}_R$ be heat release rate from chemical reactions, and $\dot{q}_L$ be loss to the walls.
- If distance between the plates is d_q, then at quenching

$$\dot{q}_R = \phi_o Q_R \dot{w}(A d_q)$$

Here, A is any arbitrary area on the plates.

- The heat loss rate because of conduction is

$$\dot{q}_L = 2Ak\frac{T_q - T_o}{d_q/2}$$

Here, T_q is the quenching temperature in the flame.

So for the sake of simplicity instead of taking like a tube or a duct we could just consider like a channel or our two walls two parallel walls right so to adopt a 2D geometry.

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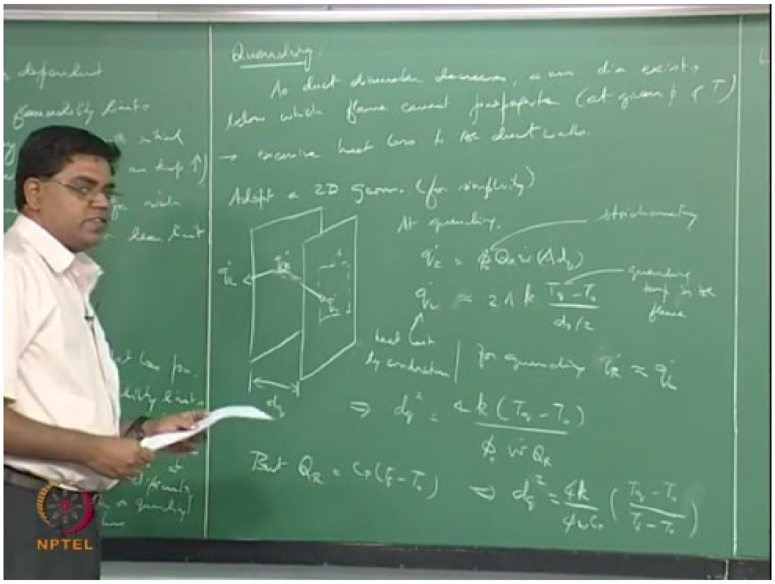

Adopt a 2D geometry for simplicity to think about this there is parallel plates so if you now think about right that looks like parallel plates does not it. So we are now thinking about a flame that is trying to propagate within this region and it is releasing a heat $q\dot{r}$ from the chemical reactions and it is giving away q_L that is a loss so this r is for release and L is for loss to the walls right, and the distance between these two these two plates is dq for quenching so we are essentially looking for the quenching distance here.

So at quenching what we have is two things one is $q\dot{r}$ the rate of heat release which is $\phi 0\ qr\dot{w}$ and Adq, so Adq is actually the volume and a is like let us say the area of the plate if you can consider a certain area in this and we will see that it does not matter we are looking we are going ultimately look at what happens per unit area, so for whatever area the area times dq is the volume over which you have the heat release that is going to the heat that is released that is going to get lost right.

So correspondingly if you now have a $\dot{q}_L$ this is actually heat loss by conduction right, and this is I am going to say approximately for a reason that will become very apparent right away we have two walls and so you start with two area times k now let us suppose that the temperature gradient can be replaced by a linear expression that is where the approximation comes from strictly speaking we should say Tq-T0/dx at the wall and look for a temperature profile between the walls and look at the gradient at the wall and so on.

But what we are essentially saying is Tq is the quenching temperature, temperature in the flame that is to say if you now think about like this propagating downwards for example you have reactants here and the reactants are supposed to be heated up to the flame temperature but that could actually happen probably near the center of the flame and you could have a fairly higher temperature that is reached for the products.

But on the sides closer to the walls the reactants are not getting heated up all the way to the adiabatic flame temperature because you now have heat loss, therefore the temperature that is actually attained for the products is now not going to be really Tf like a adiabatic flame temperature rather it is going to be Tq okay, so there is a temperature distribution that is happening across and what we are looking for is like a quenching temperature that means you need to have the reactants raised at least up to a certain temperature beyond which it can actually have appreciable reactions going on, right.

So in other words you now try to actually try to have a flame held near the wall you will find that there is still a standoff that means you do not have reactions happening right at the flame okay, and what this really means is the in this standoff the temperature is actually increasing from the wall temperature to like a Tq within a very, very short distance maybe about the few millimeters or less and that means you now have a reasonable temperature gradient between the wall and the standoff distance which is going to now feed this heat flux and that is the reason why the wall is getting heated up.

If the wall were at a high temperature to begin with right then you would not have too much heating so in fact this is one of the reasons why you need to think of it typically these are all things should be that people have to bother about if they are setting up experiments because experimentalists are the ones who are going to deal with I mean most experiments are on steady state problems or oscillatory even if it is transient very, very few people are actually doing experiments on quenching itself but those people who are interested in actually having steady state flames and their experiments want to make sure that it is in quench right, or you want to make sure that the walls that they are actually using in the experimental setup when it is subjected to flame does not melt, right.

So typically what is happening is if you now use like a ceramic wall for example right, it is an insulator so it does not really take away all the heat right, instead it is actually getting heated up by itself and it is increasing its temperature and because it is increasing its temperature this difference comes down, and therefore you have less heat that is going in that is typically how insulators work it is there is a heat transfer thing the only thing is we have to make sure that the insulator is able to withstand the temperature to which it is raised so that the conduction is decreased.

And that ceramic does the job for you therefore that is how it works otherwise if it is like a metal wall it is going to get heated up progressively because of this and it is going to stop the flame of a rise in temperature right, and there is like a limit temperature that you should be thinking about beyond which you are not going to have any appreciable reactions. Similarly $\varphi0$ here is of course the stoichiometric, stoichiometry that is how much of the fuel for a given amount of air is reacting qr of course is the heating the heat of reaction and $\dot{w}$ is the reaction rate.

Let us say assuming a single step reaction or essentially putting together qr and $\dot{w}$ we are looking at what is the chemical heat release rate these two together right, so now if you say at quenching we have $q\dot{r}$ is of the same order or equal to $\dot{q}_L$ then you now put these two together you are going to get of course the area cancels therefore we should have been looking at per unit area to begin with so dq^2= is it yeah you have a 2 here and a 2 at the bottom if you go to 4 k $(Tq-T0)/\phi0wQ_R$ but Q_R=CP(Tf-T0) this is as if you know what we are thinking is approximately you have a temperature profile that is inclined linearly near the walls and reaching up to Tf in the middle okay.

And it is stopping at around Tq there and then from there you are now having a heat loss so this is like a bulk analysis we are not looking at the spatial variation in the temperature so you would like to think that the flame is actually having it flame temperature Tf up to which you need to have the heat release heat it up but that heat is now going to go away from a value of Tq to the wall temperature by conduction as a loss. Therefore if you now plug this in you now get so this is an approximate analysis of course and I will show you where the approximation comes from as we go along in comparison with experimental data so if you now say for k/5C_P (Tq-T0)/Tf-T0.

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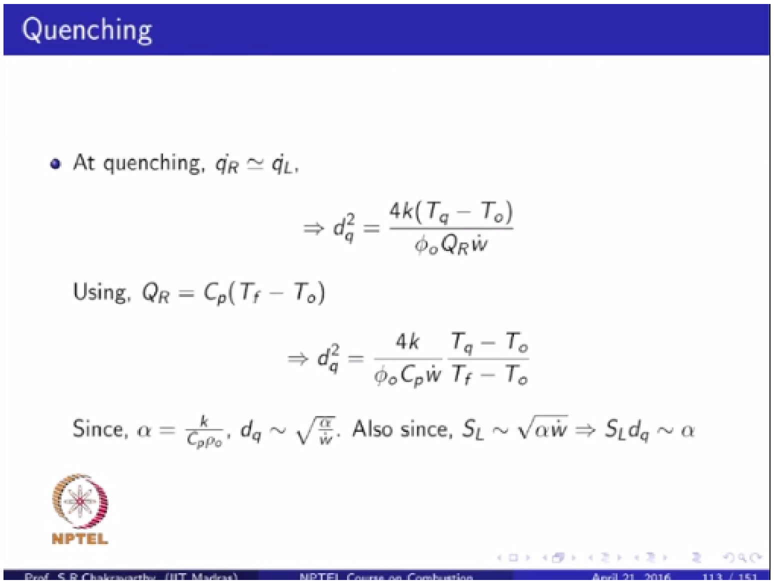

Quenching

- At quenching, $\dot{q}_R \simeq \dot{q}_L$,

$$\Rightarrow d_q^2 = \frac{4k(T_q - T_o)}{\phi_o Q_R \dot{w}}$$

Using, $Q_R = C_p(T_f - T_o)$

$$\Rightarrow d_q^2 = \frac{4k}{\phi_o C_p \dot{w}} \frac{T_q - T_o}{T_f - T_o}$$

Since, $\alpha = \frac{k}{C_p \rho_o}$, $d_q \sim \sqrt{\frac{\alpha}{\dot{w}}}$. Also since, $S_L \sim \sqrt{\alpha \dot{w}} \Rightarrow S_L d_q \sim \alpha$

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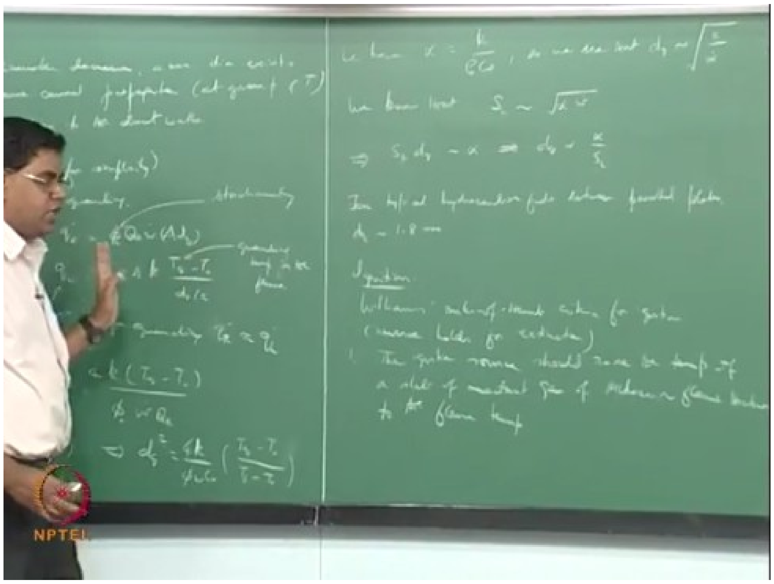

So we have α the thermal diffusivity as $k/ \rho 0C_P$, $\rho 0$ as the upstream reactant gas density, so we see that d_q, d_q is proportional to $\sqrt{\alpha}/\dot{w}$ does not it look a bit similar when we seen this here right, obviously we know that S_L goes as $\sqrt{\alpha}\dot{w}$ right, so we had something like$\sqrt{k}\dot{w}/C_P$ that is how it was going we had a $1/\rho 0$ outside the square root so if you now put that together you will now have something that is going as $\alpha\dot{w}$ of seeing this also before, okay.

So if you now put these two together then what basically remains is S_L d_q is proportional to α and there is to say α mean α is like a this is a thermo physical constant for the material so what this basically means for you is d_q is α over itself or in other words larger the S_L right, lower the quenching diameter right what that means is if a flame is going to propagate fast it is going to go through a duct which is of a smaller diameter that means you need to have a still smaller diameter for quenching the flame right, so that simply means that the flame is trying to propagate more vigorously and you need to squeeze it into a smaller ducked, right.

To give you numbers on how this works out so for typical hydrocarbon fuels between parallel plates d_q is around 1.8 millimeters right, and you can look up the actual values for let us say circular ducts in the literature for exact fuels and so on there is a these things are catalogued and that is pretty important for you when you are trying to device experiments on previous flames for example you want to make sure that the flame does not flash back from very you want to stabilize it in your experiment or if it does then you need to be able to quench it before it actually gets to the source, right.

So many times in experimental setups you have something like a settling chamber into which you would mix your fuel and oxidizer or fuel and air and then let it through a duct into which you want to stabilize this. And if you have a flashback the flame can go all the way down and into this settling chamber and this settling chamber is now like a constant volume combustion region where it can actually explode and we have had a couple of such things happen in our labs right, when students are not really careful enough I should not say that.

They go through calculations on having a small array of tubes to actually quench the flame as it tries to propagate if it is not a good calculation the calculation is wrong sometimes or they are made some assumptions or put an incorrect values like on the flame speed for example if it is if they are doing calculations for a 5 that is equal to point 7 but actually they have to turn out like depending upon how the sequence in which you close your valves at the end of the experiment you might locally get into a stoichiometric mixture that propagates faster right, and it can go inside right.

So typically you are looking at capillary tubes like stainless steel tubes that are about two millimeters in diameter and then you now try to stack them up in an area like in a hexagonal close packed structure kind of thing so you form like a honeycomb thing and you now insert it in your elect and this acts not only as a flow straightened for the flow that is going into the into this duct from the settling chamber but it is also more importantly for us from a combustion point of view and from a safety point of view and from a quenching point of view it is acting as a flame arrestor.

So this is what is called as a flame arrestor typically in crude Bunsen burners that you want to put together you would also have something like metal balls that are thrown in their small metal balls such that the voids between the metal balls are of this order or you could also put some steel wool just crimp some steel wool and then just pack it inside this is also straight in the flow it is like a porous medium and also are see the flame from propagating upstream, right. So these are all typical approaches to flame are arresting based on the idea of quenching.

Of course what happens is there are lots of applications where it says I should say for example there are these applications where you want to have some nice uniform heating in some place like in gas heaters where you want to try to heat and like room heaters or water heaters in large furnaces and so on or large boilers you want to have like a very nice uniform way by which you want to stabilize the flame without getting into turbulence and so on, so there is like a small there is an array of lot of small ducts through which you could actually send in fuel and stabilizing because flame stabilization is a big issue right.

So when you now get into turbulent flames are trying to stabilize the flame with a large induct may be difficult so you actually use smaller ducts and at that time you could even think about like a porous plate or a small d these very small fine ducks into which you can send in this and stabilize the flame that means you have very, very small you know lots of tiny premix flames that are stabilized on these.

And the question there is you could still stabilize the flame if you are having a sustained ignition to begin with and you know heat up this array of ducts right, and once the duct is heated up and the temperature is now higher then it is going to be able to sustain this so there this difference comes into picture right, so you are now trying to increase the wall temperature with the flame itself for some time and then the flame will sustain their without really getting quenched or flashback and quench, right.

So such things are done in practice in men in some applications. The next thing we should think about is ignition so this state I should state a couple of rules of thumb kind of criteria for ignition which we will, which you will see it works the reverse of the flame extinction the pay that we have been talking about so Williams this is actually following Williams rules of thumb or criteria, ignition and reverse holds good for our extinction right. The first thing is if you now imagine like a slab of slab of gas slab of reactant gas we are not beginning to talk about ignition that means you do not have a flame yet right, so you have to now think about a slab of gas that is approximately equal to the flame thickness right, and you need to have an ignition source that now in a sustained manner increases this temperature of this reactant gas up to the flame temperature, right.

So that is the criteria number one so the ignition source should raise the temperature of a slab of reactant gas of thickness of the order of the flame thickness to the flame temperature for ignition, so you can see that if you now already had a flame which had a flame temperature then this really means that the temperature has be brought down from that value for in order to get quenched right, that is what we were talking about s the difference between Tq and Tf and you can see that it is not going to be as low as T0 which is the initial temperature or the temperature of the wall, right.

So obviously the ignition is not going to work exactly the same as scrunching and that is what I was beginning to say I guess I did not really pursue that so far when you are now saying that you have d_q is going as α/S_L right, it is not just this dependence that matters what is the coefficient right, the coefficient is actually coming all the way from these things right, and what I would like to point out is you had a for sitting here in reality we are using something like a $d_q/2$ that is like half the distance is corresponding to your heat loss to one played half the distance is corresponding to a heat loss to the other plate right.

Then there is something called a notion of a heat loss penetration so the idea that we have used here is the penetration distance is equal to half the quenching distance that means the penetration of the heat loss is equally from both sides all the way up to the middle it is what we are saying. But empirically if you think about this, this is not really 2 it turns out to be actually more than 2 that means you do not necessarily have to have a large penetration distance okay, you do not have to actually have a penetration all the way to it to the middle of the of this is significantly larger than 2 okay.

So you are not going to get something like 4 it could be much more than that we are okay on an order of magnitude but this is this could be like for example 8 if you if it is a 8 and like it is about off by four times you see so for four or five times it is typically how this is going to be so as a first cut we would like to think this is what it is but you do not need to necessarily penetrate that much even a little bit penetration of the loss in the heat loss is sufficient to actually bring down the temperature to like a Tq which is going to quench this right.

On the other hand the ignition is now going to require for you to actually heat up the temperature significantly it is not like a small loss in temperature that causes quenching is going to be a significant rise in temperature by ignition source for you to be able to ignite. So this is a first criterion the second criterion is on the heat loss.

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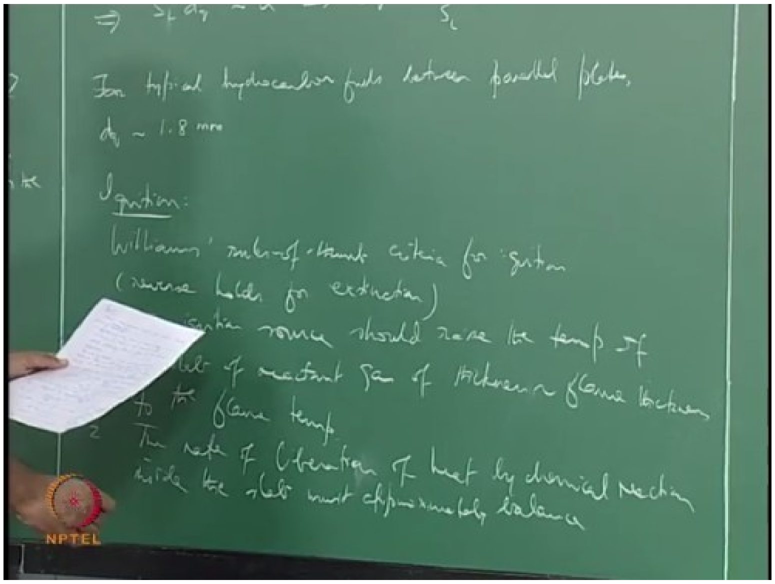

For typical hydrocarbon fuels between parallel plates,

$d_q \sim 1.8$ mm

Ignition:

Williams' rule-of-thumb criteria for ignition

(reverse holds for extinction)

ignition source should raise the temp of

lab of reactant gas of thickness ~ flame thickness

to the flame temp.

2 The rate of liberation of heat by chemical reaction

inside the slab must approximately balance

So the rate of liberation of heat here when you talk about ignition we talk about liberation of heat instead of loss so the rate of liberation of heat I am sorry this the rate of liberation of heat is about from the chemical reaction so by chemical reaction I meant to think of later of liberation of heat from the ignition source but when we try to ignite then you need to initiate chemical reactions because of the increase in temperature meeting the first criterion and does that the heat release from the chemical reaction inside this lab the same slab that we are talking about must be most approximately balance, the rate of heat loss that we just used as other panel need a rate of heat loss.

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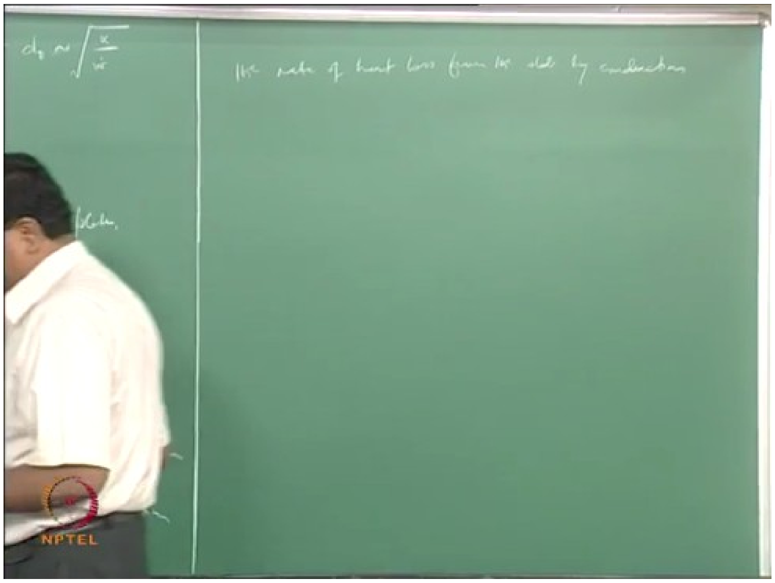

A heat loss from this lab by conduction right, so it is a it is a very similar idea as what we are thinking we will get pretty much use these kinds of expressions but I would like to show you through a little bit more rigorous analysis just a little bit more not significantly more rigorous but this is like a global heat balance if you will right we are not talking about a spatial variation but if it is possible for us to actually think about how locally the temperature gradient is going to get set up right.

And so that means you use like a dt/dx instead of having this kind of a linear expression for the temperature gradient for a global temperature variation you now try to actually look at how the temperature variation happens and take that into account for the heat loss and then that means we see we now have like a derivative like you have to worry about a dt/dx and then that means we can integrate that and so on so let us do all those things next class.

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