Introduction to Explosions and Explosion Safety

Prof. K. Ramamurthi
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture - 21

Combustion: Ignition Kernel, Quenching Distance, Minimum Ignition Energy, Lean and Rich Limits of Flammability, Flash point and Fire point Temperatures of Volatile Liquids

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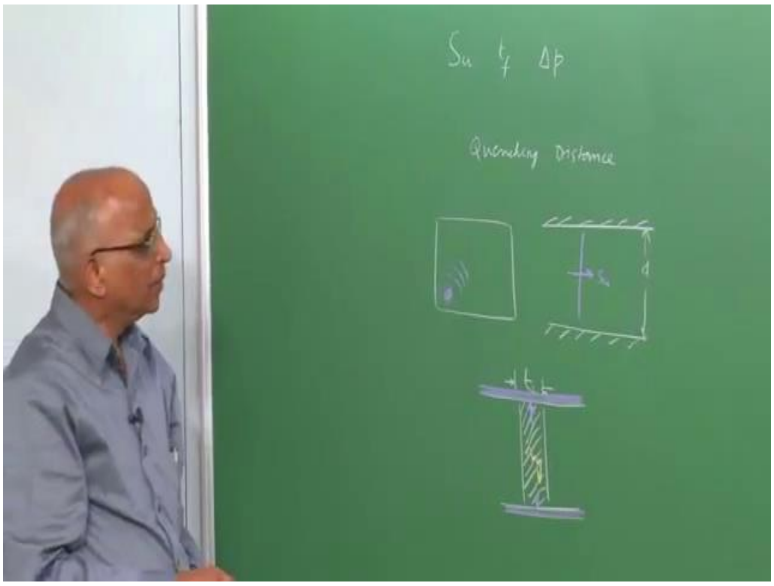

Good morning, you know we looked at a few parameters relating to these chemical reactions and what did we take a look at? We looked at the burning velocity S u. Also talked in terms of flame speed, which takes care of the burning velocity, when the observer is on the ground, burning velocity, when the observer is on the flame. That is, with respect to the flame. We derived an expression for the flame thickness. We said well the flame thickness is very small. Then, we also looked at the pressure drop across the flame. And we found that, it was almost negligibly small.

And, then we told maybe it is a time for us to examine the question of, maybe the quenching thickness or a quenching difference, the characteristics length scale for quenching. Why do we want to take a look at the quenching distance? Let us go back to our problem. We had a gaseous mixture and maybe an explosive gas mixture. In this explosive gas mixture, we released some energy in a small volume. We said, if this volume or kernel, which we called as ignition kernel is such that, it is not able to propagate the flame.

That means, heat the adjacent layer, heat the adjacent layer and propagate the flame as it were. And it sort of collapses, that means it sort of extinguishes or quenches then the flame is not possible. It is essential to have the flame kernel of a minimum size. Such that, it is capable of propagating a flame across. Therefore, we wanted to study this quenching distance. Let us have a simple format in which we study it.

Let us consider let say a pipe. In this pipe, let us say the pipe is of diameter d. Let us say these are the walls of the pipe. In this particular pipe, I have a flame which is travelling. This is the flame which is travelling, I assume it to be plainer. And let us say, it travels as you know at a speed S u. And you know, we said we look at the problem with the flame stationary. That is in the plain of reference of the flame. And therefore, we said well I can have the tube as it is.

I have the flame. Now, I put the particular thickness of the flame, which we calculated in the last class as t f, so much Millimeter. We found that, it is quite thin of the order of millimeter. Well, this is the flame as it were. And what does the flame do? You know, it to the wall. It allows some heat to get conducted to the wall. In other words, some heat gets lost from the flame to the wall. Because if I were to put the wall over here, the wall is somewhat at a low temperature, maybe of the order of the initial temperature, itself.

And from this region of hot gases, which is the flame some heat gets lost to the wall. But, along with heat loss, some heat is also getting originated or created within the flame. And therefore, there is a balance between the heat, which is generated by the flame and heat which is getting lost. If the heat lost, from this zone of flame is greater than the heat which is generated. Well, the flame will collapse and I can calculate a critical thickness or a thickness d for which, maybe I have quenching of the flame and that is what I want to work out.

Therefore, let us first determine what is the heat loss? What is the heat generated? And, then let us try to arrive at a diameter, which corresponds to the quenching. That means, the condition at which, the heat lost from the flame is equal to or greater than the heat, which is generated by the flame itself.

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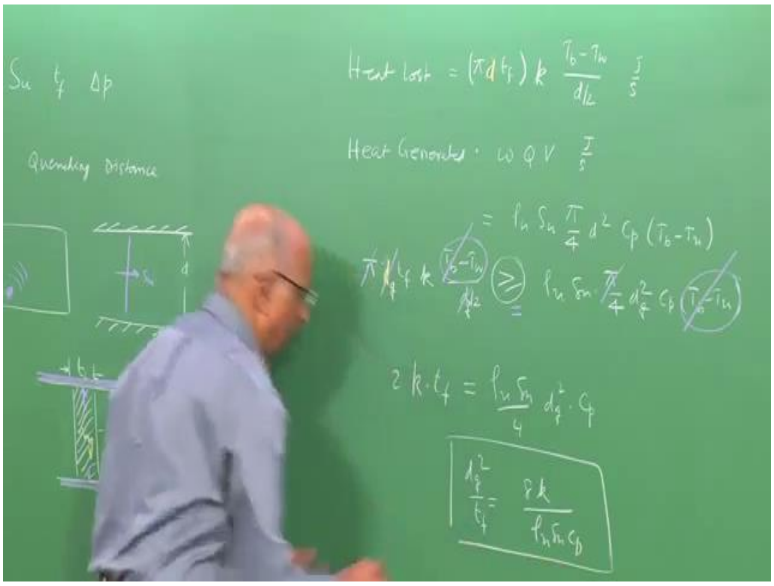

Therefore, let us write the expression. We say, heat lost from the flame zone to the wall. Well, the thickness is t, let us initially assume well the diameter is d as I put over here. Well, the perimeter is pi d into the area of contact between the flame and the wall, is equal to the perimeter into the thickness, which is equal to pi d into t f, which is the area. And h into let us presume that, maybe the temperature distribution is such that, the walls are cool the thing is hot here.

Therefore, I say well the maximum temperature in the flame is the burned gas temperature. The wall is t b. I assume a linear gradient. Therefore, I have the thermal conductivity into the burned gas temperature minus the wall temperature divided by d by 2, which is the radius. And this is the gradient. I linearising, after I am interested in the trends, I am looking at this well. This is the heat loss from the flame to the wall.

What is the heat generated by the flame? Let us say, heat generated. Well, I can we know this, we have been writing this on and off. We say that the rate of reaction is omega. So, much moles per cc second into the heat, which is so much kilo joules per mole into the volume, which I can also write as equal to which we can also write so much. Let us say, joule per second or kilo joule per second. This is joule per second or watts over here.

Therefore, I can also write the heat generated as… You know, I am sitting on the flame. Therefore, I see the mass flux rho u and S u coming. And therefore, what is the mass which is associated. Now, the cross sectional area, this is flux into the area, which is pi by 4 d square. Therefore, this multiplied by C p into T b minus T u, which is the unburned gas temperature, is the heat which gets generated by the flame, after all. You have this stationary.

Therefore, in this frame of reference I have S u coming here rho u is coming. This is the mass, the temperature increases from T i to T b. Therefore, this is the heat which gets generated over here. Therefore, for the condition in which heat loss has to be less or heat loss has to be greater or more than the heat generated. That is the condition under which quenching takes place. That is the heat loss is greater.

I have the condition, well pi d into t f, this is the area into the thermal conductivity into T b minus T w. That is the wall temperature divided by d by 2 must be greater than or equal to the value of heat generated, which is equal to rho u S u into pi by 4 into d square into, I get C p into T b minus T u. Well, you know I want to find out the critical condition. And the critical condition is, it must be equal to it and when does it become equal?

When the diameter becomes equal to the quenching thickness that is, it is just equal. That is the heat loss is just equal to the heat generated. Well, in that condition I say d is equal to d, quenching thickness. And therefore, what I put here, well. I put here, this is d this should have been small d over here. Because, that is the diameter I am considering. Therefore, I have small d over here. And therefore, what is the condition I get?

I get d q over here, I get d q over, I get d q over here. Or rather I have to solve this particular expression in which, I want to determine the value of the quenching thickness. Immediately, I find well for this particular expression when I put d q, this becomes equal to sign, because I am considering the critical condition. Therefore, if I were to solve this, well I find d q and d q cancels over here. I also find the value of pi and pi gets cancelled.

And what is left is, I have the value of t f here, I have thermal conductivity here. Well, I also find T b minus T w and I have T b minus T u here. See, you know initially the temperature at the wall is going to be something like the initial temperature or the unburned gas temperature. I can approximate T w as equal to T u. And therefore, I can cancel these two terms.

Therefore, under this condition that maybe for q, it becomes the equal to sign. What is it I get? I get k into t f and this is multiplied by 2. Because, this is d q by 2 is equal to, I get rho u into s u into divided by 8 over, then divided by 4 over here into d q square into C p.

Therefore, from this expression I immediately see well, I have accounted for all the terms here, except for those which I have cancelled. Therefore, I get d q square divided by t f is equal to 8 k divided by rho u S u divided by C p. This is the expression for quenching thickness square divided by the flame thickness. This is what I get but, if you go back to last class and see what was the value of t f.

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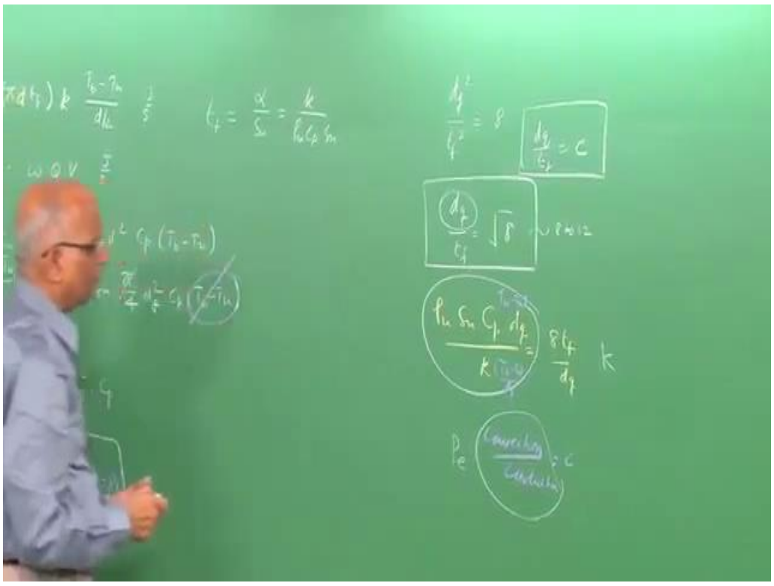

We said well, the thickness we derived or the flame thickness which we said is small, was equal to the thermal diffusivity divided by the flame speed, which we could also write as k divided by thermal diffusivity was k divided by rho C p or rho u C p into S u. Or therefore, I can write this. I have k divided by rho u into C p is alpha divided by this. Well, this becomes equal to 8 into t f.

And therefore, this particular expression now becomes d q. Let me use this part, d q squared divided by t f squared is equal to 8 or rather d q by t f is equal to root 8. Well, you know we have succeeded in getting an expression for the quenching length scale or the quenching distance. And we find that, the quenching thickness is of the order of something like 3.

But, in practice it is an order of magnitude greater, may be of the order of 8 to 10 or 8 to 12. Let us say, is the value in practices. Mind you, we have made very simplified assumptions. And that is why we get a number but, it is a representative. Therefore, we find, well the value of quenching thickness is greater than the film thickness and mind you. This quenching thickness is a very, very important parameter, from the safety point of view. We will shortly take a look at it.

But, before that let me go back and look at this expression again. Or let us take a look at this expression. I can write this expression again as equal to rho u S u C p into d q. Let me write it here. Rho u into S u into C p into d q divided by I bring k down over here. And this I write as equal to that means, I take here. Therefore, I get 8 into t f by d q. But, just now we told see d q by t f is a constant. We arrived at 8, we said it is equal to this. I can, as well write d q by t f is something like a constant, which is of the order of let say like 10 or so.

Therefore, well d q by t f I have this value. Therefore, I can say this particular parameter, which contains the quenching distance is a constant k. And what is this representative? Let us take a moment off and take an expression this at the bottom I have a thermal conductivity. If I were to multiply thermal conductivity by something like T b minus t ambient. Well, and I also bring d q from top at the denominator over here d q, such that I eliminate this. Well, it gives the conduction heat transfer. And if I multiply by the numerator also, by T b minus T w. And therefore, this I have dropped down. I have rho u C p into T b minus T w in numerator, which is something like a convection. That is the flame is moving or the burning speed is S u. This is the convection what you have? This is the conduction what you have?

And therefore, we are talking of something like a convection heat transfer divided by conduction heat transfer, which gives me a value of C. And this convection heat transfer divided by conduction heat transfer is known as peculate number. Therefore, we say for quenching to take place, peculate number has a particular value. And I can use the peculate number, to be able to determine by quenching thickness.

But, you know for us well the expression d q by t f is a constant. And this constant is of the order of 10, is sort of something which is very representative. You know, why is quenching thickness so important? Not only, can I get into my problem, which I set out to do, to be able to get my ignition energy, which we will shortly do. I just want to spend a moment or too. You know mind you, when we were in our school days, we heard of something known as a Davy's safety lamp. What is this Davy's safety lamp? Let us quickly review this.

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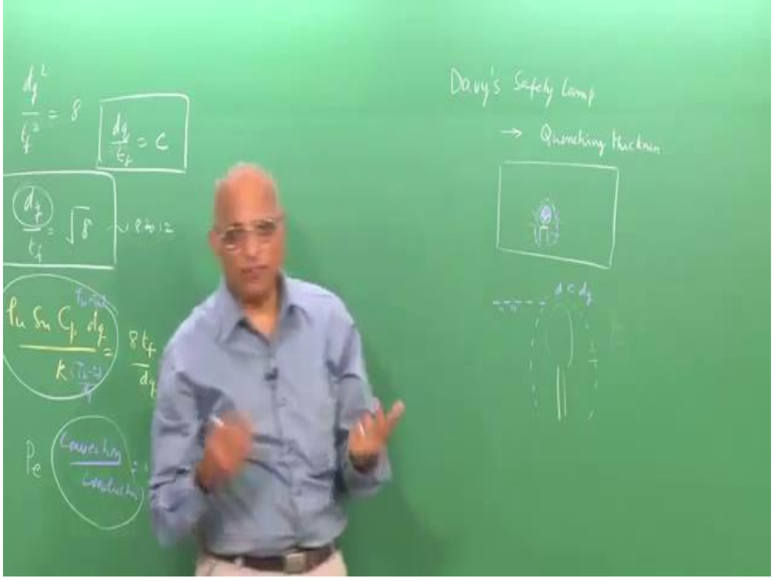

See, when a minor goes into some. Let us say a mine. And the mine contains some explosive gases, you know deep down. You know mines you know, have hydrocarbon coal, generate some methane gas, you have air available I can form an explosive gas. And a miner, you know in the dark place he needs some light. He carries a light source. And maybe the light source could be a hurricane lantern or a lamp. And therefore, let us say he carries a lamp I just illustrated by a candle.

Therefore, you have a candle here which burns. But, then if it is going to carry a heat source, which is as good as ignition source. The mine will catch fire and it will explode. Therefore, what was suggested by Davy's in those, in early something more than 100 years back is. Maybe you encase it, by something like a seed or a sort of a shield, which has fine holes in it. You know the size of these holes.

That means, I have something like a seed and you have holes in it. Let that if the diameter of the holes is less than the quenching thickness. What is going to happen? Well, a flame cannot pass through these holes. Because, the flame will quench the moment it seizes smaller hole. It cannot pass through because, the heat loss takes place.

And therefore, when you have a lamp which is surrounded by this seed, whose dimensions whose openings are of the order, whose openings are less than the quenching thickness. Well, a flame cannot propagate out. And it is something like a safety device. This is, what is the principle of the safety lamp? Therefore, we say Davy’s safety lamp uses the quenching distance or the quenching diameter, to make it fool proof. It cannot explore the gas.

And even if the gas comes over here. You know after all through the holes, it will come over here. It will burn over here but, it cannot go and cause a catastrophic explosion in the mine. In fact, this quenching thickness is also used like we have the Olympic torch these days, you know. And what happens, you have the Olympic torch which has a huge flame. And you know, you have to carry it. Maybe, you want to carry it in an aircraft, you want to carry it to different places.

And you know as a shield, if I can put something like a seed, whose dimensions are less than the quenching thickness of the gas, which I am considering. Suppose, a medium is somewhat explosive. Then, you know I am safe you know, I will not really going to make the ambient catch fire. And this is how a quenching thickness is applicable. Having said that, let us get back to our problem. We want to use the quenching thickness to be able to model, the ignition. Let us do the ignition problem. You know, I think we should also have a feel for numbers. Let us put down the type of quenching thickness, what are there for a few gases? Such that we know the order of magnitude.

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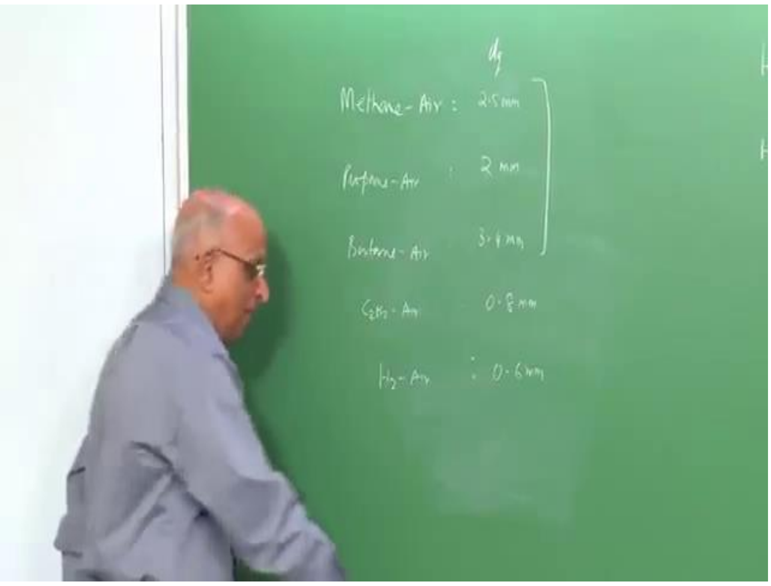

For methane air, the quenching thickness d q is around 2.5 millimeters. When I talk of propane air, the quenching thickness is of the order of 2 millimeters. When I talk of butane air, again it is of the same order. It is of the order of 3.4 mm. Therefore, we can say for the hydrocarbon gases, which are essentially saturated gases in air mixtures. The quenching distances is between 2 and 3 mm.

When, we go to acetylene C 2 H 2 and air, which we found, you know it has a much higher flame speed than these. These had around 0.5. These had almost around 1.7 or 1.8 meters per second. The quenching thickness is very much smaller of the order of 0.8 mm and the hydrogen air has a value of around 0.6 mm. Therefore, you find well I can readily make a sieve of these dimensions and protect the gas over here.

Protect, maybe the gas from explosions using the safety distances. While for hydrogen air, well I need to have pores which are much smaller. And maybe you use some particular material, some fabricated using powder metallurgy to give the small pores and still use it as a safety device. With this background, let us come back to our ignition problem. ((Refer Time: 19:29)) well I need an ignition kernel, whose dimension must be greater than the quenching thickness. Let us come back. Let us state this problem again.

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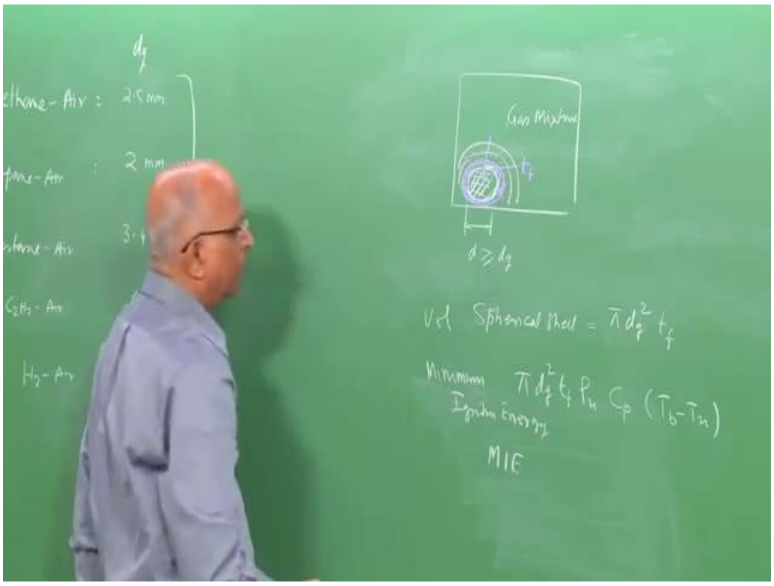

I deposit some energy over here. May be this is the volume in which. This is the place, where I have the explosive gas mixture. I deposit the gas in this particular volume. And we say, well the dimensions of this must be such that. Let us say mean diameter of this particular volume must be greater or equal to the quenching diameter. For, it not to collapse from the cooling effect of the ambient but, it must be able to propagate the flame over here.

This is the minimum thickness of the ignition kernel. It must at least be the quenching diameter such that, it does not collapse when it is cool from outside. And therefore, we tell ourselves but, what should the igniter be doing, what should the spark be doing. The spark should be able to ignite the next layer of gas, the heat which is being transferred out. And not only the heat which is being transferred out, maybe the concentration of active species which are being transported out, to the immediate next layer, which I show by this particular shaded portion over here.

It is the next portion, must get ignited by this kernel whose diameter is, let us say d q. And what must be this thickness? Well, it must be the order of flame. Therefore, it must be able to ignite a segment or let say an annular spherical volume of thickness t f. We know well t f is small, well t f is of the order of point 1 mm or so. This d q could be of the order of, as we said is of order 2 mm. May be, if it is hydrogen it is small.

But, anyway it has to ignite the next one and what will happen? This ignited gas will again ignite the next gas and so on. And this is how a flame will propagate out. Therefore, what is the mass of gas which the kernel must ignite? Well, the volume of this spherical shell which surrounds it is equal to pi by 4.

No. we are talking of a spherical shell. The surface area of this shell, of this sphere here is equal to 4 pi r square. That is equal to pi into d q square because, we say well it is of the order of quenching thickness. Well, t f is small therefore, the volume of the spherical shell is equal to pi d q square into t f. The mass of the spherical shell is equal to pi into d q square into t f into the unburned gas, which is originally there in this.

And this is the mass of the spherical shell. You multiply by C p, which is the thermal mass of this spherical shell over here, shown in color over here. And what must the gas do? It must get sufficient heat such that, it is able to increase its temperature from the initial value to say about the burned gas temperature. And therefore, this must be equal to T b minus T u. And this will be the energy required for ignition.

That means, for ignition I need to form a particular kernel or a volume, whose dimension is of the order of the quenching thickness. And the heat from this or the heat and concentration from this, should be able to form a flame of thickness t f and such that, propagation continues from layer to layer over here. Therefore, the energy required is the energy content within this kernel. And the energy content should be equal to pi d f into rho u.

It is not the energy content within this, which is important. The energy content which ignite the gases, whose thickness is t f. And therefore, we say well the ignition energy is so much. And this we call as equal to the minimum, what is required Minimum Ignition Energy or simply MIE. See we must remember this, because see we are interested in igniting the neighboring thickness of our distance equal to t f, using this particular kernel.

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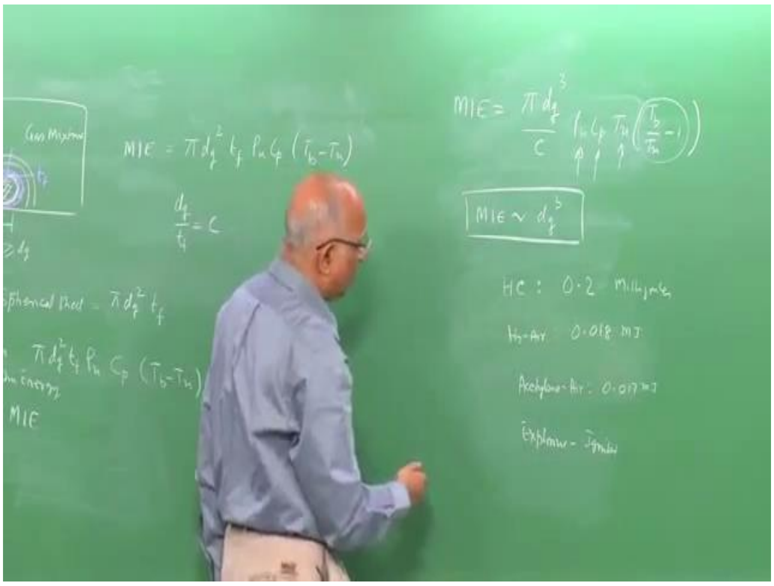

Therefore, well we write the expression minimum ignition energy. Let us say in joules is equal to, now I say pi d q square. Why is it minimum, because I am constraint the minimum thickness. Any diameter greater than this, is going to ignite. Therefore, it is minimum ignition energy in joules, pi d q square into t f into rho u into C p into T b minus T u. Well, I can simplify this expression and write this as equal to. Well, I know.

Well, we just now said d q by t f has a magnitude is a constant value. It is about 10, about an order of magnitude greater. We found it is equal to 0.8. Therefore, I can say d q or t f is equal to d q by C.

And I can rewrite this expression by MIE is equal to pi d q. I have t f is equal to, I substitute as equal to d q by C. Therefore, it becomes d q by capital constant over here into I have rho u into C p. I take T u outside and I get, if I take let say T u outside, I get T b by T u minus 1. Now, if I look at this expression well, the burned gas temperature is definitely higher than T u, it is of the order of 4.

Therefore, I say this is of the order of 3, which is anyway the burned gas temperature is very much higher. And therefore, I can neglect one over here. I just take the value as high value over here. The initial gas temperature is specified. The initial gas density is specified. I know the specific heat of the gas which is anyway a constant, for a given gas mixture. Therefore, I say the minimum ignition energy goes as d q cube. That is as the quenching distance cube.

And this has been found on the basis of experiments. Yes, indeed minimum ignition energy goes as d q cube. And this is the logic we use. And therefore, we find. Well, for ignition I can, I now I am in a position to calculate, what is the energy required for ignition. And if we use this for calculation the ignition energy, we find that for hydrocarbon gases. Well, the ignition energy is typically of the order of 0.2 to 0.3 milli joules.

You know, let us say propane air butane air may be methane air all are in this order. If I consider, maybe the hydrogen air mixtures it is much, much lower. It is of the order of 0.018 milli joules. That means, 10 to the power minus 3 joules. And if I consider acetylene air and we found, you know if acetylene was always a substance which had the 3 double bond and it was a positive eta formation, something which is unstable or which is not very stable powerful explosive.

We have energy of the same order 0.017 milli joules or so. Therefore, we find well the order of magnitude is 0.2 milli joules and we use the theory to be able to do this. Therefore, right now we are in a position to find out, under what condition an explosive can be ignited. And once it is ignited, well heated takes place and a blast wave is formed or some pressure waves are formed. Well, we know. We talk in terms of ignition, we talked in terms of maybe quenching thickness. But, are there some gases which cannot really be ignited. You know, let us think of this. We now know how to do ignition problem or to model an ignition problem. But, are there some gases which really cannot be ignited. Let us consider the following situation.

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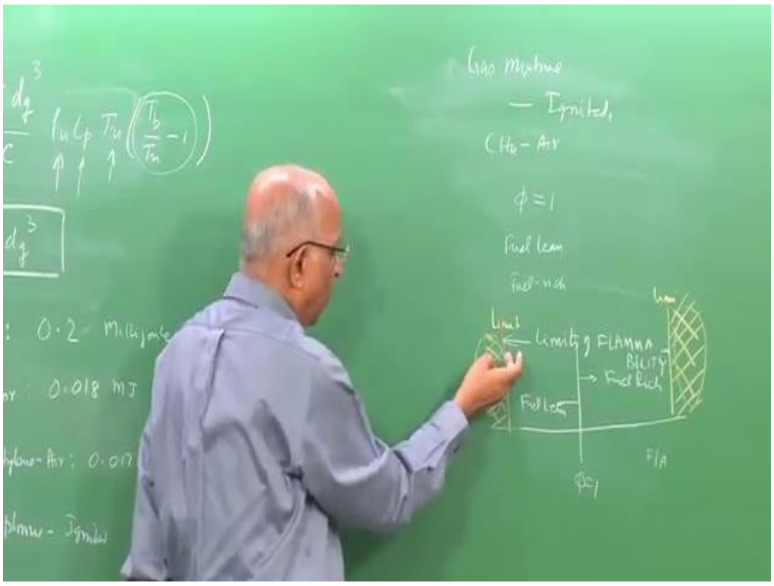

We say a gas mixture. When we say gas mixture, let us take an example. I have methane and air as a mixture. Well, the mixture could be documentary, that is equivalence ratio is equal to 1. Well, it could be fuel lean mixture. It could have so much of air, very little of fuel. It could also be fuel rich. Now, all these things are possible. So, also maybe a solid substances or a compound which contains, maybe a carbon, hydrogen or oxygen, could be either fuel lean or fuel rich.

And we have seen all these things earlier. But, is it possible to say, well on a scale like this maybe on a straight line like this. Well, I say well this is my documentary composition phi is equal to 1. To the left of it, I have fuel lean mixtures. On the right of it, I have phi greater than 1. That is my thing is, I am representing fuel by air over here. I say, I have fuel rich conditions over here.

You know, if I keep on decreasing the quantity of fuel such that, the quantity of fuel in this fuel lean mixture becomes very, very negligibly small. We know, well it is so small that even if it reacts, the amount of energy which it liberates is so small. That the temperature rise is insignificant and it cannot support a chemical reaction. And therefore, I can sort of hypothesize or I can sort of say, that maybe for mixtures which are terribly fuel lean.

I cannot really form a mixture, which can ignite which can claim to propagate under steady conditions. So, also when the fuel becomes extremely rich, that means I have almost all fuel and almost no air. That is, I am just talking in terms of maybe thinking of the problem or putting our mind, modeling in to the problem. Maybe, when the fuel becomes so rich, that means the value of phi is so large.

That means, over here I have. It just cannot ignite the amount of reaction is so small that, the temperature is small. Therefore, in practice I can think of maybe under fuel lean condition, there must be a limit below which, something cannot burn and fuel rich conditions I must have a limit above which, something cannot burn. And these are known as limits of flammability. In practice well, these things are observed.

And how do you modal it? See we talked in terms of chain initiation reactions and termination reactions, in these mixtures the chain initiations are so small. That I cannot have sufficient chains being formed and the chain termination takes over. And I have the limits of flammability. Therefore, we say as well a gas mixture can be ignited or it can propagate the flame, only if it is within from here to here that is, within the limits of flammability.

You know, this is a useful safety parameter. We will see this and how to calculate it out. Therefore, for all gaseous mixtures we have, maybe a lower limit that means, lean limit. You have upper limit for fuel rich conditions and these we call as, let us put it down.

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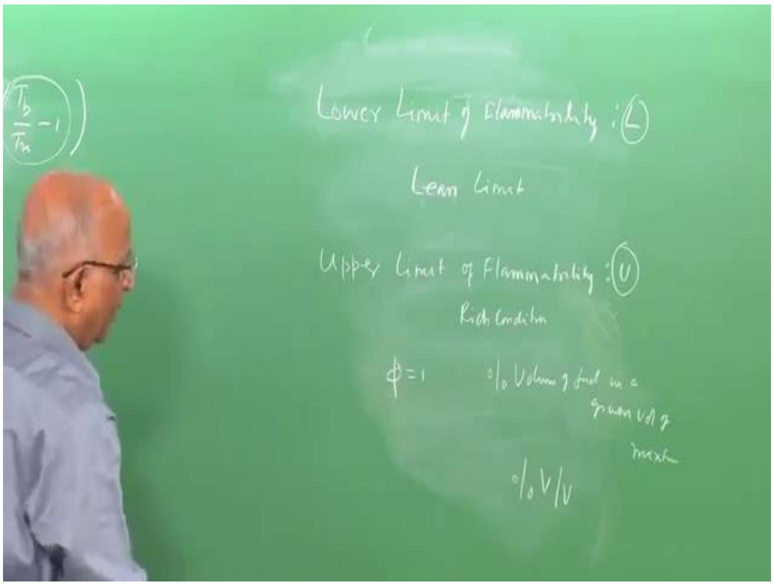

We call it as lower limit of flammability and it is denoted by l. And you also have, that is lower limit of flammability corresponds to the lean conditions. That is the lean limit and you also have the upper limit of flammability. That is corresponding to the rich conditions, which I call as u upper which corresponds to the rich conditions.

Therefore, in practice I have two limits corresponding to the lean limits of flammability and the rich limit of flammability, which namely l and u. And how do we specify them. See we could specify them, either by the equivalence ratio what we said phi equal to 1, its documentary. Then, phi is less than 1, well very small I have the lean limit. When phi is very much larger, I have this. But, what we do in practice is, we specify them in terms of percentage volume of fuel, in a given volume of the mixture.

Namely percentage volume by volume, is how the limits of flammability are expressed as. Let us do this. Let spend a minute or two, try to find out how we get the limits of flammability. Then, maybe we will look at some of the limits of flammability, as has been determined in literature.

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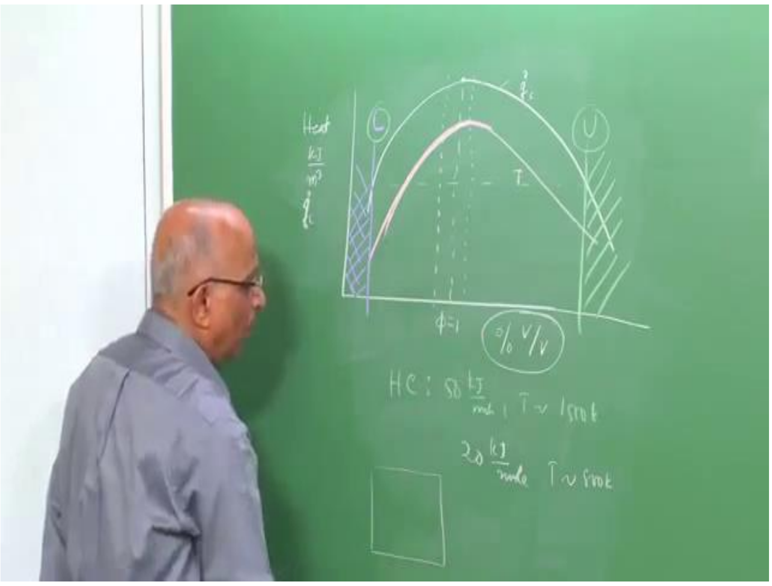

Therefore, we say well. Now, I am interested in maybe percentage volume of fuel in a given volume of mixture. And, then well I want to first put down, what is the heat which gets generated. We say well, there is a condition documentary over here, which corresponds to phi is equal to 1. And therefore, when I do an experiment we saw, well the maximum heat release happens at documentary, because completely burn products of combustion are formed.

And if I find out, what is the heat generated in terms of kilo joules per meter cube of the mixture or per kilo gram of the total mixture. What is we said, well the mass of mixture or the volume of the mixture increases over here, even though the heat of reaction is remains the same. Therefore, the heat drops when in the lean conditions. In the rich conditions, I do not have sufficient air to burn. And therefore, the heat drops off over here.

Therefore, this is the type of signature what I get for heat release. Let us say q c dot, so much kilojoules meter cube. This is the type of equation what I get or this is the type of curve, what I get. If I have to convert it into a temperature plot, what is it, I get. Well, this is a maximum for slightly not documentary conditions, were heat is maximum. But, slightly a condition which is somewhat, let us say fuel rich.

Let us put it down. This is fuel rich side over here because, what happen is many of these fuels have slightly compared to finished products of combustion high, somewhat lower specific heat. And therefore, I will have a temperature distribution which is something like this. Therefore, from this you know this is the type of temperature what I get, this is the type of heat release what I get, q dot c over here.

And if my temperature and my heat release is less than some value, let us say at this condition of heat release, for which. Let us say temperature curve, I extrapolate this curve over here. This is the type of temperature curve we have. Maybe, at this particular value I get the heat release so much for which the temperature is so small. That below this, the mixture cannot be propagate at steady state. Well, I say l is over here. In this case, I do not get a flammable mixture.

So, also when I look at the other side, maybe I am taking a mixture over here. Beyond this, the mixture is such that it cannot really propagate a flame, because the heat release is so small and the temperature is so small. That it cannot really propagate the flame and this corresponds to the u. This corresponds to the l and this is how, we look at it. In practice, for most of the hydrocarbon mixtures, the heat is something like 50 kilo joules per mole of the mixture.

And a temperate of around, let us say 1500 Kelvin, is what decides the lower limit, where as for the hydrogen, the values are different. It is of the order of semi like 20 kilo joules per mole of the mixture. Temperature around 800 Kelvin is, what decides the limit. You know, these things come from as I said from chain branching. And chain termination reactions, which really say what is the type of lealiness to use? And what is the type of richness to use?

But, l and u are very strong parameters because, you know if I have let us say an explosive gas mixture. And it is, it could explode. Maybe, I could sort of inert it and make it weak such that, it is in this region. And I am able to handle an explosive safely. And this is an important parameter. Therefore, we say l and u are the lean limit flammability and u is the upper limit of flammability.

And it is specified in percentage volume of fuel divided by the volume of the mixture. It is not only possible to have the lean and rich limits of mixture, only for the volume in volume. But, also maybe if you reduce the pressure of the mixture, like what is it you are doing. Let us consider, this simple thought experiment before we examine some values.

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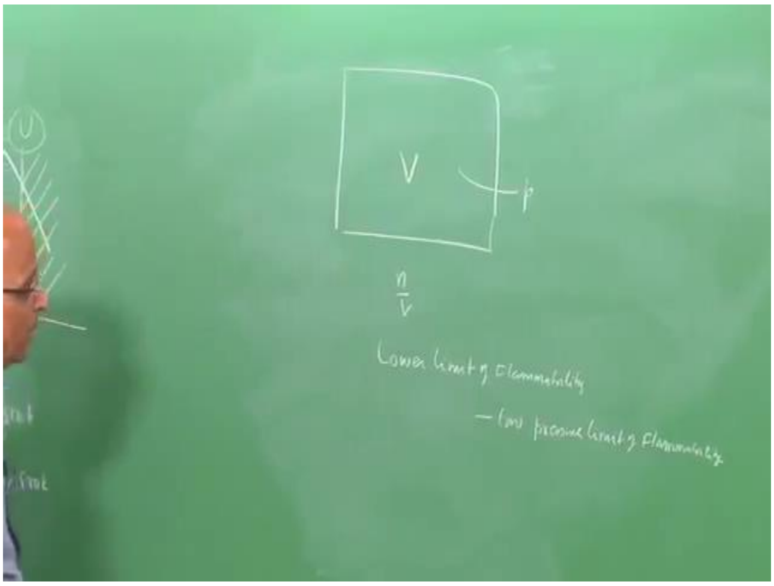

If I have a volume of the mixture, given volume of an explosive and I let us say it is a vapor air mixture or gas air mixture, I keep on reducing this pressure. If I reduce this pressure, the concentration of the moles in this gas, that means the concentration is n over v. The number of moles in this particular gas will keep decreasing. And if the numbers of moles of the gas are so small, such that it cannot react further.

Well, I cannot really have a chemical reaction takes place. And this will again correspond to the low pressure limit or corresponding to the lower limit of flammability. And therefore, I can also have lower limit of flammability, coming from low pressure of the mixture. And with this, we call as the low pressure limit of flammability. Therefore, whenever we have these explosive gases, which are formed under sub atmospheric pressure, low sub atmospheric pressure, were they may not be able to propagate a flame.

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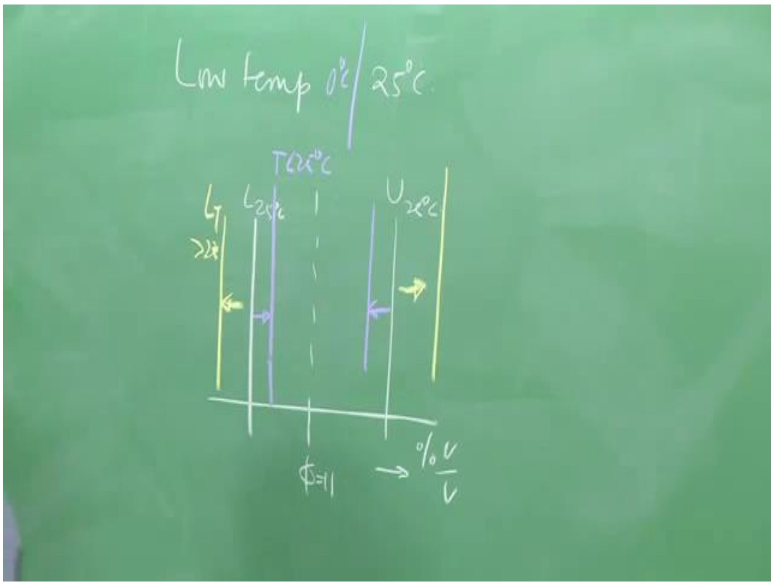

Now, we have seen from the point of concentration that is volume by volume, maybe in terms of pressure, what should be the effect of temperature, can we just presume something. Well, I tell myself well, temperature. If I have very low temperatures, what is going to happen? Well, the rate of reaction will be terribly effected because, not much of the heat of the reaction goes into increasing the temperature, to the value of the standard condition that is 25 degree centigrade.

And therefore, heat may not really be available. And if under standard conditions let us say at 25 degree centigrade and say this is my documentary, this is my percentage volume by volume; this is my scale over here. Well, this is my limit, calculated at 25 degree centigrade, low pressure lean limit that is l. I have rich limit u, at 25 degree centigrade over here. Well, if I were to plot on this, maybe at a low temperature of let us say minus 5 or let us say 0 degree centigrade.

Well, some heat has to go. And therefore, the lean limit will move up. That means, it will come to this, it will move in this particular direction. Well, the upper limit will come down, it moves over here at temperatures less than 25 degree centigrade. If the temperature were higher than 25 degree centigrade, what is going to happen? Well, using the same argument, I can tell. Well, if the temperature is going to be higher than 25 degrees, I have more enthalpy in the gases that is going to come as product gases.

Therefore, the lean limit moves becomes, even more leaner. This is at a temperature greater than 25 degree centigrade. And if that upper limit also moves upward over here. Well, let us examine some of these results for some gases. And look at the expressions in the slides, which are shown now.

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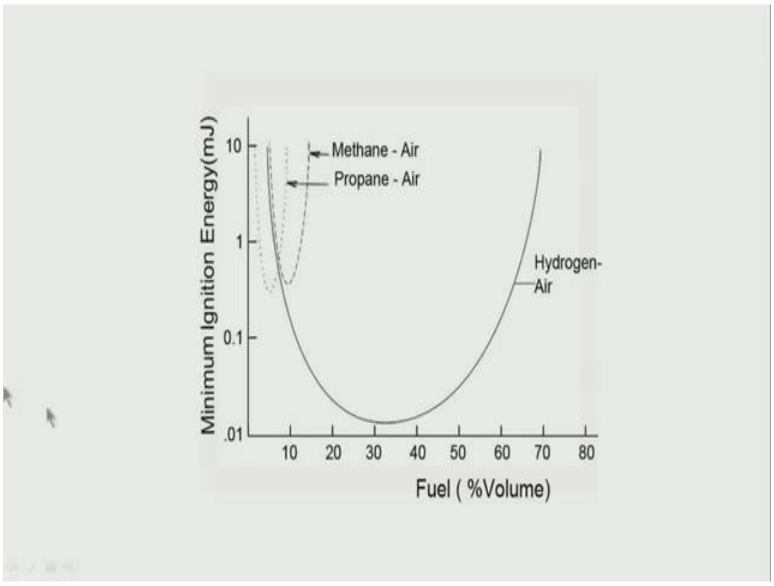

Now, well in this particular slide you see the limits of flammability, is given by percentage volume in a given volume. And on the y axis, I show the minimum ignition energy. Why is it we show the minimum ignition energy? Well, if something is not flammable, the minimum ignition energy tends to a very large numbers, that is infinity. Therefore, at the limits of the flammability, the minimum ignition energy is infinity. And therefore, I have u that is lying over here, which is a very large ignition energy.

I have u over here that is upper limit of flammability, wherein it is very large. And therefore, I have something like a u shaped curve over here. And these u shaped curves are shown in a plot of minimum ignition energy, versus the fuel percentage volume in a given volume of mixture. Therefore, you find that for hydrogen air mixture, it varies between something like 4 volume 4 percentage volume of hydrogen in hydrogen air mixture.

And it goes right up to something like may be, something like 70 or so over here, at the rich limit of flammability. If I consider something like methane air, if I look at methane air well, this is the upper limit of flammability. It is around 12 percent. If I consider the lower limit, it is the lower limit of the order of something like 3 percent or so. This is the curve over here for methane air.

If I take a look at propane air well, this is the limit over here, lean limit of flammability of the order of something like 2 percent. Propane in propane air mixture and if I go to the rich well, it is somewhere over here. Therefore, what we observe is, for different fuel air mixtures we get these u type of curves. And the lean limit of flammability is here. And rich limit of flammability is here, lean, rich, lean for hydrogen by the continuous line over here.

And if we can operate the system, within the lean limit or outside the rich limit, may be for the particular gas mixture, well there is no danger of an explosion, there is no chemical reaction taking place. But, if we are within the limits, we must be careful. But, we do get another message from this particular curve and what is the message what we get? We find that, at the lean conditions whether it is methane air, propane air or hydrogen air.

You know, we are talking of energy which are almost comparable, which are quite high now. And we find, well hydrogen we always have a feeling it is a dangerous gas. But, we find the limit of flammability of lower limit is around 4. And if you look at, maybe propane air or if you took kerosene vapor, it is almost around the same value. And therefore, whenever we have spills taking place, you cannot get very we get only lean mixtures, which are being formed.

And therefore, from these curves we get a feeling that, maybe hydrogen air mixtures which are being formed by leaks are not that dangerous after all. These are as dangerous as any other gas, which comes over here. Well, having looked at the lean and rich limits, let us go to the next one.

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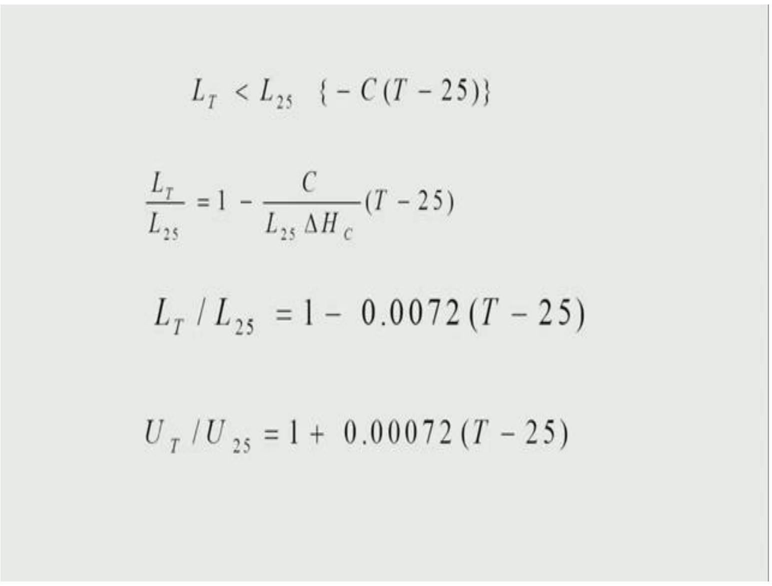

$$L_T < L_{25} \ \{-C(T-25)\}$$

$$\frac{L_T}{L_{25}} = 1 - \frac{C}{L_{25}\,\Delta H_C}(T-25)$$

$$L_T / L_{25} = 1 - 0.0072(T-25)$$

$$U_T / U_{25} = 1 + 0.00072(T-25)$$

We said, when the temperature is such that, the temperature is higher than 25 degree centigrade, I have more of the energy which is available. Therefore, the sensible heat which is higher is C into T minus 25. This is the energy available. More than the C is the specific heat is greater than this. And therefore, the since more energy is liberated by the gases. Well, the lean limit at temperature T should be less than the limit at 25 degree centigrade.

Therefore, if I have to convert it, I can say L t by L 25 should be equal to or L t is equal to L 25 minus some particular value corresponding to this. I put the standard heat over here. I get C divided by the limit at 25 degrees into the heat of combustion. And you know, you sort of say, well it must therefore, have a dependence of L t by L 25 is equal to 1 minus. The specific heat divided by the heat content at the standard condition into T minus 25. And if I do an experiment, I find that L t by L 25, that is the lean limit at a temperature T, which is higher than 25 should be smaller.

And the value is 1 minus 0.0072 into T minus 25. If the temperature is going to be lower, well this becomes lower, this becomes positive. And the temperature limit increases, as we discussed earlier. Similarly, the upper limit at any temperature corresponding to the standard temperature of 25 degrees, is also given by a similar expression. But, in this case when the temperature increases, the upper limit goes to the right. That means, it becomes the higher value.

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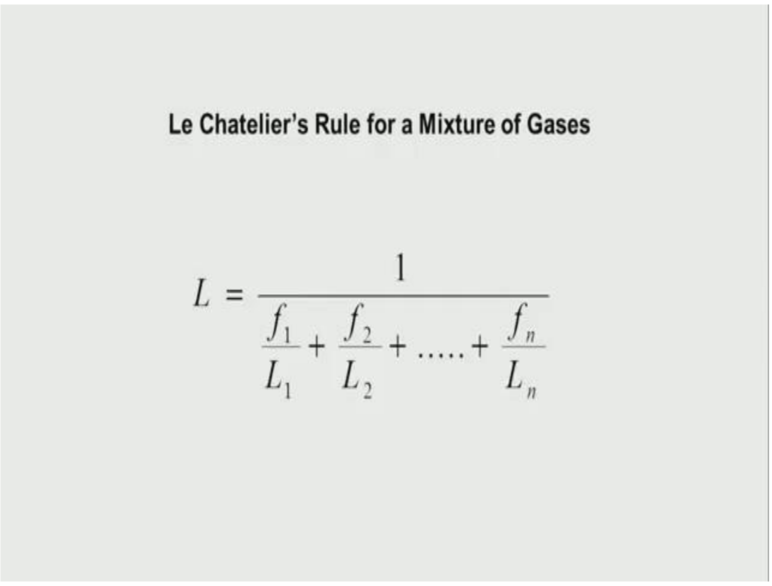

Le Chatelier's Rule for a Mixture of Gases

$$L = \frac{1}{\frac{f_1}{L_1} + \frac{f_2}{L_2} + \ldots\ldots + \frac{f_n}{L_n}}$$

Well, these are about the limits of flammability. But, in many cases I want to qualify this by a particular explanation on the board. We find, that may be you know, when we have the cooking gas at home, you know it contains not a single gas.

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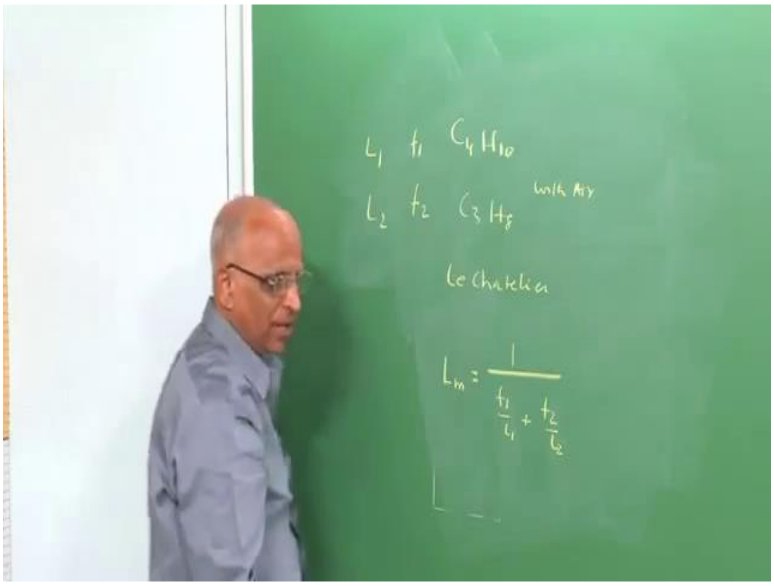

It contains, let us say butane, lot of butane c 4 h 10. It also contains some propane, c 3 h 8. Therefore, it is instructive to find out, how much what will be the type of flammability limits, for mixture of gases with air. Therefore, when I talk of mixture of gases with air, you know it becomes difficult. Because, you know if the gases are similar in structure, well it is possible to use empirical expression. But, you know in which case I need the moles of this gas and moles of this gas and do this.

But, a general expression which is due to Le Chatelia, he proposed that he follows a harmonic mean like for instance. I have f 1 of this fraction of volume of this gas. I have f 2 of this. If the lean limit in butane air is, let us say L 1. If the lean limit in propane air is L 2, well for this mixture of gases, well the limit for this mixture is equal to 1 over. I get f 1 by L 1 plus f 2 by L 2. And this is what I show in the slide over here.

All what I say is, when I have a mixture of gases which contains, maybe similar structure of gases. I have fraction f 1 f 2, f 1 corresponding to gas 1, f 2 corresponding to the combustible gas 2 and so on. And the lean limit of gas 1 is L 1, the lean limit of gas is L 2 and so on up to L n. The limit for the mixture is given by the Le Chatelier's rule, which is L is equal to 1 over f 1 plus f 2 and so on up to f n.

And this is, how we calculate the flammability limits. And using the flammability limits, well I can find out. I can solve problems for may be the conditions under which a particular gas can explode or will not explode.

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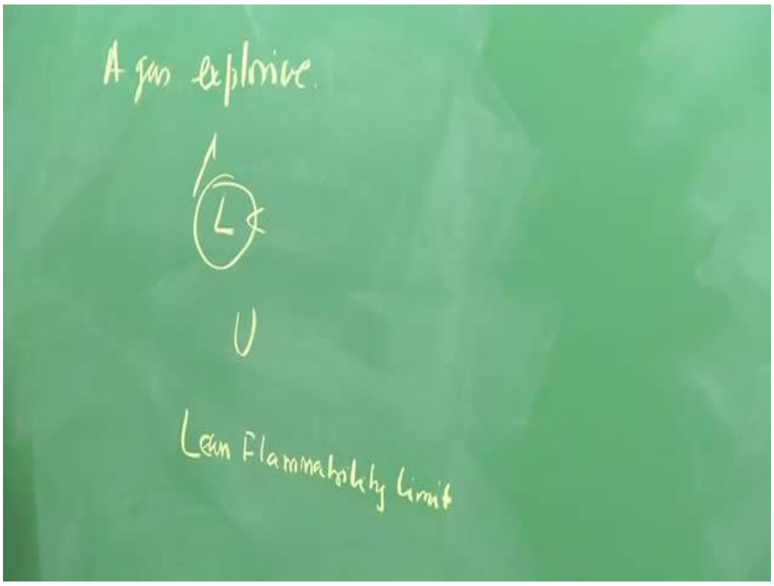

I can also find out the condition under which, maybe a gas if I have is let us say an exposures. I do not want it to explore. Maybe, how much of the inert substance I have add to it. Such that, I reduce the limit, I reduce the concentration of the gases to be less than the lean limit of flammability. See in practice, the lean limit of flammability is more stronger. That means, it is something which is an more important parameter.

Compared to u because, you know what happens is whenever some leak happens in practice, I cannot really form a very rich mixture, unless it is a very copious leak. But, in general you know we always talk in terms of small leaks. And therefore, the lean limit of flammability is an important parameter, which we need to consider. Well, these are about lean limits of flammability.

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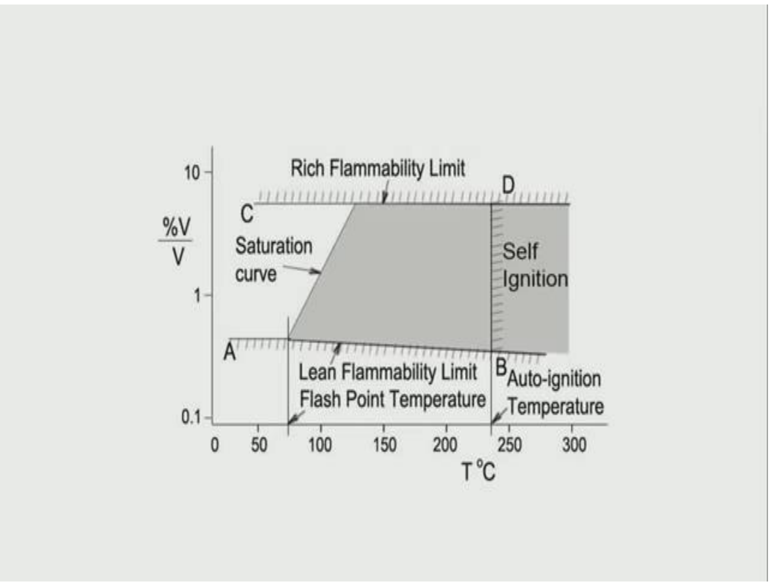

Let us take a look at the last slide over here, in which I talk in terms of the flammability limits of volatile fuels. You know, there is one problem I must tell you. See, if you look at this plot, you know I should have temperature here. And I show something like percentage volume by volume here. What is this, you know it is a little confusing. But, let us try to analyze why this particular figure and what it means. I go back to the board. Well, I consider let us say petrol, which is available in the market as a volatile fuel or I say kerosene, which is available.

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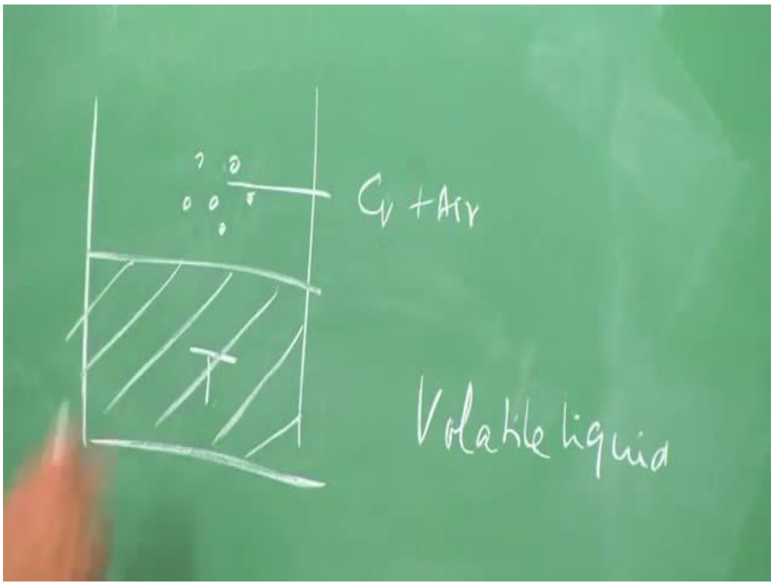

You know, when I have let us say, a cane of petrol which is available. And let us say, I increase the temperature of kerosene. What is going to happen? Well on a cold day, the amount of vapor of kerosene is small, which is getting out here. If the temperature is higher, I have more of the vapor over here. Therefore, the amount of the concentration of vapor which I can form kerosene vapor, which I can mix with air is higher, when the temperature of the volatile liquid is higher.

Therefore, whenever I consider something like a volatile liquid, the temperature of the volatile liquid will tell me, what is the type of mixture which I can form in the air above it? And if I form a mixture, which is available well, at this temperature to store petrol or to store kerosene, is going to be difficult.

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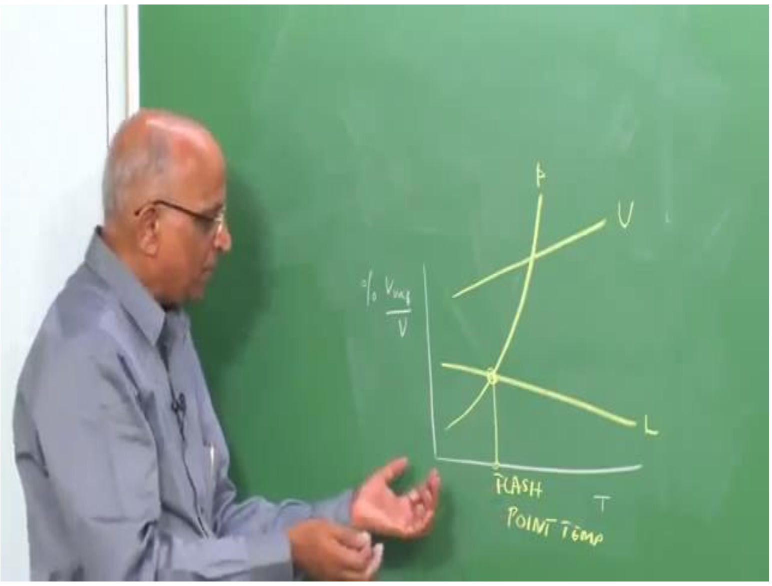

Therefore, if I have an axis which is temperature and on this plot, on the y axis, now I say percentage volume of the vapor of this particular volatile liquid, divided by the vapor of the mixture which can be formed. Now, over here I can say as temperature increases, we say yes, we say the limit of flammability decreases. Well, we also saw maybe in the rich limit, let us erase the top part over here. We saw well, the u increases with the limit of flammability.

We also know, as the temperature of the volatile liquid increases, its vapor pressure increases. This is the vapor pressure curve. Therefore, when the vapor pressure, that means I have, I form vapor as the temperature of the volatile liquid increases. At this confluents, that is the intersection of the vapor pressure curve and the L curve corresponding to this. What happens? I generate sufficient vapor, which is just at the lean limit of flammability.

And if I can increase the temperature just above it, I have sufficient vapor which forms mixtures which is above the limit of flammability. And therefore, this corresponds to the temperature that is the minimum temperature of the volatile liquid, at which a flammable limit is called, is can be formed. And this temperature, is what we call as the flash point temperature.

In other words, when we talk in terms of volatile liquids like petrol, kerosene or other substances, we talk in terms of flash point temperature at which sufficient vapor is formed above the liquid, which when mixed with air, forms a limit mixture corresponding to the lean limit L.

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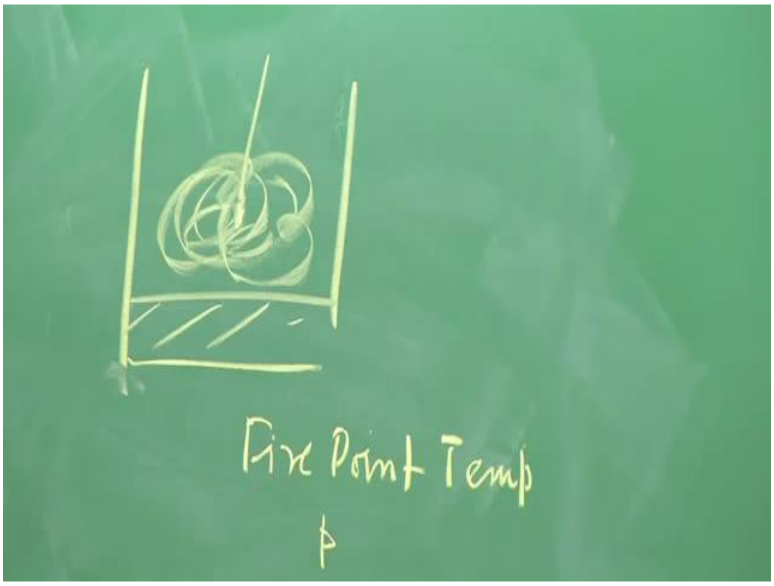

If but, you know what happens. This diagram here, I have maybe kerosene or petrol over here. I form a mixture over here which is, let us say lean limit. And supposing, I put a match stick over here. It immediately burns and the mixture is finished it. It just flashes into vapor and then the vapor gets consumed. And that is why, it is known as flash point. That means, the amount of vapor is not still sufficient to continually keep the fire on.

That means, I still require more copious amount of vapor, to be able to keep the fire on. And if I have more copious, that is still higher temperature well, I call as a fire point temperature. Therefore, this question of maybe the flash point temperature and fire point temperatures are very useful, safety parameters with how to deal with liquids ((Refer Time: 54:40)). In this slide, I showed the temperature of the volatile liquid as T degree centigrade.

I show the percentage volume of the fuel vapor divided by the volume of the mixture over here. I show the value of L decreasing with increase in temperature. I also show the rich flammability limit u increasing with temperature. This is the vapor pressure temperature curve over here. You find, well at the intersection of the vapor pressure curve and this and the lean flammability limit, I get the flash point temperature.

If I want a fire point temperature, the temperature needs to be higher. And if I increase the temperature further, maybe as we saw earlier the critical temperature or auto ignition temperature at which self ignition takes place. And this is how we categorize the safety aspects of volatile liquid.

And this is categorized in terms of flash point temperatures. In terms of the fire point temperature, wherein the copious amount of liquid comes over here and in terms of the self ignition. What we do in the next class is, we will go further and analyze one or two examples by which we can interpret this phenomenon and identify explosions due to the limits of flammability. And, then move into the chapter of detonations.

Thank you.