Fundamentals of Aerospace Propulsion
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Lecture - 23

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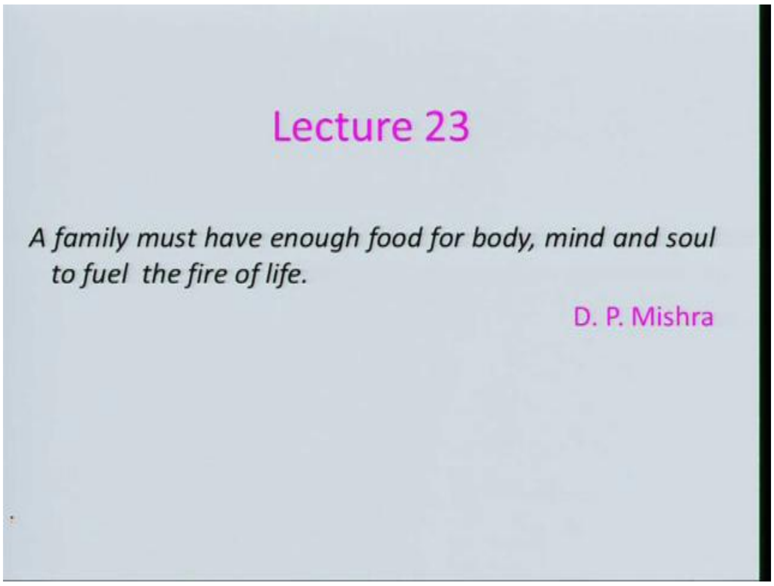

Let us start this lecture 23rd with a thought process, a family must have enough food for body, mind and soul to fuel the fire of life. If I look at today's family it is does not have that. So, let us recall what we learnt in the last lecture. If you look at we basically looked at one dimensional laminar premixed flame, right and then, we invoked the equation of mass, momentum and species and satisfying the conservation along with the energy. And then, tried to derive a relation, relationship for laminar burning velocity and if you look at why really we want to look at laminar burning velocity. Of course, the flame is laminar therefore, we need to look at laminar burning velocity.

When the flame is turbulent we need to look at turbulent burning velocity, in real situation the turbulent burning velocity will be more important than the laminar. Fortunately, the turbulent burning velocity can be related to laminar burning velocity. So, if you understand the laminar burning velocity or laminar flame we can somehow manage to you know talk about the laminar, turbulent burning velocity. Question arises, why burning velocity, why not something else? For example, flame temperature, right. Why you are looking at burning velocity, spending a lot of time to derive a relationship?

Because, that is the only one parameter in case of premixed flame fortunately, which can characterize the entire flame. And this laminar burning velocity can be related to several other concepts like flame thickness, ignition energy, quenching diameter and several other blowout phenomena and then flash back. I do not know whether you aware or not, but as we go along we will see. That means, we using a simple you know parameter burning velocity, we can really explain and understand a lot of phenomena associated with the flame, premixed flame particularly and also the diffusion flame to some extent.

But diffusion flame we define some other term, not a burning velocity right. Now let us look at flame thickness, right if you look at flame thickness and we have already defined divided the flame into three zones. What are those zones? Is a preheat zone, reaction zone and recombination zone, right three zones. Question arises, when you talk about thickness of a flame what you will say? Can you take I mean all three zones or we will take the reaction zone or we will take the preheat zone or we will take the combination of some, right.

There is a lot of debate about it, how thick is flame is and we will be using an approximation also, whenever I will be talking about diffusion flame and droplet known as thin flame approximation right. And as I mentioned earlier, flame is generally very thin right and naturally one has to take care of the reaction rate ,right, but we will be using a, what you call another way of looking at in terms of temperature. Because, in experiment one cannot really define where the peak reaction rate is occurring right and then talk about it. But of course, numerical people do used it so, there are several definitions of flame thickness you will find in the literature, but we will be restricting to one of them.

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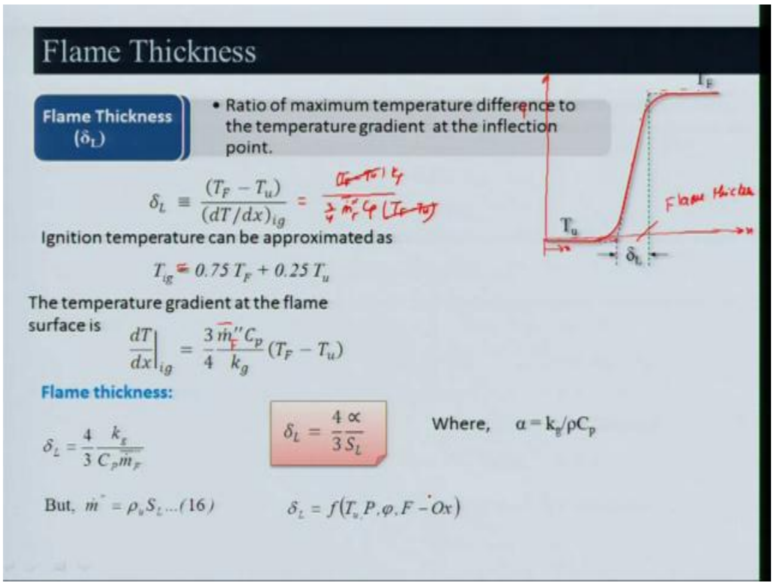

And that is basically based on the temperature look. For example, if I take the temperature over here which profile I have shown t u, this is a unburned mixtures. And if I can assume this is an along x direction this is of course, my temperature and if I take this is from you know x starting from here and it is infinity. What you can see, the temperature profile, you will see the temperature reaming constant after that, it changing the slopes and again you know like it is increasing and changing the slopes. So, when the slop is changing, right there will be some inflection point right and what I will do? I will draw a parallel line here and I will draw parallel line here, right and draw a tangent to this surface and it will cut over here.

So, that and whenever it cut this tangent I will say this is nothing but my flame thickness you know. This is physically right, but how we do it mathematically? What do we really are doing, we are basically saying the temperature difference divided by the temperature gradient at the inflection point, you know slope will be changing somewhere ignition will be occurring. So, there will call it inflection point and they know we do that. So, that means it is basically a flame thickness we can define mathematically, ratio of maximum temperature that is t f difference at that means, with respect to the unburned temperature t f minus t u divided by d t by b x ignition, right. Ignition we are taking, you know for our convenience because we know this gradient form our analysis, right. Okay, is that clear?

So, we know that the temperature gradient, you know we will be defined, but to talk about this temperature gradient we have already approximated. See if you look at, this is basically approximation is equal to 0.75 t f plus 0.25 t u, right there is nothing very stoichiometry somebody can say look it is not 0.75 it is 0.7, it may be possible right and other was 0.3 u, right it can be. But we are using it just to track this problem or make it attractable or handle this problem easily. The temperature gradient at the flame surface, we know that d t by d x this we have already derived is equal to 3 by 3 m dot double, dash keep it in mind that this is f and this is f, right.

This a path average, right c p by k g t f minus t u and what we have done? In place of t i g we have used this terminology, right. So, what we will now we will just substitute over here, if I substitute over here what I am getting? I am getting t f minus t u right divided by 3 by 4 m dot triple dash f c p and k g will go here and t f minus t u. So, this is cancel it out, right. So, what I will get then? I will get basically right delta l is equal to 4 by 3 k g right divided by c p m dot f, you know double dash bar. That means this is average reaction rate in the reaction zone, right that we are considering. It is goes on changing, but we are taking because, we will using addition equation for global kind global reaction right one for a single step chemistry, right.

So therefore, we can get that and we know that m dot triple dash, you know m dot is basically is a rho u s l, right. We can find out that delta l is equal to 4 by 3 alpha by s l, what I will do? I will just put this thing and you know like if I know this m dot f, I can substitute those values and arrive at 4 by 3 alpha by s l, right and how it is I am just leaving you can look at it. That means, it is what you saying alpha is equal to k g by rho c p, right and what you can see from here that means, flame thickness, right is a function of laminar burning velocity. As the laminar burning velocity is dependent on what? Inlet temperature, dependent on the fuel air ratio, dependent on the pressure, dependent on the type of what you call fuel oxidizer, right system.

So, naturally what I am expecting that flame length will be function of inlet temperature, pressure, equivalence ratio and fuel and oxidizers system, right. That means what you expect this one? If I say how this flame thickness will be varying with respect to the equivalence ratio that means, I need to look at how it is varying, how the flame, laminar burning velocity varying with the equivalence ratio.

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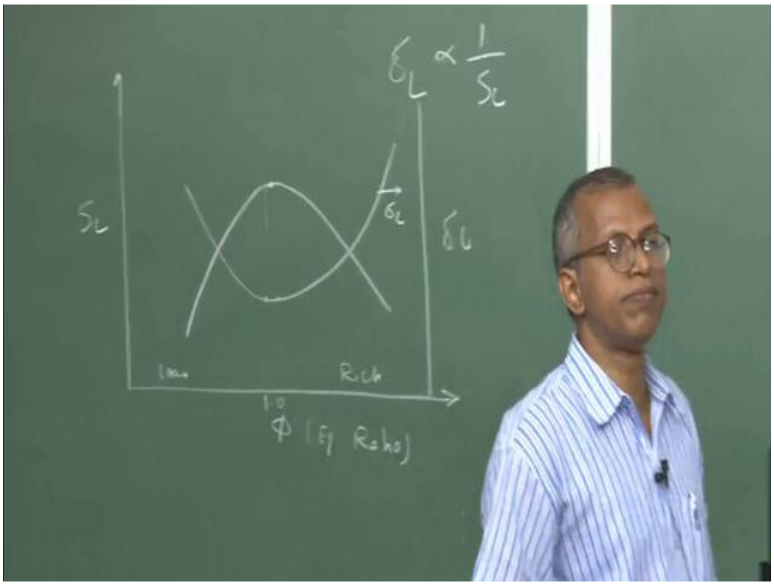

You remember, that the laminar burning velocity for a methane air system or for any hydrocarbon air system, right this is my phi, phi is the basically equivalence ratio. How it will be? It will be something, if I take around one here right and this is lean side and this is a rich side, what it will be? It will be something that means around 1.05 there will be peak values right. Now if I want to draw a how this flame length sorry, how this flame thickness will be varying, with respect to the equivalence ratio. If you look at my burning velocity is very higher here so, naturally this delta l you know is proportional to 1 by s l. So, I will get a minimum value, yes or no, right.

Because the burning velocity highest there so, if I keep all the things are same inlet temperature and all these pressure, all these things and naturally it will be you know constant. You can say like other things may be little bit changes, but it will be proportional to one over ratio, right. Burning velocity is higher that will minimum so, if it is on the lean side what it would be? If I draw you know delta l in this, what will be? My value will be somewhere very low value, you know and then other side it will be like that. This will be delta l, right yes or no?

Because, my burning velocity is dropping down both on the lean and the rich side. Of course, you know slop will be different that rate in which it will be dropping down, but it will be you know just opposite that that we will see, how it is you know. So, let us having talked about this flame thickness, we will be looking at another very important aspect, that is the flame extinction right. And if you look at, why we need to study this flame extinction? Because, we know that the fire or the flame is a very dangerous thing, we have seen that you know some of the houses gutted into the fire.

You might have seen nowadays lot of buildings you know, even catching a fire due to some, what you call negligence or part of their. But earlier days there are the lot of way of you know handling fire of course, if I remember earlier days in village, the whole village will be you know turned into ashes because, at that time thatches house have been used, right. But question arises fire is very important for our life so, also the, but how to control is also important. And why do it we do in you know, all the engines like combustor, what you call rocket engines or gas turbine engine or any other engines, you know where which generate power or the thrust.

You always try to control the, control the fire or control the flame in it right. I am using fire and flame in a interchangeable keep in mind it is not supposed to do, but I am just using for my you know just convenience. So, flame is has to be contained inside combustor that is important. Now, there are several safety issues are there.

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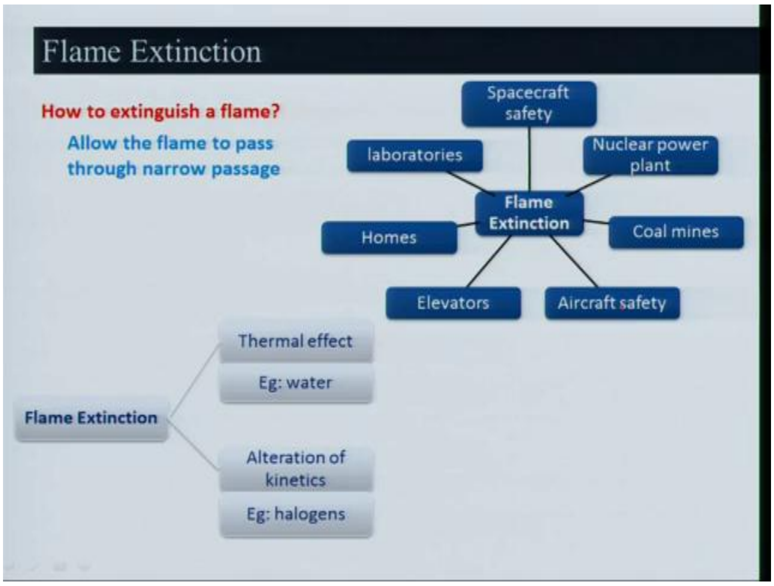

If you look at, there are several kind of safety issues which you one can think of that means, we must learn how to contain a flame, how to control a flame. One of course, in laboratories you know we always worry about whether how to you know, douses a flame if it will occur occurring accidentally. So also, in the homes, elevators of course, some example in the big houses and the very important aircraft safety is very important. That is also being talked about and you know cold minds are another place where it is quite important. You may not be knowing or some of you may be aware also that, we are having you know mine fire, cold mine fires which is existing since 1916 and today it is also continuing and we do not have any solution, how to douse the fire.

Particularly in the, you know in the Jharkhand region, ((Refer time: 15:48)) region you know like there, the fire is engulfing large amount of coal, million tons of coals you know are being burned into ashes, we do not have a solution right. So, similarly it is very important if you remember that, you know in other to contain, you know like avoid the flame in the mines, person had invented a lamp, do you remember who is that person? And then you know his is basically Humphrey Davy, right and there is of course, nuclear plant where the, you know fire is very important one and has to be contained so also the spacecraft.

Now question arises how we can extinguish a flame? How we can use a, extinguish a flame or a fire? I am using in intangibly right, what are the ways we have seen like you know candle flame whenever the light will come and whenever light, what you call electricity will go away. We generally used candle flame for temporary, right of cause nowadays emergency it will, system are there the lights system with battery, but we always what, how do extinguish a candle flame? Just blow air, what really we are doing by blowing air right, what really we are doing, how it is been flame being doused or extinguished? And whenever the fire you remember like a, I do not know whether you people are involved in extinguishing of fire or not.

Because, nowadays all are self-centered, earlier days whenever fire is there will go with a people and let us you know help them. Today the, you know in cities and other even in village people are not cooperative, right. Because, people are more selfish nowadays anyway, let me get into that what really we do we just go and pour water you know like, bucket of water we should take in the village. And today of course the, you are having a hose pipe which will go and put water. So, water also we can douse, if sometimes you know something happens, spray water right, is veined water is not there what could happened?

Now question arises, what really is happening in inside and sometimes you might be knowing there is a fire extinguisher, sometimes carbon oxide gas or some you know kind of nitrogen we used. What really happens, is it really something happening like some heat being, you know it how this flame propagator? Because of heat being generated and it try to consume they prepare that things and go, right. Now of course, like what you call when we do that means, it is a one way thinking of using the heat, you know. If I manage the heat being generated due to the flame rather, I cannot make it self-sustain. So, flame will be there, right that is a one way of doing.

Another way of looking at, you have seen a kinetics plays a very important role, if temperature is higher then only the reaction will be taking place. If temperature is low, can really take a reaction take place, even though fuel air there? For example, if this room is mixed with fuel air ratio, which can be burned, but if there is no ignition, if there is no heat source, you cannot really these things. If temperature is very very low, I know then nothing will happen heat will be there. May be it will affect your health because of fuel air there, but it would not really be converted to a flame. So, if you look at all those extinction processes can be divided broadly into two categories.

One is thermal effect right that means, what we used is that we one example is what we used, that will be spray and then you know, it will be small droplets surface, they will increase, evaporation will go on you know like evaporation will be enhanced. And then, there will be also addition of diluents you know there is a heat transfer and also diluent. And there is another way of that alteration of kinetics. For example, I will use halogens or some other gases right you know, which will be altering or inviting the reaction to take place, right. I can put some other gases, which will be accelerating or enhancing the combustion by changing the kinetics.

So, combination of both can be used, you know to talk about basically what you call flame extinction. What really is happening, we are trying to quench the flame right. For example, we quench the mob as well whenever they will go to, what you call violent. There is very interesting way of quenching the hesitation or the violent, in recent days lot of things are happening because of no reason, you know very much kind of things. So, how to do that? This is again you will have to quench, you will have to quench the aspiration or the, what you call violent mind of a persons. Similarly, the flame is considered as a violent, right.

So, you need to quench it, what is the way of quenching it, as I told it is energy which will be released, that you will have to contained right that is the basic principle, either you do thermal effect or you do by the kinetics. It is the energy which is the matter all together right. So, similarly when people, if you look at youngsters becoming violent nowadays across the globe, in India is no exception. How to handle them is important aspect, that is why you give a code like you need to look at other aspect of life. So, coming back to that that means, we will allow the flame you know, how will talk about this quenching of a flame?

One way is transferring of heat, if the flame is there how will do? We will have to put a water or something suppose, there is a tube where the mixtures are there, right. Particularly in case of premixed flame then, what we will have to do? We will have to transfer the heat, how we can do that? We can say I will cool it, you can mix or without mixing you can do that that means, we can allow the flame to pass through a narrow passage, right. Then, what happens? It will be quench or it will be accelerated, if there is a fuel air mixture you know for example, I am taking a passage you know, like a tube.

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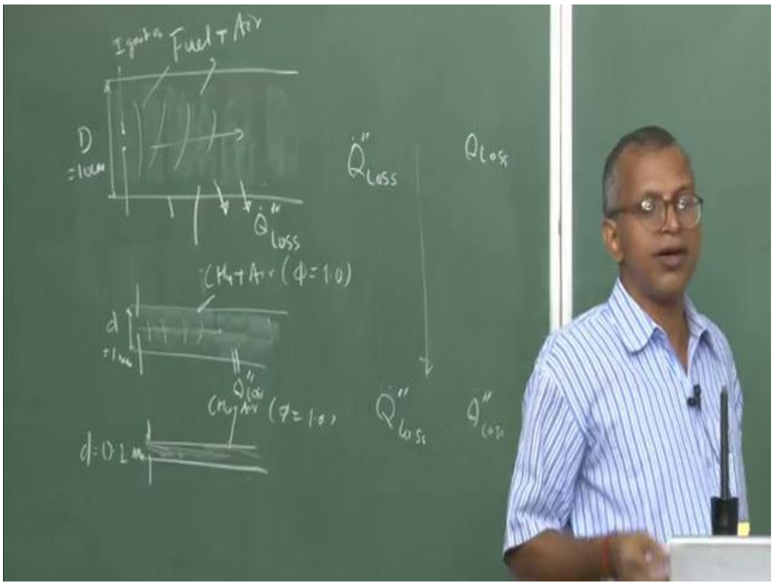

This is a tube where, this is a fuel air mixture you know, air mixture right and there is another tube, which is very very small. If you keep in mind that, this is d very big diameter this is a very small diameter. This is also mixed with the same you know, fuel air if I say this is methane plus air and this is also methane plus air, you know, both are same and same equivalence ratio. I can say let say phi is equal to 1 for example, both are same and I will ignite here, right. This is an ignition source or a spark I am creating similarly, I am creating spark, what will happen? This is let say you know like, a 5 centimeter or may be 7 centimeter this is a or let say this a 10 centimeter and this is a 1 mm, right.

I will say this 10 centimeter this is 1 mm, 1 order of magnitude difference, what will happen? Is it flame will propagate in this you know, if I will do it in same amount of ignition energy I am giving, same fuel air mixture what will happen in flame, will it propagate? And keep in mind that, there is a lot of heat transfer is taking place here that means, you know is going out heat transfer, right this is going out, right. Similarly, this is also going out, what will happen in small diameter? Will it flame will go, if I make it small it is going at 1 mm, if I will make it 0.5 mm, will it go really? If it I will make it 0.2 mm or 0.1 mm, I will take another tube you know 0.1 mm, right.

The same thing you know mixture c h 4 air phi 1 this is 0.1 mm. So, you will find that what is happening to the heat, it is a two thing. One is heat been generated because, the same fuel air mixture you are giving ignition energy let say some fuel, right. And in another heat loss, heat loss can be several things, right it can be conduction, it can be convection, it can be radiation, right. Let say total heat loss whatever is happening. So, heat loss, how heat loss is changes along with this that means, heat losses. If I look at losses you know, heat loss, heat loss is changing how it is changing? Is it a same heat losses happening for a, the all diameter what I have taken, what is happing?

Heat loss is decreasing as I going like, it will decreasing like this or it will remain same, it will remain same or it will increase there might be three things. One is heat loss will increase from here to there and another heat loss from 3 cases you know, will be you know decreasing, right. That means, here it is increasing, here it is decreasing, right or it will remain same, it would not change between three cases, three diameters, right, what I have considered. What will be happening?

Student: Heat loss will increase.

Heat loss will increase as you go along with this that means, less heat losses from here, more heat loss from here and most heat loss are largest here, smaller, right. Because, the surface area is mean increases as compared to the volume of you know, as compared to the volume of fuel air mixture being burnt, that is a very important, right. So therefore, and this concept was recognize by Humphrey Davy, longtime back and who employed in a mine you know, we employed in devising a mine safety lamp. Did you observe these things, your experiment in plus two science suppose, there is a premixed flame, right.

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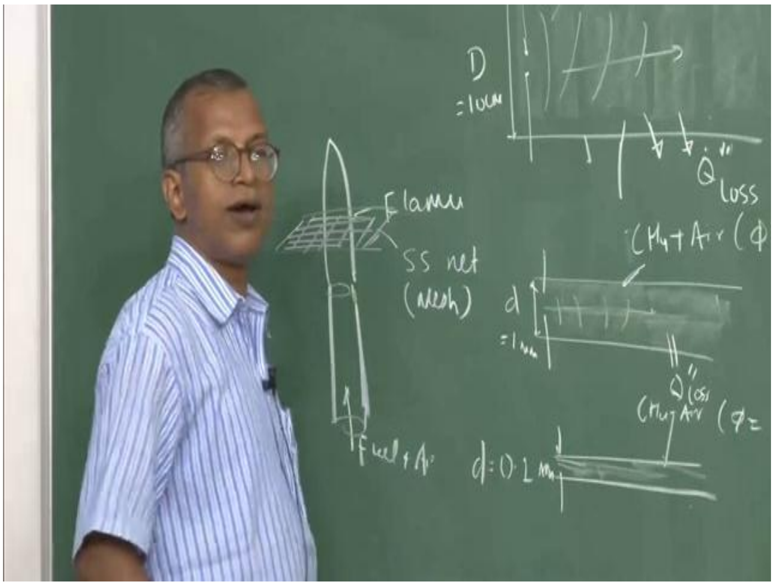

There is a premixed flame, this is fuel plus air mixture, keep in mind that like Bunsen burner, right. This is a flame, if I put a net you know over here, you know net what is the net? This is a stainless steel net, very fine mesh or you call net or mesh you know mesh is a better word, right stainless steel mesh. What will happen to flame, if I, flame is there I put like this cross what will happen?

Student: Spray

Spray, what will happen? In the bottom there will be also flame and the top there will be also flame, right isn’t it? What you have observed, what did you observe? There will not be any flame here, right flame will be and you move this mesh, you can take flame with you upward to some extent, right. Flame will be dangling if you and if you dance, you can make the flame to dance by, with the help of mesh and this concept was used by Humphrey Davy to contain the flame. Why it is so? That is because he will be handling with the quenching you know, he will be trying to quench the flame, flame cannot propagate through the poor holes of the mesh and then, we need to look at what is the flame quenching, right.

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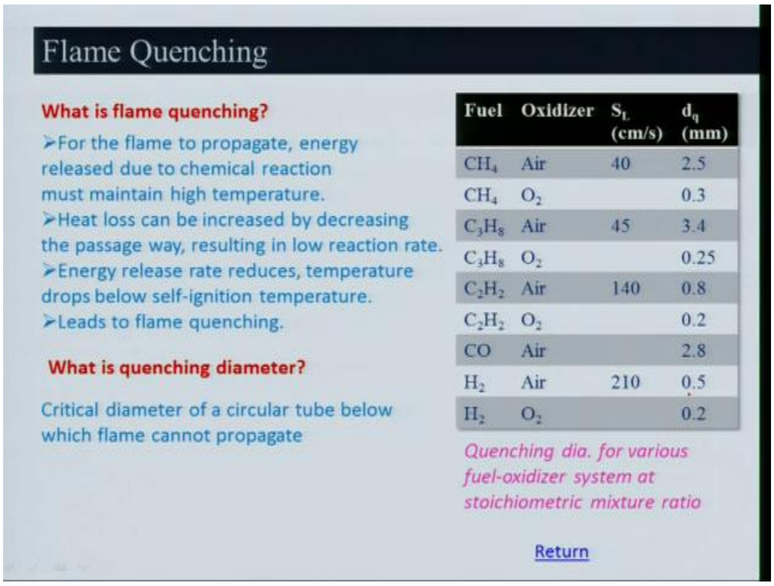

So, that is a very importance concept. So, what is flame quenching? As I told you that whenever you know, heat loss is higher as compared to heat being generated there will be flame quenching right or equal to, right. That means, for a flame to propagate energy released due to chemical reaction must maintain high temperature. Otherwise it cannot, if it is there is all the heat being generated is going away due to heat loss then, natural temperature cannot pick up. So, you cannot have, right and heat loss can be increase by decrease the passage way resulting low reaction rate.

As I told you surface area will be increasing when you decrease the diameter or the width of the you know two channel, right as compared to the volume, amount of heat being generated in a specific volume or particular volume. So, energy rate reduces temperature drops below the self-ignition temperature, as a result there will not be any quenching and that leads to the flame quenching. If you look at the whole process involve is what? It is basically the heat balance right. So now what is a quenching diameter, as I told you I will conduct the experiment, right in this way?

I will take a, some diameter d and see whether the flame is travelling or not right and I will take the same mixture go to the small diameter. I will go to smaller and find out at which diameter flame is not propagated or not going through the thing and that is known as quenching diameter. This is a critical diameter of a circular tube below, which flame cannot propagated, right and people have conducted the experiment also for channel, it is a tube. This is a channel to plate they can take and conduct experiment, that is also known as flame quenching width or the thick width kind of thing, right.

So, some of the data's you can look at it methane air, right if you look at it is having 2.5 mm quenching diameter, but if I use oxygen, methane and oxygen you will see it has been reduced 0.3. And similarly, for propane air acetylene air, if you look at this quenching diameter is 0.8 as compared to the methane air, why it is so? Because the burning velocity is higher, that is 140, as here it is ((Refer time: 32:30)).

If you look at hydrogen air, the burning velocity at an you know for stoichiometric, whatever the data I have given, burning velocity for the stoichiometric, equivalence ratio is equal to 1. So, it is very higher and it is also smaller and whenever oxygen, you are you know put. So, naturally it will be you know smaller. So, we need to now relate this quenching diameter to the laminar burning velocity, we will do that.

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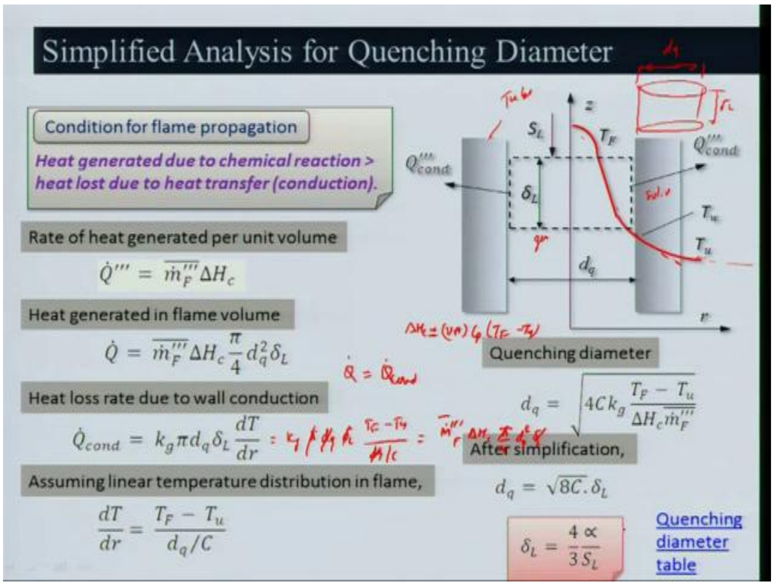

And using a very simplified analysis, what I am doing? This is basically a tube, this is a tube, what you call this is a tube having diameter of d q, I am saying this is a quenching diameter, right. And this is the flame, which is travelling through that with a velocity, burning velocity that is s l and the delta l is a thickness of the flame, right. That means, thickness in which all heat being released or all the things are being and some conduction is going on. And here we are considering that, there is no heat loss due to the addition right and also convection we are not considering, right what we are doing? Whatever the heat being released is basically going away due to the conduction, this is an approximation, keep in mind.

And we will be some more application, app you know simplification that means, for this condition, the flame can propagate only if the heat release you know or heat generated, due to chemical reaction is greater than the heat loss due to heat transfer. In this example or in this analysis we are talking about only heat conduction right, but in complex analysis you need to talk about to the radiation as well right, but. Now, that means heat will be quench whenever the heat generated is equal to the heat loss due to conduction.

So, let us look at the rate of heat generated per unit volume that will be what? In this volume it will be q dot q dot triple dash will be m dot f delta h c, right heat of combustion. This is being consumed and this is being released so, this amount of heat of course, keep in mind that here we are assuming all the fuel is being burned and releasing it. In real situation it would not be, this is an idealization. So, heat generated in the volume will be, basically in this volume this is per unit volume, this per volume will be what? This term into pi by 4 d q square, this is the you know like a cross sectional area, if you look at this will be like this, you know right and this is your, what you call delta l and this diameter is basically d q.

So, this is a cylinder kind of things so, 4 by pi by 4 d q square and delta l. So, heat being loss due to the wall conduction, right will be what? Conduction is k g pi d q, this is the surface area you know pi d q and delta l is your surface, you know and d t by d r is a temperature. We are saying only the temperature gradient along that r direction, the temperature gradient along the z direction is negligibly small, but in real situation it is not, right. We are assuming because, gradient along with is much higher as compared to the gradient along the z direction, that is one assumption.

And if you look at I want to estimate this d t by d r for that, you need solve you know solve conjugate or you need to handle the conjugate heat also. Because, the solid, this is a gas, gas will be here right and this is solid. So, you will have to take care of conjugated transfer is quite complex. So, what we will be doing? We will be just simplifying it and what we will doing? If you look at this temperature profile higher here and this is a not a linear, right it cannot be linear, it will be going and then you know also increasing and then after certain distance, it will be almost constant asymptotically it will be decreasing, right.

But what we are assuming? We are taking a, what you call linear temperature distribution you know like, we are saying that this is like that and we are also assuming there is an another assumption. You are saying that this uniform temperature in gas, but here it is linear it will be like this kind of thing linear, right it is not the asymptotically decreases. So therefore, we can say that d t by d r is nothing but you know t f minus t u because, we are assuming these things and d q by c in principle c can be equal to 2. If you look at roughly, but we can make it more accurate by considering c as a constant you know, which can be greater than the 2 because, if you look at it can, right.

And linear if I take it can be two kind of thing and do manage that, but we are not right. So, quenching diameter if I put this things here substitute values here and then I can say that q by heat released is equal to q conduction, right and I will get that what I will get? If I look at this I can write down as k g pi d q delta l t f minus t u d q by c is equal to m dot triple dash f delta h c pi by 4 d q square delta l. So, this we will cancel it out, right and this d q I will be cancelling it here pi will cancel it out and I will get the d q because, d q square is there, right in this right hand side.

So, d q will be nothing but 4 c this is my 4 will go this side, right and there is a c will go here. So, 4 c c is a constant which can be varied will be garter than the 2 always k g t f minus t u divided by delta h c m dot f triple dash, right. And you know that delta h c is what? If you remember the delta h c approximated as nu plus 1 c p t f minus t q, this is an approximation, right. So, we can use that and 1 over m dot f, we can express as what? As a burning velocity, you can look what those expressions and if when you do that, what I will do, I will do approximation, simplification I will get d q is equal to root over h c and delta l. Once I get laminar burning velocity, this I can put in terms of flame thickness.

So, if you look at this d q is basically proportional to the flame thickness and it is a constant that means, d q will be higher than the flame thickness right. So, of course a quenching diameter you know, table we have seen I am not going to talk about that. Let us see that how it is varying, right and keep in mind that delta l is a proportional to the, what you call burning velocity. Because, it can be related 4 by 3 alpha by s l that means, the d q will be also function of or quenching diameters a function of what, equivalence ratio. It can be function of inlet temperature, it can be dependent on the pressure, it can be dependent on the type of fuel oxidizer system, right.

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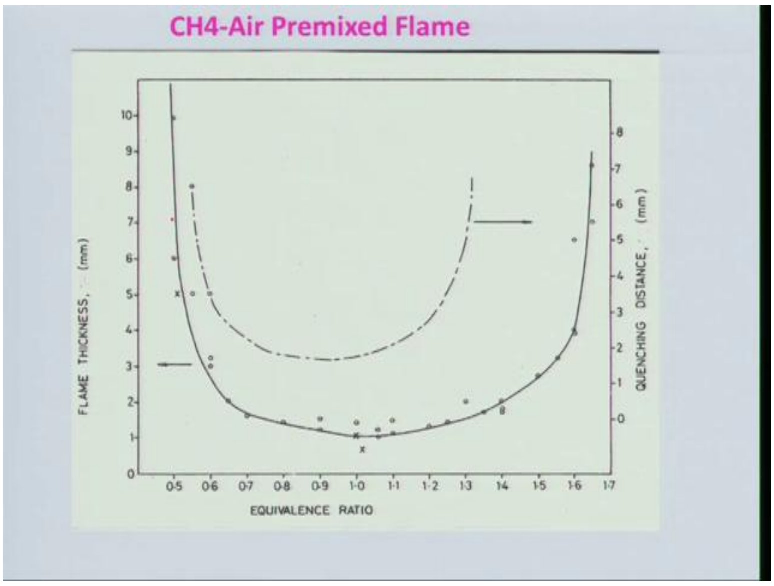

So, let us look at how it is varying this I have shown you flame thickness and these are methane air premixed flame system, flame thickness verses equivalence ratio. And this plot is basically quenching distance in mm right and this is flame thickness on the mm. If you look at it is around you know 1 or 1. This is a very minimum value and similarly, here also is having, but it is little shifted to that. That means, you know around 1 it is having lower values and this is having, what you call higher values than that of the quenching atmosphere. That means, quenching distance is having higher values than that of the flame thickness, right and nature is almost similar, but only thing in rich side it is little closer to that. Because, you are having multiplying and there might some kinetics involved do that.

So, what I am saying by using a very simple analysis, right which is quite simple, what we have done. We can show the trend and trend is quite good I mean it can give you the overall feature and it can replicate. These are the all experimental data’s you know, it is replicating the trend and you can use also for as a design tool for that.

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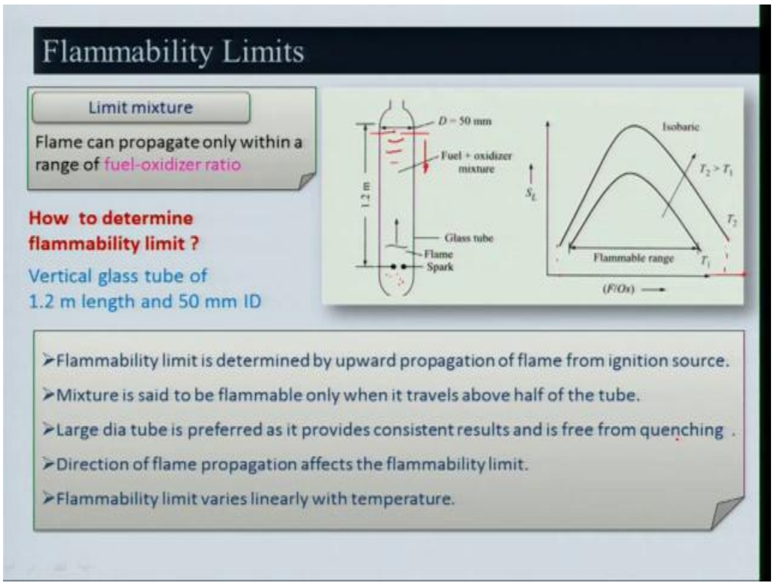

So, limit mixtures if you look at we will be talking another concept known as flammability limit. Limit mixture that means, there is a flame can propagate only when within the range of fuel and oxidizer ratio, right. And it cannot propagate beyond certain limit, right both on the lean and rich limit and. But question arise how to determine the flammability limit and this is very important from the safety point of view as well. And also you should not go on you know claiming or trying it out to burn some mixture which you, it cannot be right.

And this again will be related to what, this flammability limit is related to what, that we will see. So, there is a several ways of doing it, but the most important or which is being used is a vertical glass tube. Particularly for at isobaric pressure condition, which is length is 1.2 meter length and 50 mm ID, inner diameters and why not a smaller diameter, why not a big diameter, why 50 alone? So, if you look at typical experimental setup will be looking like this, it is a tube and it will be filled with the fuel air mixture or fuel and oxidizer mixture air is of course, one of the oxidizer. And then, you ignite in the bottom and let this flame propagate and see that, how far it is moving, right.

Generally, it should move half of the length that is 1.2 meter as per the standard of American you know standard like, American petroleum standard kind of thing they use. It should move half of the thing, right suppose, you know then only you can say this flammable. Otherwise if it is moving initiated, but it not moving half of the portion then, we call it as inflame or like not flammable, right. So, that is the limit it can have both what you call lean limit, if you look at here the burning velocity have been shown or the fuel air mixture there will be limit, beyond which flame cannot move. That means, flame would not be having what you call any tangible burning velocity, right. Because it would not really move, now question arise like you know like it is having a, why it is happening both the lean and rich? Why it a flame is getting quench, basically flame is getting quench isn't it, why?

Because, I have already told you and when I am saying the word flame is getting quench that means, heat losses there and then it is just getting douse and not propagated, that is the one aspect. And other aspect what you call you can see from this that flammability limits you know changes from you know, certain range in which it will working as you are increasing the temperature, right. Because burning velocity dependent on temperature and s l also is increases. So, you will find the limit mixtures are also enhancing you know that means, it is become broader when you increase the temperature.

And keep in mind that I would ask you the question, why 50 mm because, if I used a small diameter than the, then what will happen? It will be affected by the heat loss then, whatever mixture you will get, the limit mixture in will not be write, but if I use a bigger one you can say I can go for the 50 then, it will be little harder digits to handle. So, therefore 50 people have found out these things, there is another way of that when the flame is propagating from top to the bottom of the tube in vertical, this vertical tube. So, what is happening? The flame is affected by the hot gases, these hot gases will be here, it will be trying to push the flame. As a result you will get a different mixture, if I ignite over here that means, flame will be propagating downwards, right.

What will happen? My limit data's would not be or the flame burning velocities or the flame propagation, would not be affected by the hot gases or rebinds a natural convections, right. Therefore, the people always prefer the downward propagation of the flame for making the flammability limits. In other words flammability limits obtained by the upward propagation and downward propagation will be different, right that you can keep it in mind and that is due to as I told you flammability limits determine upward propagation flame from the ignition source.

Mixture is said to a flammable only when, travels above the half of the tube, larger diameter prefer as it provide consistent result and free from the quench, this is very important.

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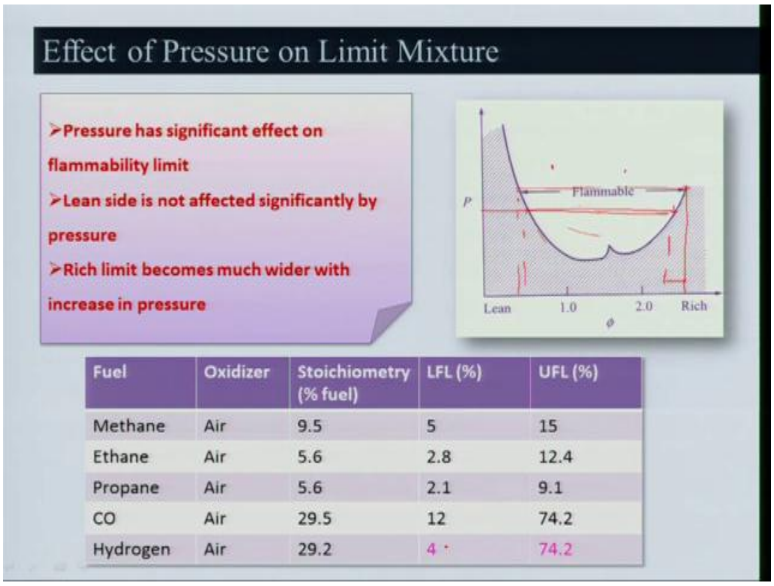

Fuel	Oxidizer	Stoichiometry (% fuel)	LFL (%)	UFL (%)
Methane	Air	9.5	5	15
Ethane	Air	5.6	2.8	12.4
Propane	Air	5.6	2.1	9.1
CO	Air	29.5	12	74.2
Hydrogen	Air	29.2	4	74.2

Like, as I told you direction of flame propagation affect the flammability limit. Flammability limit varies linearly with temperature so, it is as I told you it is dependent temperature, it will also dependent on the pressure limits, if you look at the pressure has shown this equivalence region. These are the flammability lean mixtures here, inside here, but here outside it is inflammable, right. So, you can see that lean side it is having a kind of things whereas, the rich if I look at this pressure you know, right here it is a, slope is little shallow it is little stepper here.

So of course, you know so, pressure has a significant effect on flammability limit, lean side is not affected significantly by pressure, right. Whereas, the rich limit becomes wider because, it is you know like if I go on doing that you know, I will be not changing. Suppose, I will go to another pressure whereas, here if I go over here, there is lot of more change. This change is higher so that means, you know rich limit is become much wider right than the lean side. And let us look at some data, which have taken methane air, stoichiometry is 9.5 and lower flammability limit, that is this side lean side or you can say you know, lean flammability limit, but generally lower flammability limit people talked about it 5 percent.

Upper flammability is 15 percent, what you can see is that you know, is a similar trend you can see for ethane air that is 5.6 and 2.8, 12.4 percent and propane air you can see 5.6 stoichiometry and l f l 2.1 and 9.1. If you look at these data's, can you observe something from the data's? For all hydrocarbon what I have shown, can you look at data and tell me what do you observe? Some trend you can get out of this, if you observe that the lower flammability limit is almost the half of the stoichiometric you know fuel, isn't it half a roughly. If it is 9.5 it is your now 4.7, 0.5 kind of things.

So, it is actually approximately 5, 5.6, 2.8 similarly, whereas, the rich limit is not really related. Of course, when you go for c o air is having a very wide flammability limit, but if you go for the hydrogen air, the flammability limit is quite wide you know as compared to hydro carbon, 4 percent of fuel and 74.2 percent of fuel under atmospheric condition, right. This is whatever data I have given at atmosphere therefore, whenever you are handling hydrogen one has to worry about it because, it having wider range of hellion from safety point of view.

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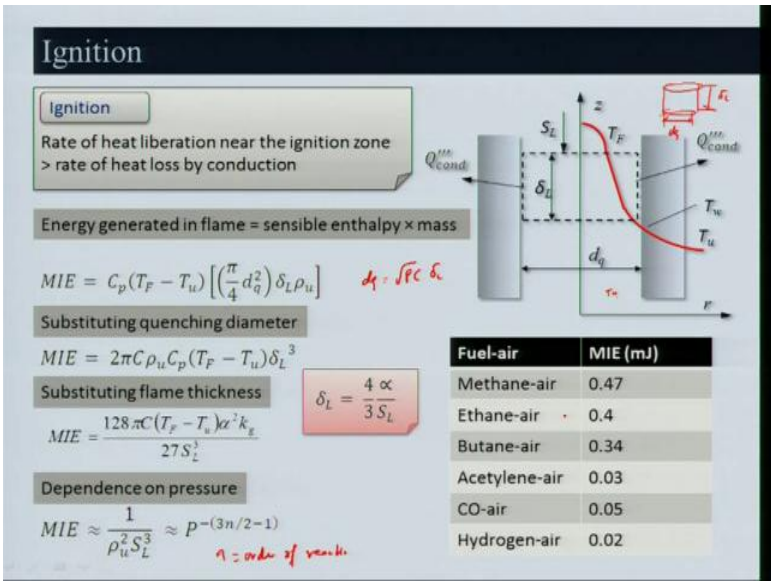

So, there is another concept, which I will be trying to look at today, that is the ignition, you know what do you mean by ignition? Ignition is the rate of heat liberation near the ignition zone, right, must be greater than the heat loss by the conduction. That means, if I am giving same amount of ignition energy, right and whatever you know heat being, it is going away and loss. Then, natural air my mixture cannot really reach a self-ignition temperature to have a combustion, right.

So therefore, one cannot have an ignition at all may be fuel air mixture there in the flammability limit, but I cannot have it. That means, I what will the minimum ignition energy one can think of? One can think of the energy generated in the flame you know like that means, the ignition energy must be you know is equal to, the whatever the heat loss or greater than you know heat loss by the conductor. So, now what we will do? We will have to look at energy generated in the flame in a, is equal to what? Sensible enthalpy into mass of it and for that what we will do? We will use the same idea, what we used for discussing about quenching diameter, we look at in between these diameter, the flame is there and which is travelling and having a thickness of delta l and it is the d q.

Of course, I need to have ignition energy beyond the quenching distance, right. If I will give more than that then, you know my flame will be can propagate, I can initiate ignition, right. So, let us look at we will be doing again some heat balance, how much heat being generated, how much heat being going away, such that I can have a sustain a flame for the ignition to occur. So, if you look at the energy generated in the flame we will be basically sensible enthalpy this c p t f minus t u. Because, I am assuming this the t f and the mixture which is coming basically t u you know like, if flame is travelling here the mixture will be here, which he is under t u, right.

So, t f minus t u c p pi by 4 d q square this is the you know into the delta l, as I told this is will be like a cylinder I am considering. So, pi by 4 d q and into l this is nothing but your delta l right and this is your d q. So, that volume you know how much it is into the density rho is there, rho into a volume it will give you mass and this amount of energy, it is nothing but your minimum ignition. This will has to be given so that, it can attain the flame temperature, once it attain flame temperature it will propagate there nothing more right. So, that is the minimum ignition energy. So, substituting the quenching diameter you know, I can talk about this you know substituting this value in the quenching diameter I can get 2 pi c rho u c p t f minus t u delta l q, right.

Because, this d q I can used those whatever I have used for this d q is nothing but root over h c d and delta l, right d q is equal to root over h c delta l that I have, we already put that values. And we know that delta l is nothing but 4 by 3 alpha s l so, you will get m i when you substitute these values alpha by s l q, you know t f minus t u k g. So, if you look at dependent on pressure, if I look at this expression I will find that alpha is nothing but k g by rho u c p and k g and c p you can say it is not changing with respect to the pressure. But however rho you will be using so, m i will be propositional to rho u square s l q and pressure 3 n by 2 minus 1, right.

So because, we have seen that s l is you know like n, n is order of reaction. So, if you find out that minimum ignition energy is dependent on the pressure. So, you can look at some of the things here, the minimum ignition energy methane air, these all stoichiometry mixtures, you can see some number it is in order of mille joules, right. And these are from the calculation one can get so, let us now little bit dwell on how it is dependent on the pressure.

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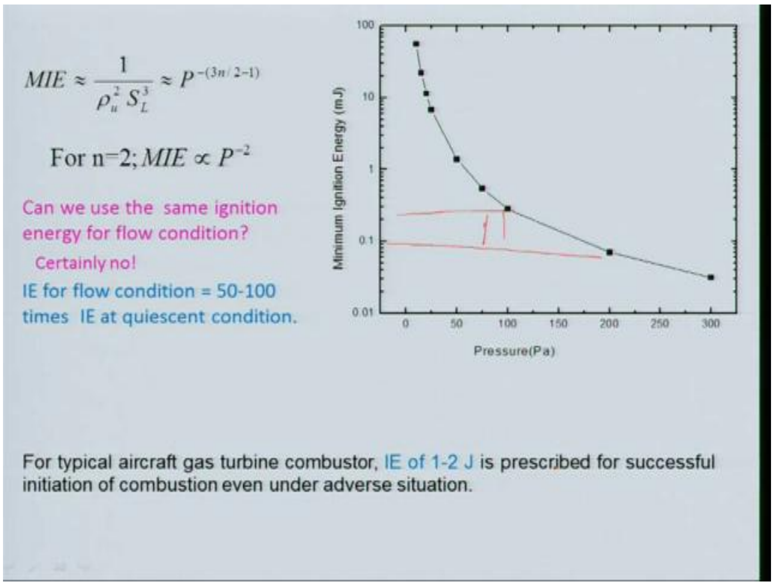

So, we have already seen that it is if order of reaction is 2, what is happening here? You know, it will be something 3 minus 1 it will be 2 kind of thing, right. So, if you look at the, if order of reaction is 2 minus propulsion to minus p 2, it is a very strong you know dependent on the pressure. So, if you look at if I plot this minimum ignition energy and plot here with respect to the pressure, you will find that if around 100 at pressure you know kind of thing. Some amount of energy is happening, but if the pressure decreases right what happens? That amount of ignition energy is very very high, but you of course, it is because it is going asymptotically you know or going vertically.

A slope is very higher right and of course, here if it is the higher pressure, if I go from 100 to the 200 there is much more differences. If you look at this difference is very very small right kind of thing. So, what you say can you used this same ignition energy for flow conditions? You know and that is the one question, but before that I want to ask you know we will be facing lot of problem in the gas turbine engine particularly, at the higher altitude where pressure is low. So, can we used this same ignition certainly no for the flow condition we need to use 50 to 100 times that of ignition energy in quiescent atmosphere.

Because, what happen like you know there is a flow condition heat loss will be there by convection, which you have not considered and quiescent atmosphere we do not consider, right. So, generally for the typical gas turbine combustor ignition energy 1 to 2 joules is prescribed for successful initiation of combustion, even under the adverse situation. So, if you look at we will be looking at some of the things, when we discuss amount gas turbine combustor kind of thing. Okay fine.

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