Fundamentals of Aerospace Propulsion
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Lecture - 24

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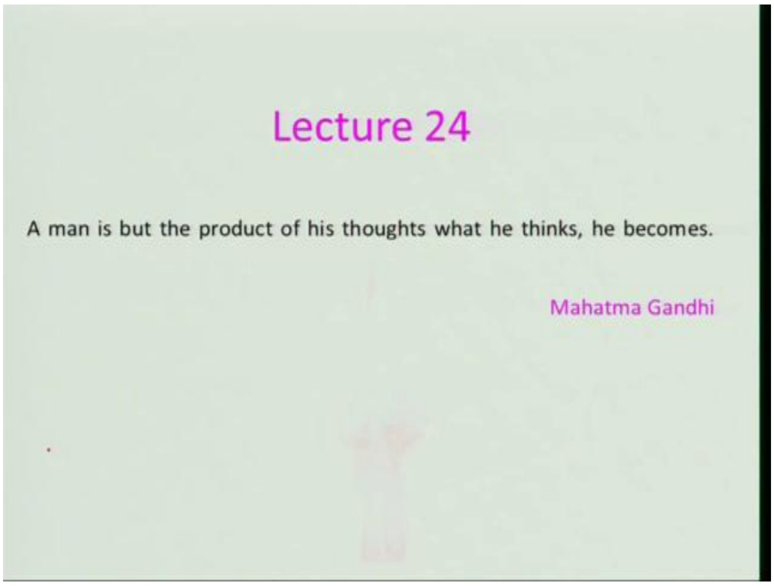

We will start this lecture 24 with a thought process from Mahatma Gandhi, was instrumental in giving us freedom and he says a man is, but the product of his thought what he thinks and what he becomes. How many of you believe this right? You please, mall about it and then we will may be discuss some other occasion, but let us now recall what we learnt in the last lecture or what we are trying to do last few lectures.

Basically, we are looking at premixed flame and which is quite important because, you can have a control over the, well a ratio at your disposal. And lot of phenomena will be associated with characteristics of the premixed flame, that is burning velocity. In the last lecture we discussed about flame thickness, we related flame thickness with the burning velocity that means flame thickness is inversely proportional to the burning velocity, right.

And then we moved into, about what you call quenching distance and of course, before that we discuss about flame extinction. What is the importance of flame extinction and quenching distance and quenching distance again we related to the flame thickness, to start with then, burning velocity, right because, flame thickness is related to burning velocity. And then I discuss about ignition energy, what is the minimum ignition energy once would give. Because that is very important, right particularly in aircraft applications when you are in higher altitude. What happens if there is a you know blow off, the flame is not there you want to ignite it or you are taking a, what you call a somersault you know fighter aircraft, right sometimes flame may extinguish, right.

Due to some reason, due to may be malfunction of a, air intake so that it is you know differentially coming, you know like velocity gradient or some other thing. Then how to ignite, if would not ignite you are sunk. It is not like in a, you are travelling on the road and otherwise if you do not ignite you leave the vehicle, but there you cannot leave the vehicle as it is right. So, if you remember that ignition energy will be proportional to the or will be dependent on the pressure, if the pressure of the combustion chamber is higher than the atmosphere or ambient or it is increasing, what will happen to the requirement of ignition energy? What will be?

It will be less or more as compared to the ambient condition, what it would be? It will be less, less amount of ignition energy is required if pressure is high, but if the pressure is low, you please look at your notes, right that you need to give more amount of ignition energy, right. And it is a you know one order of magnitude higher as a pressure increases because, it is going at a steeper rate as compared to the higher pressure, that means if it is, right. So, then it is very important and this discussion what we have done? We have done under ((Refer time: 4:01)) atmosphere, but when we give certain amount of flow which is more prevalent in a combustor like gas turbine combustor, rocket engines and other places then, we need to give more amount of energy.

Because, lot of heat will be going away due to conversion, right there will be radiation and other things, which we have not considered, those has to be considered. Therefore, in gas turbine engine we give much more than that of the minimum ignition energy. Minimum ignition energy order of mille joule, but we give in terms of joules, right. So, you should keep these numbers in mind, this is very important to have a feel where, what is going on. Beside this pressure, is it like this, minimum ignition energy or ignition will be dependent on any other things. Of course, it will be dependent on the fuel air ratio and fuel air type systems and also the temperature that is the un-burn gas or the whatever it is coming.

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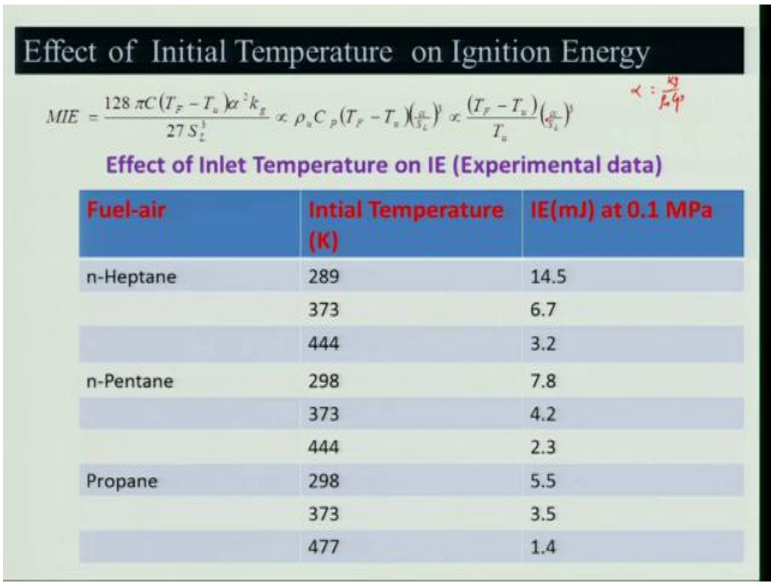

Fuel-air	Intial Temperature (K)	IE(mJ) at 0.1 MPa
n-Heptane	289	14.5
	373	6.7
	444	3.2
n-Pentane	298	7.8
	373	4.2
	444	2.3
Propane	298	5.5
	373	3.5
	477	1.4

So, now today we will be looking at effect of initial temperature on the ignition energy. If you look at, we are using the same expression what we have derived keep in mind that it is a very simplified one, but actual one if I want to derive minimum ignition energy expression then, I need to consider the unsteady one. We, here we have done considering the steady lot of approximation we have done, just to understand what is happening, right. But, however it can be used as a design tool when you are designing a combustion system, right. Because, it is quite simple you need not to go for a very highly couple non-linear equation to solve it, right, but if you need to look at really the intricate processes then one has to go for, but that it can be a research problem.

If you look at minimum ignition energy is basically proportional to the rho u, rho u here what the density of the un-burn mixture, in case of a premixed flame. And of course, the c p is specific heat and t f minus t u, right and it is proportional to alpha by s l q, this is a very higher you know, what you call dependence. Because, is 3 right, but if I take this an ideal gas you know because, most of the ignition what we really talk about is the gaseous phase. Of course, some of the ignition might be taking place in the liquid, particularly in hypergolic propel lance and other thing, which we will discuss little later on. That is not real ignition, it is the initiation reaction by itself or some catalyst or something which we are not considering most of the, you know ignition what we are discussing about in gaseous state.

So, if I use ideal gas law then rho u is proportional to what? Will be 1 over t u it is rho is proportional. So, if you remember that when we discuss about adiabatic temperature this t f minus t u will be for a particular fuel air system, for particular fuel air mixture will be dependent on what? It will be roughly increasing by the same amount by which t u will be increasing isn't it? That means t f minus t u will be increasing by the similar amount and so also the t u, if t u increase by what you call 300 kelvin, let us say 300 kelvin is there, it becomes 600 kelvin.

So, this change also whatever it will be happening, because of change in u will be also 300 kelvin roughly. So, therefore alpha by s l q is a more important, alpha if you look at what is alpha? Alpha is equal to basically k by k g by rho u c p, right, it is also temperature comes into picture. So, if you look at s l also is a function of temperature that means, it will be more towards this quantity what it would be. So, let us look at certain data how it is effect of inlet temperature on ignition energy, these are experimental data I have taken for three fuel air ratio, two fuel air system. And of course, this is that stoichiometry, right as you know that ignition energy will be depending on the equivalence ratio.

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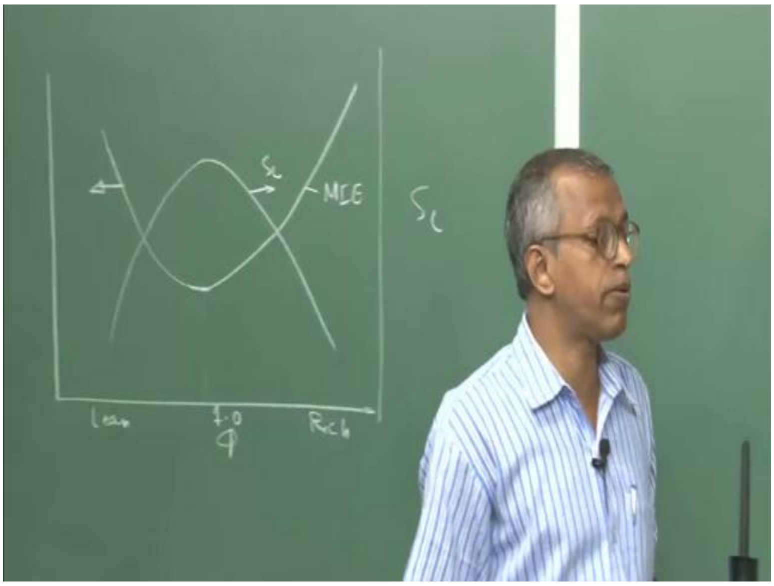

Stoichiometry, it will be minimum and as you go towards the, what as you go towards the lean mixture, this mixture ignition energy requirement will be higher. Because, losses will be higher right and burning velocity is lower, which is the first I told, losses will be higher. But then I told burning velocity, which is a right one in this? The correct statement would be the burning velocity is lower in the lean and rich mixtures, as you go from the stoichiometry, right.

So therefore, ignition energy requirement will be higher that means, what I am saying basically if I look at this ignition energy versus equivalence ratio per particular fuel air mixture and particular fuel air system. So, this will be minimum ignition energy if I say this is around 1 and this is the lean side lean means fuel lean and rich side. So, if you look at this will be, right that means, this is the minimum and it will goes on increasing depending upon how close it towards the limit mixtures, right. Lean limit and rich ingredient because, if you look at this is can be related to the burning velocity you by plot over here s l.

So, it will be you know kind of thing this is the s l and this is MIE, right. So, you should keep in mind, but here I am looking at the inlet temperature kind of things What you could see you could see that n heptane I have given some initial temperature in the next column, that is here 289, 373 and 444. If you look at this ignition energy for 298 it is 14.5, 6.7 and for 444 kelvin is 3.2 that is n heptane. Similarly, when I am saying n heptane is basically normal heptane, there may be iso heptane, right and n pentane I have given some data here 298, 373 the same temperature. But 7.8, 4.2, 2.3 it is also decreasing you know like this way, this is also decreasing with increasing temperature and so also propane here, it is also decreasing, right.

Apart from this, can you observe any other thing in this table data, I have talked about okay, with the increasing temperature it is decreasing. Because, s l will be increasing, right the ignition energy will be decreasing, it is expected from this relationship right. Or in if you do not want to feel very comfortable, burning velocity you can say reactivity will go on so that, you need you know, what you call less amount of ignition energy, right. But apart from that can you observe from this table and tell me this quality is very essential can anybody tell me?

Student: (Refer time: 12:26)

Yes, you are right that means why it is so?

Student: Octane number is less

One can talk about octane number, but other things one can talk about is that you know, there are several bonds has to be broken, you need to give more amount energy in a very simple way. So, this what I am saying when we looking at it observation power is very very important for not only in the science for other field as well. So, which we are not getting nowadays, which is a concern for the most of all educationists, right. So, now we will be looking at basically another concept which is very important, that is flame stabilisation. In other words how to stabilise a flame in a combustors and that is the, one of the greatest challenge for a combustion engineer, you know to contain the flame, like we contain the anger, right.

I always, whenever flame comes to my mind I always will talk about anger. The anger can be used for a positive way, so also the flame can be used in a positive manner like, running a what you call running a vehicle or flying air aircraft, making an engine you know like or an missile or a space craft like. Therefore, it is very important, but how to do that, what are the ways, what is the basic principle for that, first to stabilise a flame, what are the problems associated, right.

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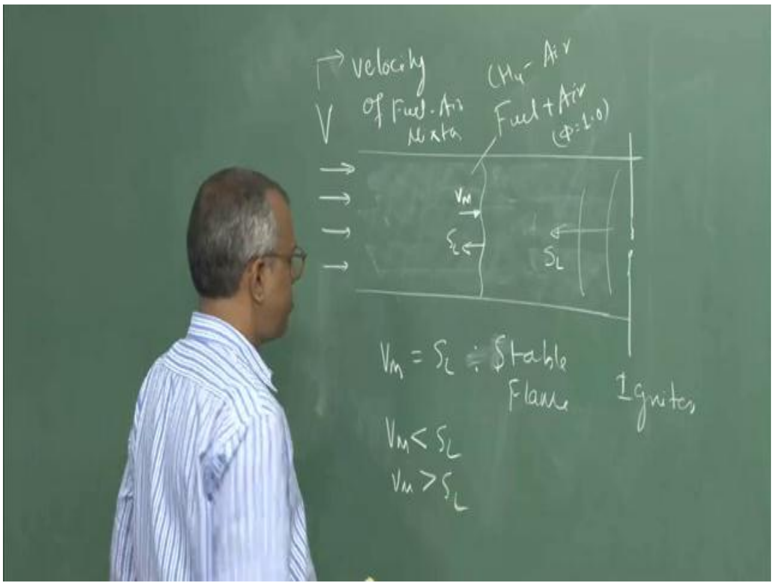

For example, if I take this a fuel air mixture in a tube and then I will ignite it. For example, if I take in a tube fuel air mixture, these are fuel air mixture which is mixed well. I mean like you know plus air mixture and I am igniting here and keep in mind that this is at phi is equal to 1, just for the sake of it and i will say that c h 4 air system, right.

Phi is equal to 1, fuel air mixtures are being mixed, I ignite it that means I am giving some ignition, ignitor, ignition energy what will happen? Flame definitely will be moving toward this, right. As long as the fuel air mixture, it will be go on moving of course, it would not move toward that because, there is no fuel air mixture.

Only air will be there, may be something might have diffused, but that is not good enough, right. Now I want to contain this flame, this a propagating flame if it will be propagating flame, I will be in deep trouble you know. But I want to make it stationary so, how I will do that? Yes.

Student: (Refer time: 15:43)

That means, I need to give this fuel air mixture from this, with a velocity something, I can say fuel air mixture, this is velocity of fuel air mixture. If I will give this v f and which will be same as that of l, s l is the burning velocity with which flame is moving then, what will happen? Flame will be stationery, right that flame can be you know stationery, I can say somewhere here let us say it will stationery, it is moving at s l, when v m is equal to the same. Of course, this is locally that means if I take this v m when v m here I am talking about local velocities, is equal to s l. Do not think this v m is same, I can say that this is v simply and v m locally, right. Then, stable flame and if it is there might be another situation v m less than s l and v m is greater than s l, right.

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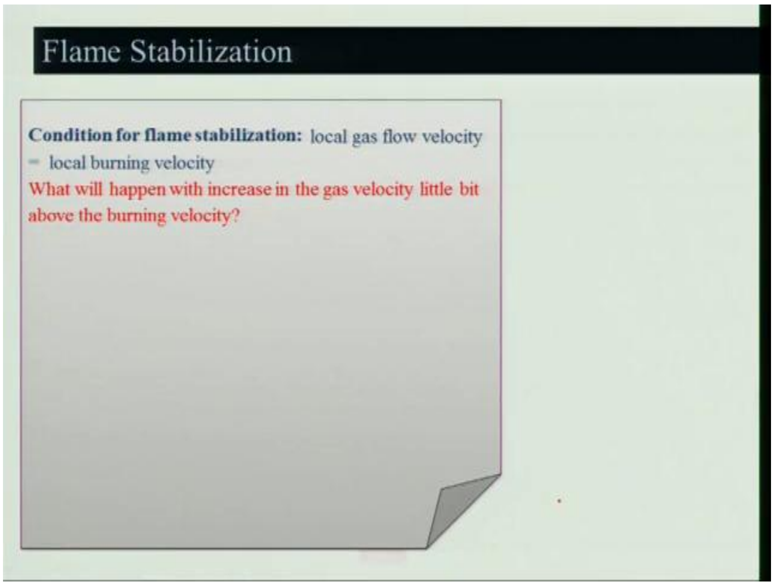

What will happen, right I have already told you that local flow velocity should be equal to the local burning velocity. This is very important, local point is very important, one is global other is local, right. Local means at that point, right of course, the shape of the flame need not to be as shown I, that is why drawn little undulation, right, just to say that it will be not flat although we have derived all those, you know burning velocity relationship for a one dimensional. But flame in nature it will need not to be one dimensional right, but when I am talking about locally, I can consider this as a one dimensional.

For example, if I consider this one and I can consider that as a one dimensional and manageable right, is it acceptable or not? But may be flame will be curve, but you need not when I am looking at like your earth surface is around. But when you look at on the surface it is just a flat, right or a similar way. So, what will happen when there is a increase in gas velocity, a little bit from the burning velocity?

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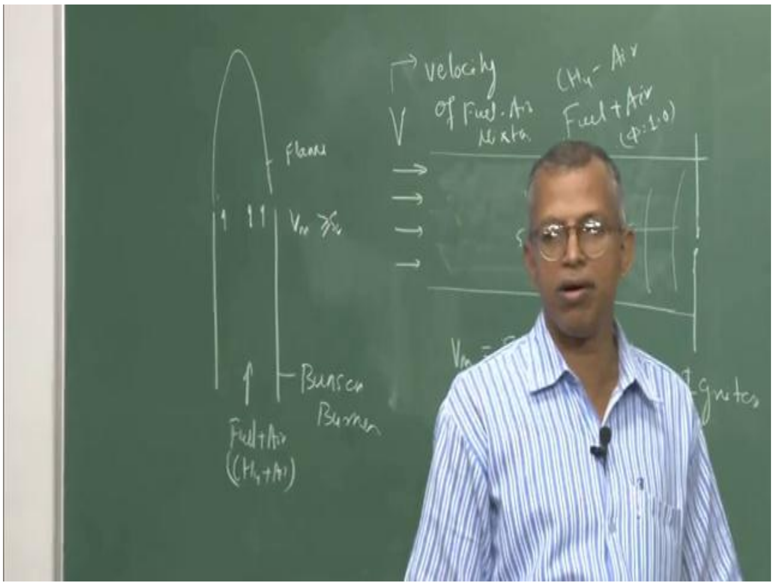

For example like I will take my what you call, I will take this Bunsen flame you know, this is my Bunsen burner, fuel plus air, for I am taking methane plus air mixture, right. And if this, there is a flame you know, there might be a situation where there is a flame here to start with, but when you this velocity mixture, you know like v m is greater than s l slightly, you know like greater than equal to you can say little bit, you know right.

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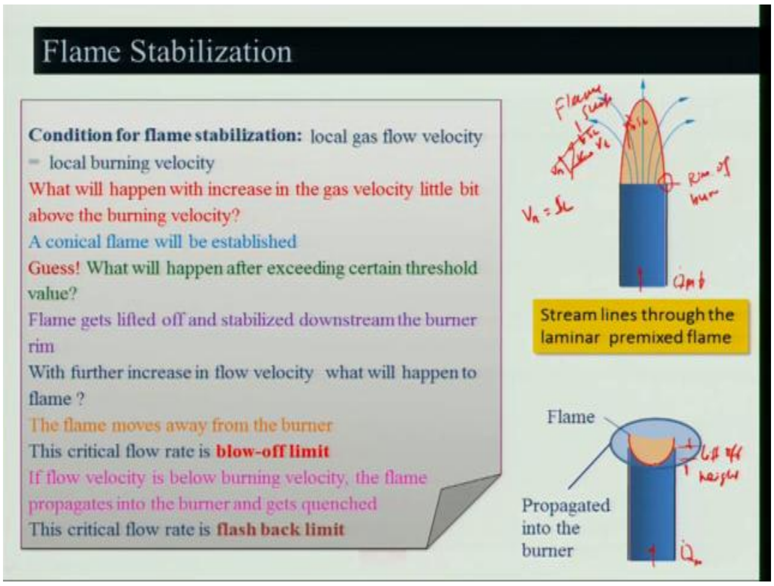

What will happen? A conical flame will be established, right a conical flame will be established. Because, the streamline to the lamp inner flame, you know which I have shown here and this will be moving, right, why it will be moving in this direction, why in the central line we are going straight? Because, after this there will be expansion and this surface of the flame is the curved one because, the locally if you look at, this is moving at a velocity s l and this will be moving you know, velocity this. So, when I am what you call locally when I look at it so, then if I resolve this component, what you call this is my flame surface. If I resolve this component over here, this is my v and this is my along with the flame surface, this is my flame surface v.

I can say tangential and this v normal and this flame current is moving with a velocity of s l. So, when v n is equal to v s l you know, then only the flame will stabilise at that point, I am talking about this place, right. That means, this v l tangential the velocity with respect to the flame surface, right would not be really affecting the stability of the flame, right. So, therefore, each place it will be different and then it will be go on locating wherever this surface is taking. So, this is a very important aspect we you must understand and why it is so. What will happen after you know like, if you go on increasing?

For example, if this flow rate or fuel air mixtures you know, I am increasing for the same diameter. If I am increasing then what will happen? It will be, velocity here it will be go as an increasing. So, when it is increasing then there might be a situation where the flame which is stabilised to the rim because, this is known as rim, rim of burner, right rim of burner. What is happening in this region, we will see little later on, there is a lot of things will be happening. One of course, I can say there will be heat loss because, the flame is connected to the solid surface here and there will be also radicals which will be, you know being lost at the surface, solid surface, right. Because of heat losses they will be quenching so, that will be affecting the flame.

And when it will go certain velocities what happens? The flame will be lifted up that means, it will be no longer stabilised at the surface, right and the flame will be lifted up that means, flame and this height you know is known as the lift of height. That means, flame has gone deep the, what you call, your burner rim and lifted and then as you goes on increasing, what will happen? It will be, If you go on increasing this flow rate here once it is lifted up, what will happen? Will further increase in flow velocity, what will happen to the flame? It is simple flame will again lifted a more lifted height will increase, goes on increasing right and then flame will go away and flame moves away from the burner, right.

When it will go away from the burner is known as blow off, flame has gone away that is the same thing with our life, right. When we do not have faith in our family relationship, we do not have faith in the heritage, what happen? We are lifted up, we feel independent, but we are not, we go away from that and we are lost in the process of life. This is very important point I am telling and this is similar to flame it is very natural, right. So therefore, it is very important to be have a faith in the heritage, in the relationship and the, what you call, spirituality that is very important. So, that is so also for the flame because, that is the nature which is has to be accepted.

So, otherwise you will be blow off and blow off means, it is not of much use you know, flame has gone out, what I will do, I do not want anything, you know. That is also another aspect which is, if the flow velocity you know will be or sorry, if it is the flow velocity is very very low, right and then, what will happen? Suppose, you started the flame here and you go on reducing this flow velocities, what will happen?

The flame will be trying to enter into it because, the flow velocity is very low and the burning velocity is very high. Then, it is known as the process the critical flow rate at which flame will be entering into the tube is known as flash back and that is also similar thing. If you stick to your, you know your heritage, culture and your family without thinking, without really finding out what are the flaws with them like, superstitious things then, you are also sunk. So, what is required is balance so also, the flame to stabilise you need a balance, you need understanding where it will be stabilised. So, therefore these are very important to know about flame stabilisation, I call instead of flame stabilisation, it is life stabilisation is more important, right in life.

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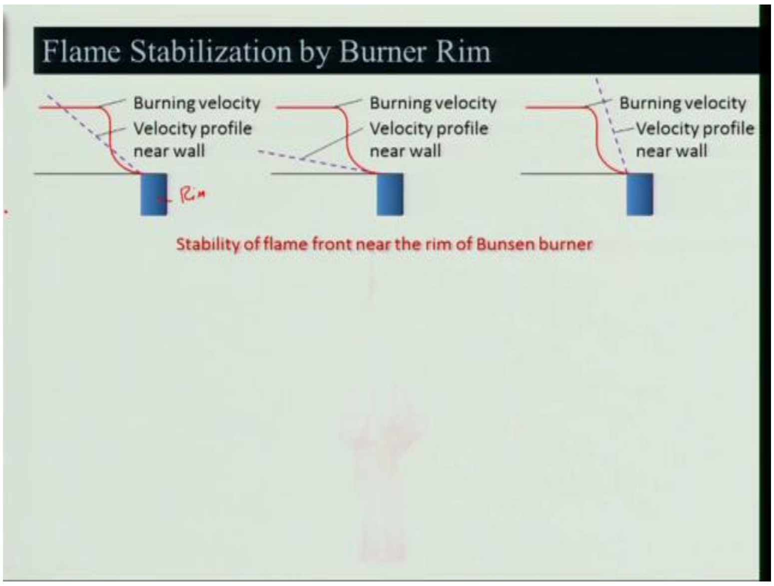

So, now let us dwell upon little bit further and say that this is the burner rim you know, this is the rim. You keep in mind that this one only, one portion of the rim I have drawn here that means, other side there will be also rim.

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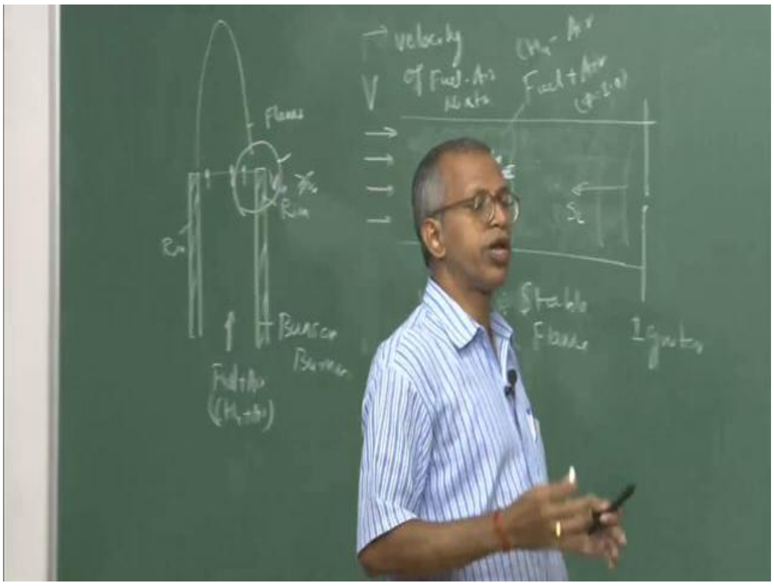

For example, if I take this you know this is my burner rim keep in mind, this is rim what I am taking, I am considering you know this portion and magnifying it, you know this portion and magnifying it and showing that, what is happening. I am considering two things here, one is the velocity profile you know dash line this near the wall, right and I am considering the burning velocity, which is the red colour I have shown here. Now in this case what is happening in this region is a more important, the burning velocity is what you call, this is lower, smaller as compared to the burning, what you call velocity profile and at this point it is just matching well.

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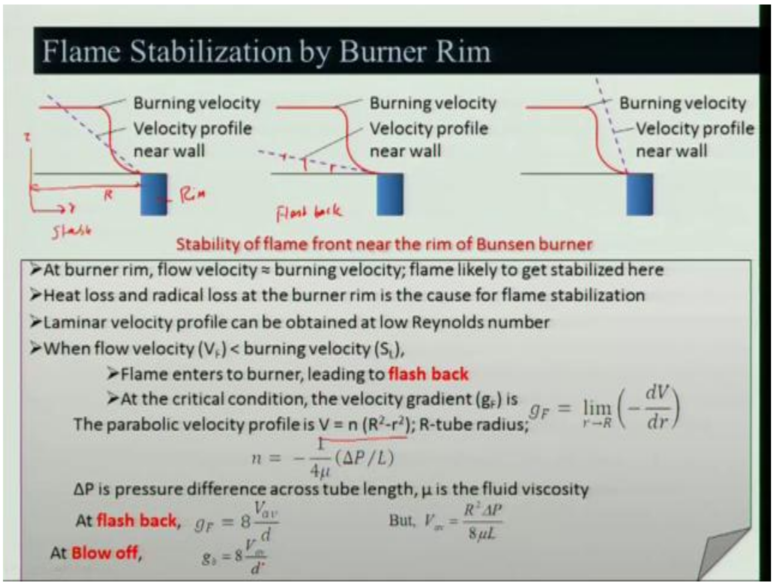

So, this will be quite stable of course, other region it is sometimes crossing it is fine, but we are interested in region this stable one. That means, at the burner rim flow velocity is almost equal to the burning velocity right and flame is likely stabilised here and also as I told earlier heat loss, radical losses at burning rim is the cause of the flame stabilisation. But in this case it is good enough to maintain the flame and what, why it is, what we are doing at? Because, we are looking at basically the gradient that means, how this you know what you call this velocity profile gradient along with direction. If I look at this is my r, this is my z so, how it is changing with respect to r, that velocity we need to look at.

Laminar of course, we are considering laminar velocity, it can be obtained at low Reynolds number, this all whatever we are considering laminar burning velocity, right that is very important concept. But in real situation it would not be, it will be problem, but similar argument can be given, when flow velocity reaps is less than the burning velocity that is s l then, flame will enter into the burner leading to the flash back. And flash back is very very dangerous, why? Because, it may lead to explosion because, fuel air mixture is there, right and it is inside, if it is close or something is happening you know it will be dangerous it must be avoided.

So, then when this condition will be, how we will know that whether it is? For example, here if you look at the v f, this is the v f velocity profile if you look at, these are velocity profile right and v f is less than the burning velocity. So, therefore this is basically flash back, but how will characterise in real situation, particularly in the lamp inner floatism. Then, we need to look at gradient right because, we are comparing which is the higher. So, for that we are considering the gradient so, at the critical condition, the velocity gradient g f will be d v by d r and r tending towards r.

If you look at this is basically r, if I have taken this as a central line right then, it will be the r tending towards r, that is the velocity gradient we are talking about. Now if I consider the velocity profile, you know to be parabolic, when it will be parabolic in nature? When it is fully developed flow in a pipe or in a channel right, fully developed means where both the boundary layer you know, thickness will be merged from the, all the side, right. And then of course, we know that this velocity like profile will be equal to n capital R square minus small r square, r can be anything right, are you getting my point right?

Because this r is the radius of the tube and r is the, your r theta z co you know coordinate system, r will be varied from 0 at the centre to the capital r. And this relationship could you remember, could you recall what it is, from where we got this relationship, this relationship? It is from your paisley flow, right and what is this n? n will be equal to minus 1 over 4 mu delta p by l, where l is the length you know of the pipe where it will be kind of thing fully developed. And delta p is the pressure gradient and mu is the fluid viscosity, if I will now you know, put these values here and gradient I will find out at the flash back g f is equal to 8 v average by d, what is v average? v average is basically r square delta p by 8 mu l, right.

So, and these all we are doing because, why I consider laminar because, the paisley fuel equation is there, it is easier for us to carry out this gradient and talk about it. But in turbulent you need to you know find out way, means not that easy, that is why I have used laminar. And blow off velocity h g is equal to 8 v average by d, keep in mind that this gradient velocity gradient in case of flash back will be low or high as compared to blow off, it will be quite low in case of flash back as compared to blow off. That means, at a higher velocity flow rate, the flame will blow out, but at a smaller flow rate or the velocity of the mixtures, the flash back will occur.

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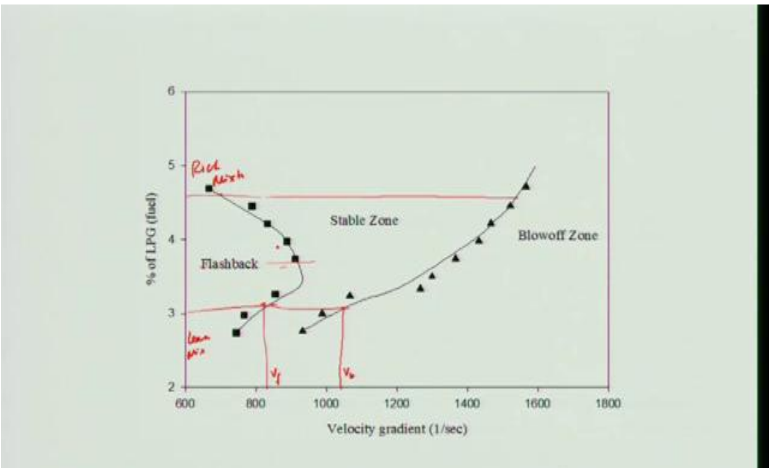

Region of stable zone of LPG-air premixed flames in terms of velocity gradient for 15 mm burner diameter [20].

So, how it is occurring we will be looking at, I have taken a percentage of fuel in the y axis and x axis, I have taken velocity gradient 1 hour second. If you look at this d v by d r and you know meter per second it be can just 1 hour in 1 hour second or second in watts. So, what you could see? You could see that there is a region, three region in this one is flash back, other is stable region and this is the blow off. That means, if I take a what you call particular, let us say three percentage of l p g that means, rest of the will be air, right. If I take this, at this gradient you know flash back will occur that means flame will be moving into the fuel at this point if it is lower than, but if it is beyond that this point then, what will happen? It will be stable.

Similarly if I will go for this, it will be at a very higher this is your, what you call v b and this is your v flash back, right. The gradient is more in case of blow off and in case of and very interesting in this, this is what will be lean region, am I right? Less amount of fuel so, this will be lean mixture, this will be rich mix, mixture and in the rich mixture the operating condition is very high. That means, between the flash back and between the blow off, it is quite higher range. So, therefore, but there of course, the some other problem will be happening that you know emissions and other thing.

So, people look at around you know like stoichiometry kind of things maybe, somewhere here it will be stoichiometry, you know somewhere here stoichiometry people and always we look at that point, but there is a problem. So, if you look at in the premixed combustion kind of thing today now a days it is coming up gas turbine, people always tried to work on the lean side. But when you look at work on the lean side from the emission and from the energy utilisation point of view, you will be in deep trouble of the flame instability, which I may not discuss, but that is a very important point.

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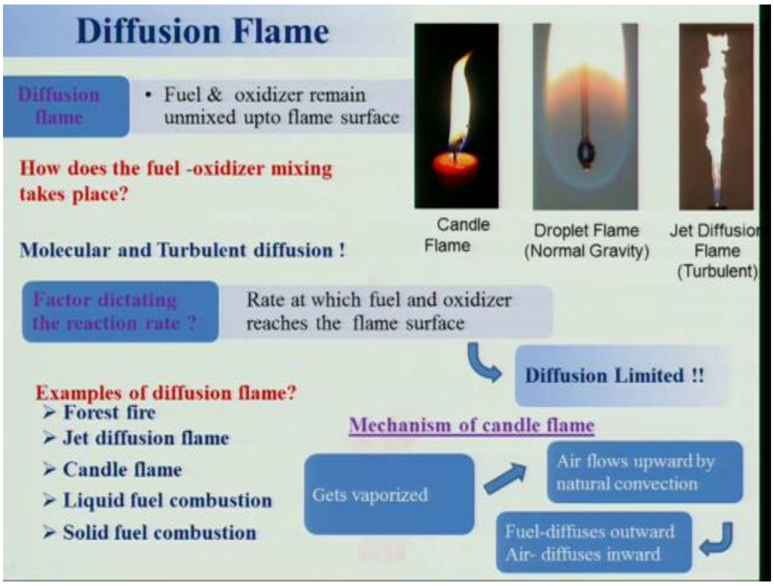

Now we will move into the, another class of flame, which is more prevalent in the case of a both gas turbine combustor and the rocket engines is the diffusion flame. As shown three examples of here, one of course you are very much aware is a candle flame. Another I have talked, shown here is a droplet flame and there is a jet diffusion, that you just, this is a burner and where you just you know push certain amount of fuel and you get a flame which is known as a jet diffusion flame, right. These are all diffusion flame, how this diffusion flame is different than the premixed flame, how, is it different or same how?

Student: At the time of combustion only fuel and air are not mixed.

Here in this case, fuel and air are not mixed before the combustion take place and however, you know in this case whereas, the fuel in the case of diffusion of fuel and oxidiser diffuse. And as soon as diffuse and mixed together the reaction will take place and combustion will occur. Therefore, this is known as diffusion flame and so, in this case the molecular and turbulent diffusion will be taking place, not only the molecular but, also the turbulent diffusions and that depends upon, whether it is a laminar or turbulent you know flame.

For example, this show looks to be a turbulent flame you know because, lot of undulation is there in the flame and it is not very smooth. So, we can consider, but whereas, here this will be a kind of a, you know droplet combustions and keep in mind that this is under normal gravity. Normal gravity means, gravity is present if there then what will be flame shape, flame shape will be like this what is coming as this. Of course, there is a blue region, there is a yellow region all those things and there is a candle flame you know like which shows a very nice, if you look at although it is shape is not you know little bit change in shape.

But it is quite smooth as compared to the jet diffusion flame this, there is a corrugated shape kind of things here. Whereas, it is a very smooth so, one can consider to be laminar, but when you really use your high speed camera and look at it, it need not to be laminar as it looks to be in naked eyes, right and sometimes of course, it will be oscillating okay. So, you know lot of some people have studied that you know, they found it is in transition region. So, what are the factors that dictate the reaction rate in this case of flame? In case of premixed flame what is the factor dictates so, for the you know reaction is concerned, it is the driven by kinetics, premixed flame is controlled by kinetics.

Therefore, we are defining a term or we are using a term that can characterise premixed flame is the laminar bonding velocity. If you recall or you can look at you note, you will find the burning velocity is basically dependant on the reaction rate that means reaction rate term will be there, right. And in this case, diffusion flame it is the kinetics is very fast, very very fast therefore, it is really not dependant on the kinetics. Because, as soon as fuel air mixture mixed together then reaction will take, that means which time is governing the flame to occur? It is the diffusion time. So, therefore this is known as the rate at which fuel and oxygen reaches the flame surface will be governing the, what will be the reaction rate and therefore, it is known as diffusion control or diffusion limited flame.

Let me repeat, the premixed flame is kinetically controlled and diffusion flame is diffusion controlled, right. Because, here reaction rate is quite so, what are the examples of diffusion flame I have already shown you, but in the practical situation what it would be? You know like forest fire is one example, natural you know that is the diffusion flame and of course, jet diffusion flame is a man made, but we do use it right in our several applications right. And jet diffusion flame or jet flame rather can be also premixed, where you use jet premixed flame, where, do you use really, in your day to day life?

No, what happens to your burner in your cooking stove, those are also multi jet you know flame. And in your welding, when you weld gas welding what you do? You also premix right or use a diffusion one. So, there is a candle flame and liquid fuel combustions or the basically combustors and solid fuel combustors, you know combustion like there we do use the, what you call diffusion flame, right. So, what we will be talking about, we will be basically interested in the liquid fuel combustions and solid fuel combustion I will be talking about, when we will be discussing about rocket engines and other parts of it.

Now we will be concentrate on liquid fuel combustions right, but before just you know get into that, I want to ask because, candle flame we have observed, we have seen from our birth right, from our childhood, how does really combustion is taking place? What are the processes are involved, can anybody tell me? Because you have observed, you have seen, you know like, when you observe something you learn a lot than that of reading a book or attending lecture, right. Observation is one of the important tool for learning anything as a matter of fact. Of course, I strongly believe that, what did you observe till now? Let me ask you few question as you are not answering anything, right.

For example, how this, how this fuel is going up, there is a wig right in this portion there is a wig that means, why wig is there, can I not burn just like that?

Student: (Refer time: 42:31)

Capillary action that means this wig is there and it is driving, right and how it is doing in capillary, can I take the gas? I cannot take gas, it is a liquid which will be going that means, liquid will be going through the capillary. For example, you have gone on a vacation so, mechanism let us look at what is the mechanism of candle flame and as I told you that, melted wax flows upward by capillary action like this you know you might have used this technique you know for keeping a plant, as I was telling you. Suppose you are on leave or you are having a pot in which you have placed a plant, how you will do that, you can use the capillary action right, which is a slow process, but it can keep your plant alive, right.

Similarly, you can use this concept in the life as well I do not want to dwell on it, right and gets vaporised, this liquid get vaporised because of what? Because there is a flame around it and of course, you need to initiate the flame then only, right or you put a naked flame like a from match stick and then, it will get vaporised. Once it gets vaporised then, it will be moving because the diffusion will be taking place, right and there is a temperature. So, air flows upward in natural convection because of hot which will be moving, right and when it moves and mixed together, whenever it will be mixed and the temperature being higher, the reaction will take place.

And you will get you know like a combustion, what I am saying in this case fuel and air diffuses outward and then, mixed and whenever they mix, you know combustion take place and you will get a shape of the flame. And if I put some kind of a probe inside what really is happening, is it a rim flame inside the flame? Suppose, I will put a tube in this candle flame, you can conduct an experiment yourself and see what you are getting, right I do not want to dwell upon it.

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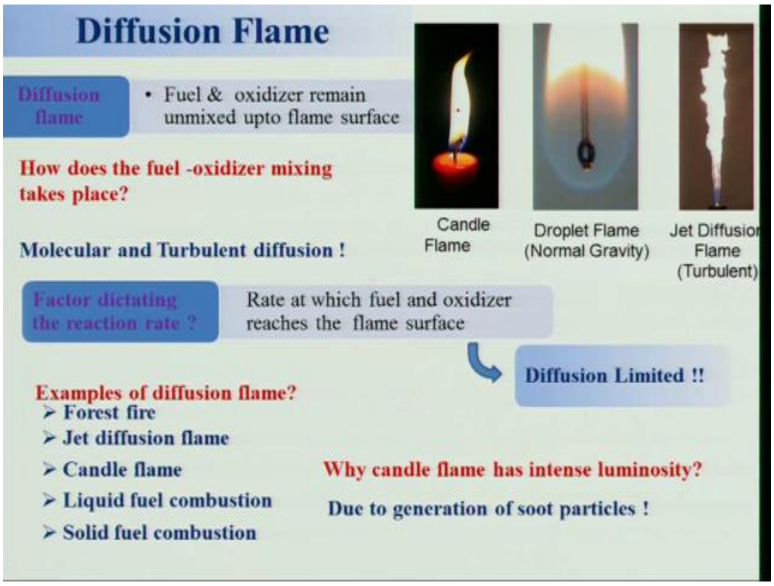

So, that another question comes from mind, why candle flame has intense luminosity? There is a yellow you know of course, small portion is blue, but it is a yellow colour, answer is very simple because, it will be having lot of soot particles and that gives you know this things. So, if you look at it is not really good for health as soot is you know not good for health, but we are using it for time memorial.

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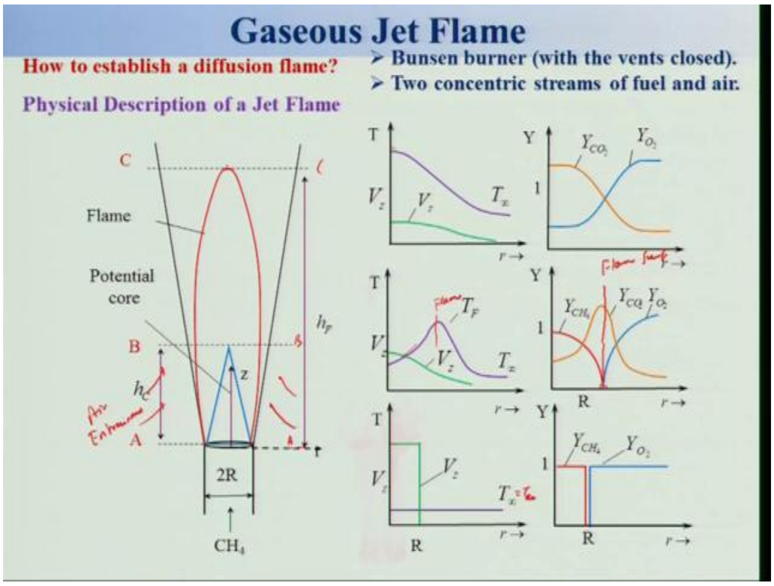

So and how to establish a diffusion flame or a rather a jet diffusion flame, which is a very simple like, we can use a Bunsen burner with a vented cloths. You remember that there is a vent in the Bunsen, if we close it become a diffusion flame or two concentric streams of fuel and air or a simple jet you take a tube like this and put some mixtures, sorry some fuel only. And even ambient atmosphere air is there, it will burn like so, you can get that kind of thing that has several way and we will be looking at a physical description of a simple jet flame.

If you look at methane is in there, in this tube it can be piped, it can be also a 2 d right and if you look at, if you look at this jet kind of thing, we you know this potential core and in which the velocity at the inlet it would not be changing. You know that like, for example if I take a cross section at this, this place right, there is a dash line, if you look at the velocity is v z, in this case v z and till this r and when r is capital R beyond it will be 0, ambient you know. And of course, the temperature is uniform in this because, the same as that of the ambient, the t infinitive is same as that of ambient. Now, of course it will be there will be mixing zone and this zone, which I have shown here in the line is a mixing zone and when the fuel air mix together and there will be combustion and the flame will be occurring.

And this height from a to the b cross section a, a and you know cross section and b, b and c, a to b this we call it as a core height and this h f we call it as a flame height, right. And if we look at this flame height because, where here the flame tip and come here to end, it please note that the flame height is an important parameter for a jet diffusion flame, right. And if I take a cross section at the b what is happening to the velocity? Velocity along with the odd direction, keep in mind that this is the jet direction along the central line of this tube and the flame and also r in the radial direction. And the velocity will be maximum at the r is equal to 0 and it goes on reducing, why it is so?

Because of mixing, there will be entrainment of air, there will be some air entrainment which will be taking place, you know air entrainment. As a result, what will happen? Of course, in this suppose I will plot over between a, a and b, b what it would be, as the time is not there I am not going to discuss. But please plot and you know see yourself you are having doubt what will happen to velocity, what will happen temperature? But what I am doing at the end of the provincial core I have plotted. So, there will be little bit, you know reduction or almost similar to the central line velocities, right and the temperature if I look at here is a flame here.

So, the temperature is very low in this case of course, this is higher than this ambient temperature then, it goes up and it became fixed at the flame. Because, this is my flame surface you know, right and then it recedes because of you know heat transfer and when I will go over here, I will get a highest temperature over at the central line. Because, there is no flame here so, this will be decreasing and whereas, the velocity as decreased from the previous case because, more entrainment is taking place. If more entrainment average velocity will be dropped down, it will be spreading, but let us look at the methane air, what happens?

This methane air, it will be methane all the places in this region and whereas, the oxidiser here and it is meeting at r and if you look at oxygen is a maximum in the, when r is equal to infinity or far away. And at the flame surface, this is your flame surface you know and oxy again and the methane, mass fraction also becomes 0 here at this region maximum at 1. And if you look at this c, you will get the what you call product c o 2 product will be here and because the flame is already burnt and of course, this is the oxidiser, will be oxidiser, will be minimum over here. Because, almost all it is burnt and maximum at the infinity.

So, keep in mind that when this fuel and oxidiser you know are meeting at a point and then reaction take place this diffusion flame and diffusion approximation that means, it is not crossing each other. I can have cross over each and when it is not crossing, we call it as a thin flame that means, flame thickness is very very infinitely small. So, with this I will stopover, in the next class we will try to look at, look at this phenomenon of the jet flame and derive the relationship for the flame length. Then, I will be moving into the droplet combustion.