Fundamentals of Combustion (Part 2)
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Lecture - 55
Flammability Limits and Flame Stabilization

Let us start this lecture with thought process.

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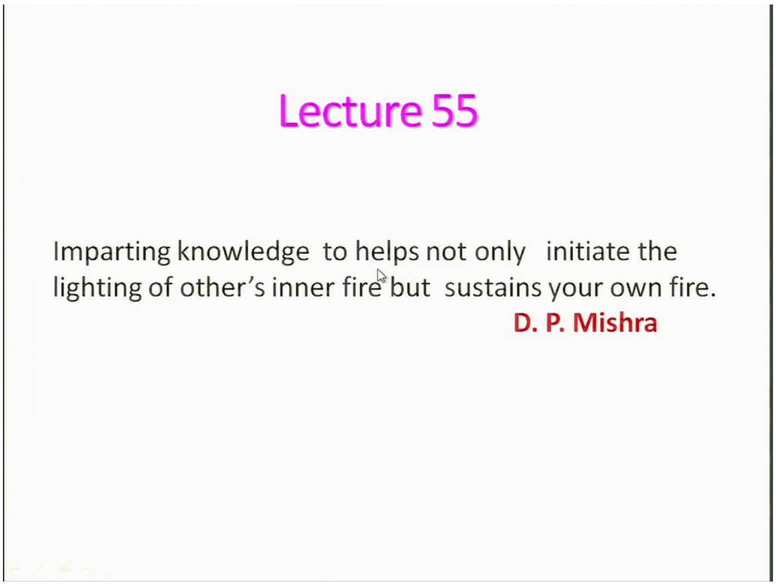

Lecture 55

Imparting knowledge to helps not only initiate the lighting of other's inner fire but sustains your own fire.

D. P. Mishra

Imparting knowledge to others helps not only the initiate the lighting of others inner fire but sustains your own fire. So, in the last lecture we basically looked at quenching diameter and quenching distance and also derive relationship for a quenching diameter, and try to relate to the both the flame thickness and the laminar burning velocity.

And today we will be looking at the flammability limits.

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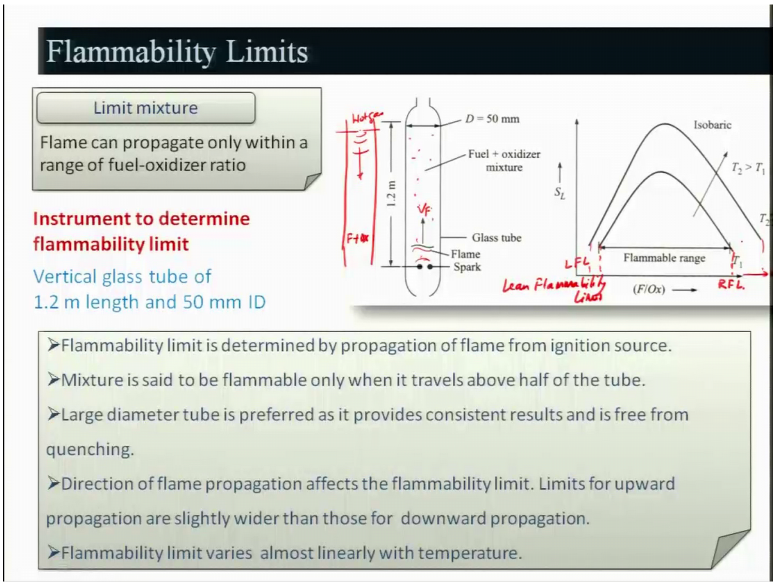

Flammability Limits

Limit mixture

Flame can propagate only within a range of fuel-oxidizer ratio

Instrument to determine flammability limit

Vertical glass tube of 1.2 m length and 50 mm ID

- Flammability limit is determined by propagation of flame from ignition source.
- Mixture is said to be flammable only when it travels above half of the tube.
- Large diameter tube is preferred as it provides consistent results and is free from quenching.
- Direction of flame propagation affects the flammability limit. Limits for upward propagation are slightly wider than those for downward propagation.
- Flammability limit varies almost linearly with temperature.

As I had told you, that there will be some limit mixtures in which beyond which the flame can propagate. In other words, this is a limit mixture within which flame can propagate for a certain range of fuel oxidizer ratio, right.

So, how to determine the flammability limit experimentally is a very important question. So, generally what happened that people use the vertical glass tube of 1.2-meter length and 15 mm of ID. Why they have gone for 50 mm of course, this is the American standard what people use across the globe. And because of fact that if we use a smaller diameter. What will happen? There will be some heat losses, right. If the heat losses are a considerable, then you will not get the right properties related to flammability limits, right.

So, that is the reason why it is being used 50 mm where so that you do not have that problem of heat losses right. And 1.2meter length being so, what is being done; you feel this tube which is must be transparent tube, right. Or if it is not transparent, then one has to put a sensor so that you can look at the flame it will be mixed with the certain proportion of fuel and oxidizer. So, these are being mixed first right.

Then what will happen? You ignite the flame at the bottom then there will be kernel which will be moving right the flame will be moving with certain velocity of V F. And it will be passing through and then keep in mind that there will be because the hot gases will be on the where bottom, right because it is coming from here. So, it is bottom it will be trying to expanding and moving. But if it is the top, then anyway it will be going it will not be affecting your flame, right.

So, this if it will travel at least half of the distance; the flame for a particular mixtures, then we call it flammable. If it will not travel much, but it will be initiated on the ignition and it will extinguish, then we call it as a basically limit mixture. That means, it has reach the limit beyond that you cannot early make the flame to propagate. And keep in mind that, the ignition source right or ignition energy must be good enough. Suppose, you are not ignite giving enough energy, then it is not igniting, you cannot call it as a flammability limit.

The flame has to be established and it has to you known it may not propagate, but it has to be established fully right. So, that is very important of course, the similar the ignition limit is also there right. So, mixer is said to be flammable only when it travels half of the tube 1.2meter; that means, 0.6 meter it should travel at least.

But also there is some other apparatus which is being used nowadays that is the chamber combustion bump and other thing, but this is a standard one which is being used throughout the globe. And the large diameter tube is preferred as it provide consistent results is free from the quenching, right that I have already discussed.

And direction of flame proposition affects the flammability limit. Because of fact that this is a being it is subjected to the buoyancy effect, right. Because the hot gases will be trying to go up that will be accelerating there will be expansion. But in the case, if it is let us say there is a tube here, and you are igniting the mixtures right here. This is a fuel plus oxidizer then (Refer Time: 05:10) what will happen flame will be traveling toward this? Direction this is the downward propagation of flame. And in that case what will happen? The hot gases, these are the hot gases, right which will be going up it will not be affecting the flame propagation.

So, therefore, that is why the limit for upward a propagation are slightly wider than those of the downward direction propagation, that you will have to keep in mind. And beside this if we look at this, one like at the temperature effect for example, T 1 is here. These are the lean flammability limit, right. This lean flammability limit and this is let us say, this is your rich flammability limit. And between this lean flammability limit and rich flammability limit, this will be flammable; that means, flame can propagate and flame you can establish flame.

Beyond these things, beyond this LFL and RFL, that is rich flammability, you cannot really establish the flame whatever the amount of initial ignition energy you need, right. And when you increase the temperature of the mixtures, right like, what will happen? There is a change in the lean flammability; both the lean flammability limit and rich flammability. In other words, it is as broad and myths, are broadened with increasing temperature because of fact that the laminar burning velocity will be increasing right.

But if you look at the pressure effect what will happen? If the pressure effect is to reduce the laminar burning velocity, naturally the flammability limit will be narrowed down. It is will not be broadened like the temperature that you should keep in mind. And as I told the flammable limits varies almost linearly with the temperature.

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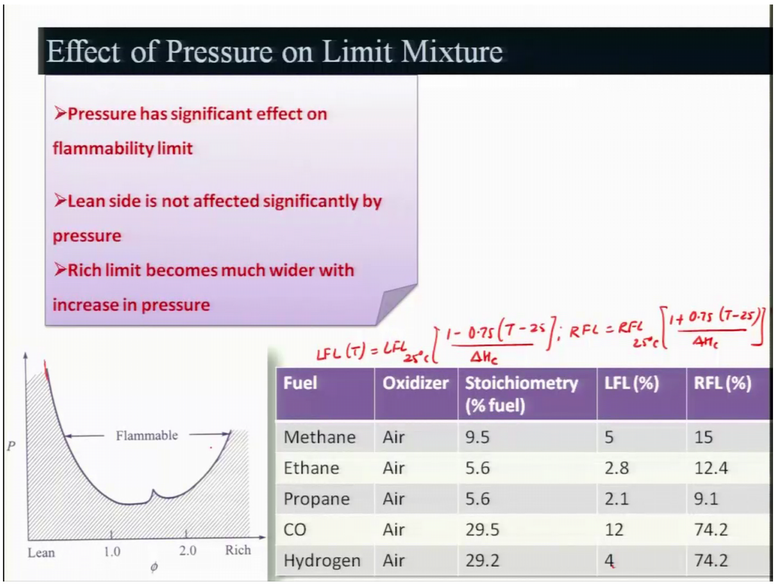

Effect of Pressure on Limit Mixture

- ➢Pressure has significant effect on flammability limit
- ➢Lean side is not affected significantly by pressure
- ➢Rich limit becomes much wider with increase in pressure

$$LFL(T) = LFL_{25^\circ C}\left[1 - \frac{0.75(T-25)}{\Delta H_c}\right];\ RFL = RFL_{25^\circ C}\left[1 + \frac{0.75(T-25)}{\Delta H_c}\right]$$

Fuel	Oxidizer	Stoichiometry (% fuel)	LFL (%)	RFL (%)
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

And let us look at some of the data's right the fuel oxidizer this is a stoichiometry. This is the methane air and stoichiometry 9.5 percent. The lean flammability limit is 5, and rich flammability limit is 15 that is a percentage by volume, right. And whereas, the stoichiometry percent of fuel is 9.5, right. And ethane if you look at it is little narrowed down as compared to the methane. And if you go to the propane it is also being narrowed down.

And CO air it is a wide enough; like, hydrogen air also very wider range, the flame the hydrogen air and the carbon monoxide having a wider range of flammability limit. That means, it can be flame can be established between this 2 range. So, therefore, one has to be very careful in handling the hydrogen and also CO. Particularly, hydrogen one has to an because little bit fuel being leaked out of the cylinder, it will mixed with air then it will be flammable right.

So, if you look at that way, one can give a relationship because, some people have given how estimate this flammability limit lean flammability limit. Lean flammability limit one can find out at as I told in the last lecture, it will be depend on the temperature right. So, that temperature you can look at LFL l at 25 degree Celsius is 1 minus 0.75. This is at T, this T will be at basically 25 degree Celsius, minus 25, and divided by delta H c. Delta H c is your heat of combustion right.

And this is RFL will be similar; RFL and these are semi empirical results right and RFL at 25 degree Celsius, 1 plus 0.75 T minus 25. Keep in mind that this will be delta H c, right. This is being used basically within certain range of the things.

And let us look at effect of pressure on the limit mixtures right. So, if we look at the pressure is given here, pressure plotted was the different. And this is for generalized I will be showing for the methane. And you can see that in the lean side, there will be not much change, you know, the slope is almost you know negligibly small here. But whereas, the rich side there is a much change in the play equivalence ratio, right with the change in pressure right.

So,that means, pressure has significant effect on the flammability limit. But lean side is not a fact that significantly by the pressure. And reach limit becomes much wider with increase in pressure.

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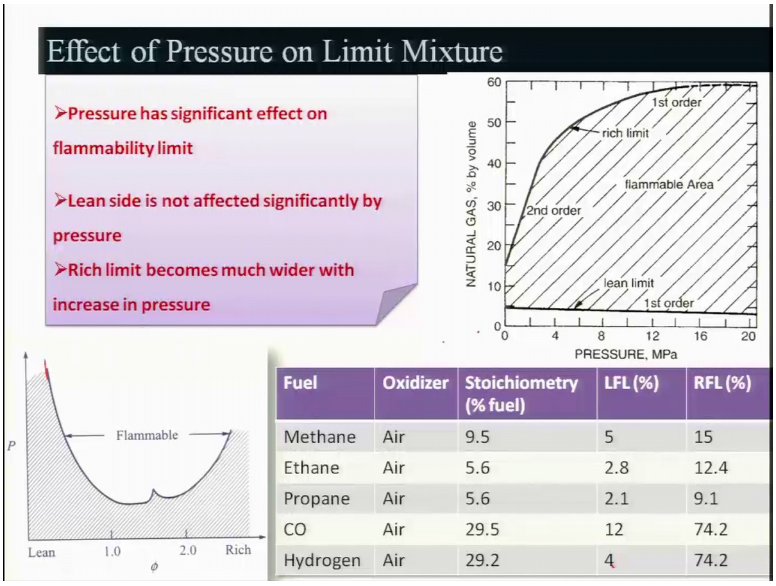

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And let us look at natural gas.

Student: (Refer Time: 11:18)

Yes, this is a general it is not data is not given this is a general trend, right. What people are saying particularly for a hydrocarbon air, right? This is hydrocarbon air mixture, hydrogen and CO the other fuel or not. But here it is given natural, if we can look at this is the lean side, right is being plotted at a different pressure the data, right. If you look at this is the almost remaining constant, it is not constant, it is changing, but very, very small change.

And because of fact what people are saying it is affected by the first order chemical kinetics right. The order of reaction is faster first order reaction. Whereas, here this is a rich limit, rich limit is affected by the second order reaction. And of course, when here the pressure is increasing that become a faster. So, it is remaining constant this range you know kind of thing.

And keep in mind that the flammability limit is governed by the kinetics right. Unlike, in stoichiometric other like these is governed by the kinetics. And we will be looking at basically how to handle the mixture of gases. For example, you are having methane, you know the lean flammability limit and reach flammability limit.

And let us say propane you know now if there is a mixture of gases, fuel right. And also air and this is data is experimentally data is there. You need to find out what will be the lean flammability limit or the rich flammability limit. So, by that actually one person has given, you know, relationship this is known as Le Chetelier rule, right which will be using for that.

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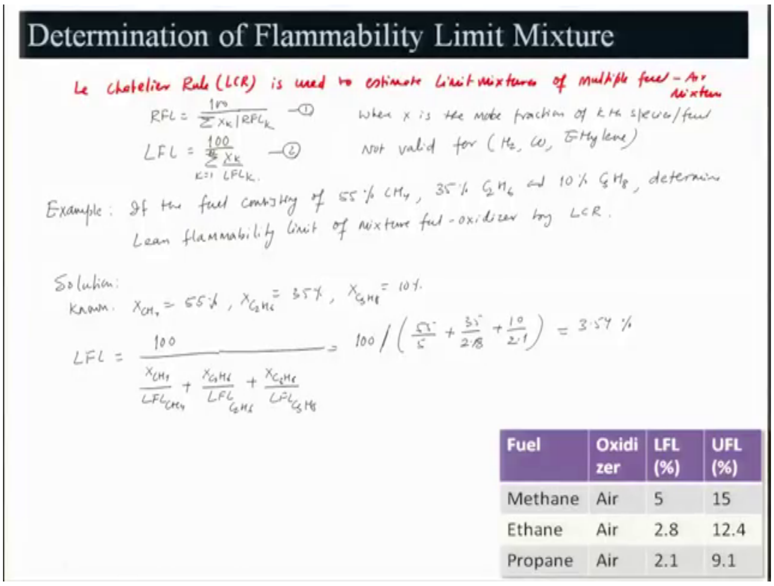

Determination of Flammability Limit Mixture

Le Chatelier Rule (LCR) is used to estimate Limit mixtures of multiple fuel - Air Mixture

$RFL = \frac{100}{\sum X_k / RFL_k}$ —① when x is the mole fraction of kth species/fuel

$LFL = \frac{100}{\sum_{k=1} \frac{X_k}{LFL_k}}$ —② Not valid for (H_2, CO, Ethylene)

Example: If the fuel consisting of 55% CH_4, 35% C_2H_6 and 10% C_3H_8, determine Lean flammability limit of mixture fuel-oxidizer by LCR.

Solution:

Known. $X_{CH_4} = 55\%$, $X_{C_2H_6} = 35\%$, $X_{C_3H_8} = 10\%$

$$LFL = \frac{100}{\frac{X_{CH_4}}{LFL_{CH_4}} + \frac{X_{C_2H_6}}{LFL_{C_2H_6}} + \frac{X_{C_3H_8}}{LFL_{C_3H_8}}} = 100 / \left(\frac{55}{5} + \frac{35}{2.8} + \frac{10}{2.1} \right) = 3.54\%$$

Fuel	Oxidizer	LFL (%)	UFL (%)
Methane	Air	5	15
Ethane	Air	2.8	12.4
Propane	Air	2.1	9.1

So, let this is basically Le Chetelier, Chetelier rule. It is known as LCR; is used to estimate limit mixtures of the multiple fuels right. Fuel, you know air mixture (Refer Time: 14:06) mixture.

So, this will be valid particularly for the you know hydrocarbons right. And this formula is like that LFL is equal to 100 X k divided by LFL k. This is a very simple formula. K is equal to 1 to n right. X is the basically mole fractions of the constituent fuel right.

And similarly I can have RFL is equal to 100 divided by X k into RFL k, right. This is let us say 1 and this is 2. And keep in mind that X is where X is the mole fraction of kth species. A species means basically fuel you can say.

And keep in mind that this is not valid, this relationship not valid for what for hydrogen CO and ethylene. Generally, hydrocarbon this is this Le Chetelier rule is being valid people have found out. So, what we will do? We will take an example just to illustrate this point. If the fuel consisting of 55 percent by volume of course, this is methane and

35 percent of propane sorry ethane, C 2 H 6 and 10 right; this would be 10. 10 percent of C 3 H 8 and of course, with air right determined lean flammability limit or lean limit of mixture fuel and oxidizer by Le Chetelier rule LCR right.

So, what will have to do? We will have to basically find out equation 2 solution. If you look at what are the things are known? Known X CH 4 is you can say that 55. So, we can find out LFL lean flammability limit 100 divided by X CH 4 divided by LFL CH 4 plus X C 2 H 6 LFL C 2 H 6, plus X C 3 H 8 LFL C 3 H 8 right. If I substitute these values, you will find out basically 55 by 5.

Because these are all in percentage you will have to take care of the unit. This LFL is in percentage and these are also in percentage right. Plus 35 by 2.8 plus 10 divided by 2.1. So, you will get 3.54 percentage right. Which is a very simple rule one can use particularly for designing you know purposes. And which might be having some error, but that is not much maybe 5 to 10 percent error might be there, because you are just using this values incurred right. So, having talked about this flammability limit, how to calculate for a mixture of fuel provided you know individual lean flammable limit or the rich flammability limit means data, then only (Refer Time: 19:52).

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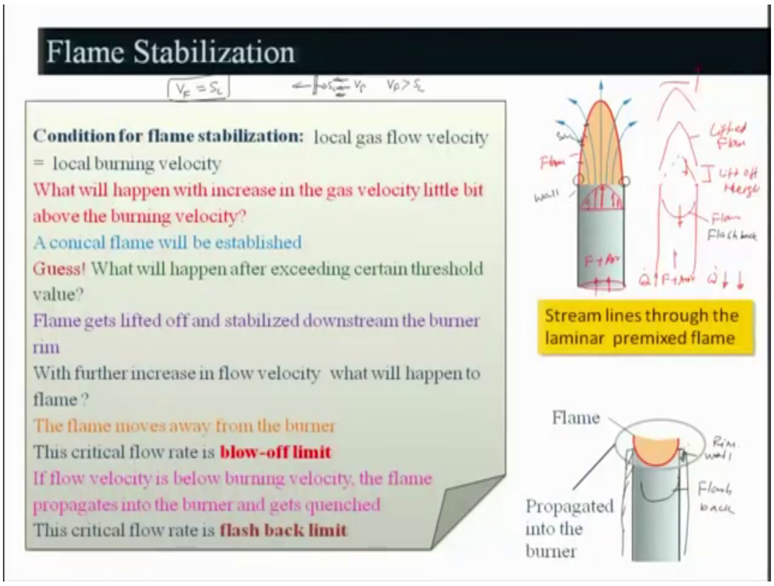

Flame Stabilization

Condition for flame stabilization: local gas flow velocity = local burning velocity

What will happen with increase in the gas velocity little bit above the burning velocity?

A conical flame will be established

Guess! What will happen after exceeding certain threshold value?

Flame gets lifted off and stabilized downstream the burner rim

With further increase in flow velocity what will happen to flame ?

The flame moves away from the burner

This critical flow rate is **blow-off limit**

If flow velocity is below burning velocity, the flame propagates into the burner and gets quenched

This critical flow rate is **flash back limit**

Stream lines through the laminar premixed flame

So, look at this flame stabilization, because what are the condition for the flame stabilization? We have already seen earlier that if the local velocity right, of the fluid is equal to S L like, local laminar burning velocity the flame will be stabilized. For example, if the flame is here which is moving with the S L, and the fluid is moving with a something V F it is possible only when V F is equal to S L right.

That is a very important thing; that means, local gas velocity is equal to local burning velocity right. These are all local, if there is a gas velocity will be higher right. If it is V F is greater than S L what will happen? The flame will be moving toward back right, flame will be going away, right.

And the conical flame will be established for example, if I take this is a basically a tube through which the fuel plus air is going and then this is your flame surface right. See the flame will be moving at a velocity S L at a local surface. And it I have shown you in the earlier that the laminar burning velocity changes across this flame, ok. In certain region it will be remaining constant here, but in this region it will be and higher, and this region it will be because this is the wall region this is the wall stabilize right which will be there.

So, and if it is a certain values right if it will exceed this velocity, if I take this sum average velocity of course, there will be velocity profile right, there will be velocity profile which will be coming over here, right. Something like that. This is the parabolic profile, because this is a tube and which you have given enough distance. And that will be giving like if it is certain velocity, this velocity is increasing for the same fuel air mixture, if you are increasing the flow rate right. If it is flow rate is increasing what will happen?

The flame will be trying to destabilize right. Let us say this is the things and flame may be lifted off right somewhere right. There will be lift off, this is lift off height this is known as lifted flame. If this flow rate is go on increasing further. So, what will happen? Flame will go away and then after that flame will be going away from the one. That is known as blow off or blows out right.

But suppose you thinks that for the same air mixture if the Q dot is decreasing further. So, then what will happen? Flame which ever established here right, flame will come back here with the decreasing this thing flame will be moving toward this. And when you decrease it further right what will happen? Flame will be coming over here.

Flame will be moving towards this one. This is your flame. And under this condition it is basically the flashback, when the flame is inside this is known as flashback. As I told that earlier the flame lift gets lifted off stabilized downstream of the flame, right this is the lifted flame right.

And with further increase in velocity this will happen the flame will blow out. And the flame will be blowing out. And this is known as blow off limit. And if the flame velocities below the burning velocities of the laminar flame propagates into the burner and gets quench and this is known as the flashback right. So, this is the flame which is basically known as the flashback.

Now, let us understand what is happening in the flame stabilization during the rim because, what is happening here? In this case the flame this is the wall right the rim of the burners right this is the wall rim right, rim of the burners, that is holding the flame right. And it also the heat losses will take place then flame make quench back, because once in flashback if heat losses are more than only it will quench.

Otherwise it will propagate and that is dangerous right. Flames should not enter in to it may dewasted, the things right. Because they before this fuel air mixture will be there in a very big chamber explosion may occur right that one has to avoid.

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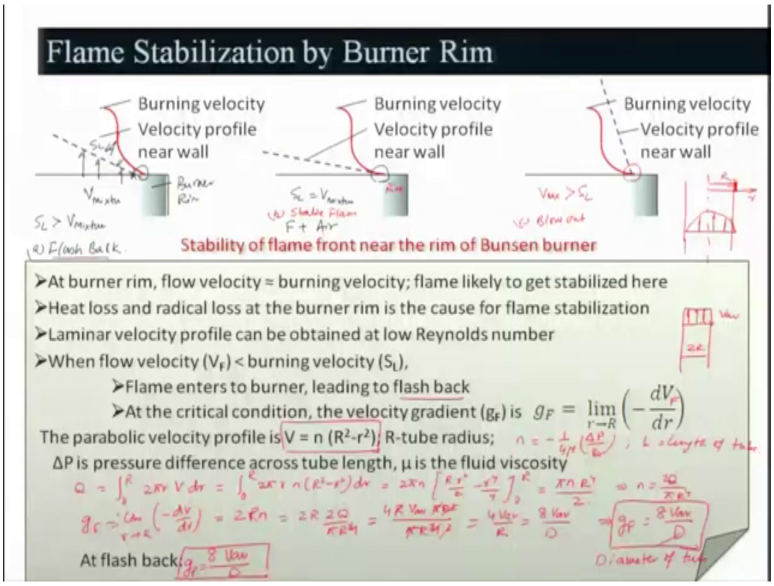

Flame Stabilization by Burner Rim

Stability of flame front near the rim of Bunsen burner

- At burner rim, flow velocity ≈ burning velocity; flame likely to get stabilized here
- Heat loss and radical loss at the burner rim is the cause for flame stabilization
- Laminar velocity profile can be obtained at low Reynolds number
- When flow velocity (V_F) < burning velocity (S_L),
  - Flame enters to burner, leading to flash back
  - At the critical condition, the velocity gradient (g_F) is $g_F = \lim_{r \to R}\left(-\frac{dV_F}{dr}\right)$

The parabolic velocity profile is $\boxed{V = n(R^2 - r^2)}$; R-tube radius; $n = -\frac{1}{4\mu}\left(\frac{\Delta P}{L}\right)$; L = length of tube

ΔP is pressure difference across tube length, μ is the fluid viscosity

$$Q = \int_0^R 2\pi r V\,dr = \int_0^R 2\pi r\, n(R^2 - r^2)\,dr = 2\pi n\left[\frac{R^2 r^2}{2} - \frac{r^4}{4}\right]_0^R = \frac{\pi n R^4}{2} \Rightarrow n = \frac{2Q}{\pi R^4}$$

$$g_F = \lim_{r \to R}\left(-\frac{dV}{dr}\right) = 2Rn = 2R\frac{2Q}{\pi R^4} = \frac{4R\,V_{av}\,\pi R^2}{\pi R^4} = \frac{4V_{av}}{R} = \frac{8V_{av}}{D} \Rightarrow \boxed{g_F = \frac{8V_{av}}{D}}$$

D = Diameter of tube

At flash back: $\boxed{g_F = \frac{8V_{av}}{D}}$

So now let us look at that what really how does the flame stabilize what is the reason? If I consider this is your burner rim, and that helps in stabilizing a flame and this is your velocities, right V of the fluid right or mixture. And this is the flame which will be moving you know locally it will be moving right with S L. This is a perpendicular that S L. If in this place it is in this region if it is higher, then what will be happening in this case? In this region if you look at S L, S L is high greater than the V mixture. Then what will happen? Flame will be entering into the burner right.

So, that is known as the flashback, are you getting? But here the at this point right the S L is equal to V mixture. This is of course; the fuel plus air I can say just to discuss it can be oxidizer. So, then this is known as stable flame. Flame is stabilized at the burner rim right, this is your rim.

So, in this case what is happening? The in this region the velocity is very high which was the V mixture is greater than S L. So, therefore, the flame is going away, right. And that is known as c blow out. So, I have already explained this thing. Just I am repeating again. At the burner rim flow velocity is equal to the burner burning velocity.

Flame is likely to get stabilized here. Heat loss and radical loss to the burner rim is the cause of the flame stabilization ok; that means, what happened when the flame will be near to the wall, there will be some of the losses will be occurring because the radical loss will be there, heat loss will be there.

Laminar velocity can be obtained at the low Reynolds number, right, particularly when it is and when the flow velocity is less than the burning velocity S L, right. Flame enters into burner leading to flashback, I have already explained this thing this is your flashback. And at critical condition the velocity gradient, let us say at the flashback will be when r tending towards capital R. If I consider this is the tube, if I consider and then this will be and is basically R.

At any there is a 10 in to a is equal to r means it is at the wall, right what you are considering d v by d and this is a corresponding to mixture velocity or the fluid velocity whatever of the mixture.

So, we know because velocity parabolic profile. So, therefore, we can say V is equal to n small r square for a r is the tube radius. If you look at basically, minus 1 by 4 mu Delta l is the length of length of tube in which (Refer Time: 30:55) and this is you will be knowing.

So now let us look at look at that how we can relate this and evaluate this g F. As I told that delta P is the pressure difference across the tube length, mu is the fluid viscosity. And if you look at the flow rate, volumetric flow rate is nothing but your R 2 pi r V. I am considering V as the fluid velocity and dr, and when you put this V over here, right you will get 0 to R 2 pi r n R square minus r square dr.

When you integrate all those things, you will get basically ok, let me do that maybe it will take little time, 2 pi n I can take it out. And integrate that thing, and then I will get R r square divided by 2 minus r 4 right by 4. And when I put this 0 2 r, I will get basically pi n R 4, R 4 by 2 I will get, ; that means, I can write down basically n is equal to Q 2 Q dot divided by pi R 4

So, if I will this g F if I look at it is equal to limit r trending towards R d v by d r I can use this again this expression. V is equal to nr square on this thing. So, I will get is equal 2 r n, and if I will put this thing to sorry, this will be r tending towards 0. So, this will be 2 capital R n and n this is nothing but your

Student: 2 Q (Refer Time: 33:37)

2 Q dot by pi R square.

Student: (Refer Time: 33:42)

It is basically

Student: (Refer Time: 33:45)

I can express in terms of average velocity, right.

Student: (Refer Time: 33:48)

So, if you look at Q dot basically I can say V average velocity pi by R square, area cross sectional area if I take a tube here, right. I can take a velocity profile which is average. This is basically parabolic profile right, but now I am considering into average because that will be good one this is V average, right. And this is your basically 2 R right.

The cross sectional area will be pi R square right. And you putting that thing you will be putting 2 4 R in Q dot will be V average pi R square divided by pi R square

Student: R 4.

R 4 right?

Student: Hm.

Pi R 4 it will be yes it will be 4. So, this will be cancel it out, it will be 2 pi will cancel it out. And the R also will cancel it out. I will get basically 4 V average by R is equal to 8 V average by D; that means, I can get basically g F is equal to 8 V average by D. So, if you look at this gradient I can obtain very simply conducting it is an average velocity. And diameter if I know I can get these values. This is the diameter of tube.

So, similarly you can get the gradient velocity gradient for the blow out also right. And which is happens to be similar in nature. I will leave that as a derivation for you to do that. Now, at the flashback as I told, this g F is equal to 8 V average. I think all right. This is 8 V average divided by D.

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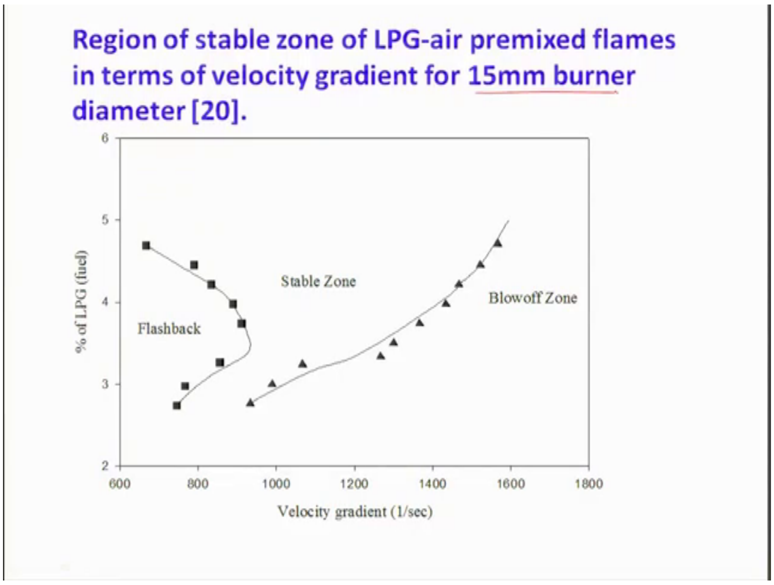

Region of stable zone of LPG-air premixed flames in terms of velocity gradient for 15mm burner diameter [20].

So, if you look at this velocity gradient both the flashback and blow out, you can see this is for LPG air premixed, and it is considered for the 15 mm diameters. That is percentage of LPG is plotted here, you can see that this region you know if it will go beyond, it will be flashback and this region is a stable region. And it will go beyond this is the blow off region kind of things right.

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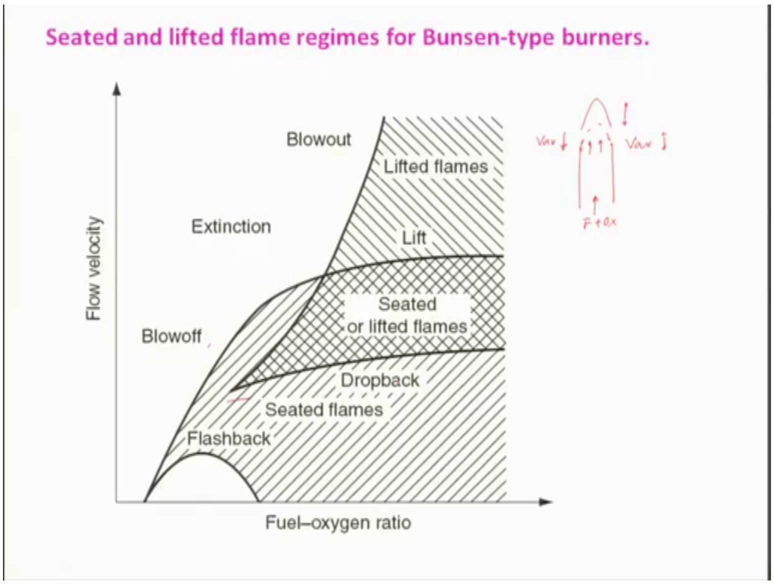

Seated and lifted flame regimes for Bunsen-type burners.

So, and if you look at the whole regimes of the Bunsen type of flame, where the tube will be there, you can see that in this region, you can see that is the flow velocity being plotted over the fuel oxidizer oxygen ratio is the blow off which will be occurring here right. And this is the region below which the flashback like a flashback will be occurring in region.

This will be seated flame. And this is the lifted flame what I have talked about. And this lifted flame will be oscillating; that means, when you are making this flame here, let us say this is a lifted flame, when you reduce the velocity right. This is let us say it is having some V average here this is having some V average, right.

Then what happened? Flame will be going up and coming up depending on whether it is changing V average little bit right. So, this seat is n and then flame is lifted and then it will be of course, when you go beyond it will be blow out. And this when you decrease these V average velocities, you can flame can be coming back and sitting over here when the V average is reduced. This is basically drop back region. So, with this I will stop over here. In the next lecture, we will be basically discussing about the ignition and ignition energy and other aspect will be looking at it.

Thank you very much.