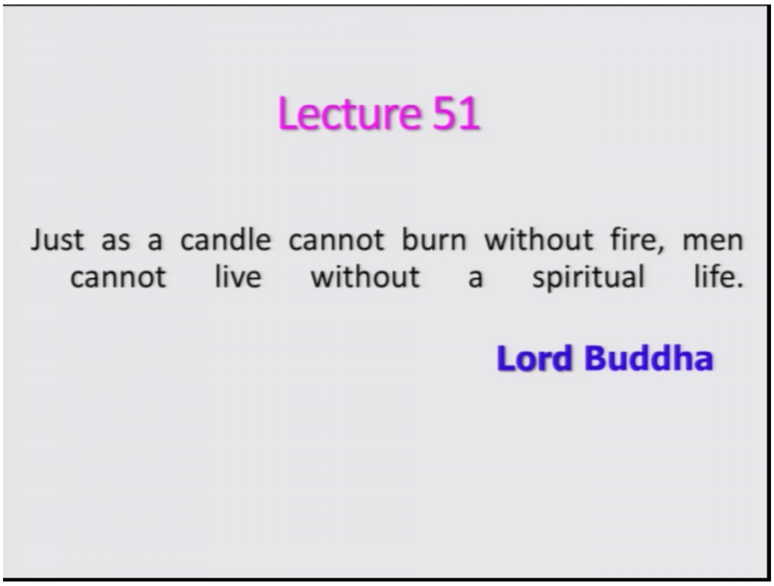
Fundamentals of Combustion (Part 2)

Dr. D. P. Mishra
Department of Aerospace Engineering
Indian Institute of Technology, Kanpur

Lecture – 51
Effects of Chemical and Physical Variables on Burning Velocity

(Refer Slide Time: 00:20)



Lecture 51

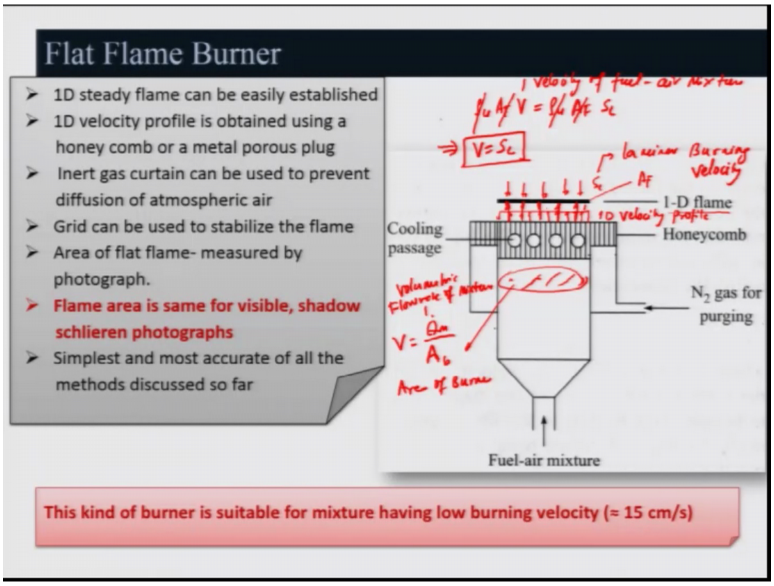
Just as a candle cannot burn without fire, men cannot live without a spiritual life.

Lord Buddha

Let us start this lecture with a thought process from Lord Buddha, who says, just as a candle cannot burn without fire, men cannot live without a spiritual life. It is really very profound statement which is a missing in our day to day life, as we are not bothered about the spiritual aspect of human life. In the last lecture, we discuss about stationary flame method for determination of burning velocity. And in which we looked at 3 methods. Basically, one is very sophisticated method of measuring local burning velocity using PIV or particle image velocity symmetry. Other is a little simpler, but crude as compared to the sophisticated method. Other 2 methods which have been routinely used in the laboratory are the area method and the nozzle method.

So, today we will be discussing about another method of measuring the burning velocity; that is, flat flame burner method.

(Refer Slide Time: 01:33)



Flat Flame Burner

- 1D steady flame can be easily established
- 1D velocity profile is obtained using a honey comb or a metal porous plug
- Inert gas curtain can be used to prevent diffusion of atmospheric air
- Grid can be used to stabilize the flame
- Area of flat flame- measured by photograph.
- Flame area is same for visible, shadow schlieren photographs
- Simplest and most accurate of all the methods discussed so far

This kind of burner is suitable for mixture having low burning velocity (≈ 15 cm/s)

In this case if you look at the a burner is designed in such a way that you can have a uniform velocity profile over here by using honeycomb, and this can be bundle of tubes, very fine to use; generally hypodermic stainless steel tubes are being which used which is quite difficult to manufacture. And beside this for us sintered metal, this can be used. In this case, there is a also the cooling passages are been provided so that you can cool this portion to have to stabilize the flame.

And besides this there is a provision is being met here as I have shown here, to dilute to create a curtain with the dilution gases that there will be no interference will be coming from outside with the flame. As a result, that this one dimensional flame is being established. And sometimes people use also the mesh, metal mesh to stabilize the flame, such that one dimensional flame can be established in of course, you need to supply the fuel air mixture to this burner.

So, with this provision one can really manage to gay establish a dimensional steady flat flame burner. So, far this as a tool that one dimensional velocity profile is to be established and either using a honey comb or a metal porous plug, and this inert gas curtain has to be provided so that the age of this one dimensional flame should not be affected by the ambient or atmospheric air. And as I told the greed is being used to stabilize the flame.

And in this case, as the flame is one-dimension nature, you can take the photograph of this flame, and then by carrying out a mass balance one can really find out the flame burning velocity, laminar burning velocity easily if you look at the mass balance and let us say this is the velocity with which is going and the flame is propagating with the same velocity s l. So, if you look at this is the velocity which is coming.

So, if would take mass balance you will find row u A F you can assume this the flame surface this is your, f is same as that of the tube diameter or the burner so that you are considering only this portion A F. And V is the velocity of fuel air mixture. And which is does not vary along the radial direction is equal to row u A F S L; this S L is the laminar burning velocity. So, therefore, this is cancel it out, A F will be cancel it out, you will get V is equal to S L.

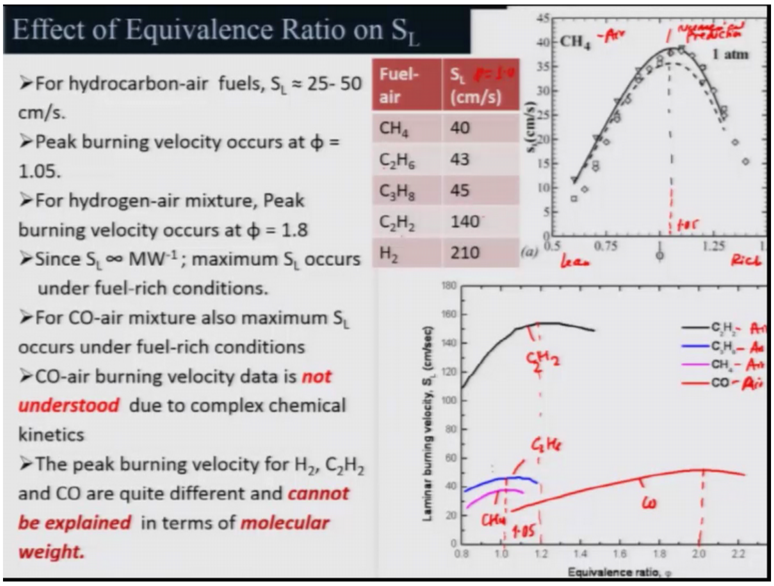
So, that it is a very simple method by which you can get velocity very easily, because you know the mass flow rate of the fuel air mixture. So, V I can get the basically the volumetric flow rate of the mixture divided by A of this is your area, this area is basically known as the area of the burner, this area of burner. So, that by this you know this thing q dot m, that is the volumetric flow rate of mixture. So, very easily you can get this thing and then that is nothing but equal to the laminar burning velocity.

So, flame area is interestingly is same for all methods like visible shadow Schlieren photographs, because of fact that it is all remaining the same place. So, there is no change in gradients, density gradient. And it is one of the simplest and most accurate methods so far we have discussed, and therefore, it is being used routinely.

But the problem with this kind of burner that it is not suitable, for mixture having low burning velocity, and people of course, are device it further of using cooling passages so that you can establish the flame even little bit lower than the 15 centimetre per second. So, but it is a difficult to manufacture this burner flamer burner, because I had done this thing earlier. It was really very difficult because, I had used some kind the hypodermic tubes. And which will be getting blocked very easily, and once you some of the passages are blocked due to the dust in the fuel air mixture. Then, you cannot really get the one dimensional flame because of change in the velocity at a local places are at local.

So, therefore, one has to be very careful of using this burner. So, let us now look at basically effect of equivalent ratio on the laminar burning velocity.

(Refer Slide Time: 08:41)



Effect of Equivalence Ratio on S_L

- For hydrocarbon-air fuels, $S_L \approx$ 25- 50 cm/s.
- Peak burning velocity occurs at ϕ = 1.05.
- For hydrogen-air mixture, Peak burning velocity occurs at ϕ = 1.8
- Since $S_L \propto MW^{-1}$; maximum S_L occurs under fuel-rich conditions.
- For CO-air mixture also maximum S_L occurs under fuel-rich conditions
- CO-air burning velocity data is ***not understood*** due to complex chemical kinetics
- The peak burning velocity for H_2, C_2H_2 and CO are quite different and ***cannot be explained*** in terms of ***molecular weight.***

Fuel-air	S_L ϕ=1.0 (cm/s)
CH_4	40
C_2H_6	43
C_3H_8	45
C_2H_2	140
H_2	210

So, as I told that you one can vary this fuel air mixture in any of these methods. And then you can get different laminar burning velocity. For methane air system, it is being shown here the laminar burning velocity is equal and in the vertical axis, in the horizontal axis, the equivalence ratio is being plotted. You can see that these points are basically different experiments, and there is another set of experiment, which can say there is a little bit variation. And the solid line is corresponding to the numerical prediction and of course, dash line is another theoretical prediction which is not very good.

But one can see here that these are the experimental data’s of laminar burning velocity. And this is at conducted at one atmospheric pressure. It can be noted that this is your equivalence ratio one it is not and the peak value is occurring somewhere in this zone, which is the peak value is occurring around something 1.05, and on the left hand side the burning velocity is decreasing, this is basically your lean mixture, and the reach mixture it is also decreasing.

So, if you look at equivalence ratio around 1.05 for methane air flame the peak laminar burning velocity occurs. And let us look at for other fuel air system profiler systems like your acetylene air system, propane air system. This is your of course, your methane air system and carbon monoxide air system. This is basically C 3 H 8. This is methane, and this is acetylene, and this is of course, C O and all with respect to A. And one can note one thing that for and for hydrocarbon like methane and the propane, the peak burning velocity will be taking place around equivalence ratio around 1.05 whereas for carbon monoxide it is something occurring around 2, and for C 2 a C it will be occurring around something 1.2. And one can also conclude from this data of laminar burning velocity is that for hydrocarbon air fuels laminar burning velocity will be varying from 25 to the 50 centimetre per second, accept the acetylene air.

And whereas for and for the unsaturated hydrocarbon, air the peak laminar burning velocity occurs at equal to 1.05 and for hydrogen air mixture which is not shown here, but the laminar burning velocity will be, or the peak laminar burning velocity occurs at equivalence ratio 1.8. And how to explain this is very important. Because for C O carbon monoxide acetylene and hydrogen air, the peak laminar burning velocity is occurring at reach conditions, right. Unlike the hydrocarbon air or unsaturated hydrocarbon air where the peak laminar velocity is occurring around equivalence ratio of 1, generally 1.05 or around one can say.

And we know from laminar burning velocity that S L is basically proportional to 1 by row u. And row u is inverse is proportional to basically molecular weight of the fuel air mixture; so, therefore, if M W molecular weight, this is your molecular weight. And when molecular weight increases, then what happened? S L will be molecular weight will be decreasing. Or vice versa; that means, molecular weight of the mixtures or the thing will be decreasing the laminar burning velocity will be increasing.

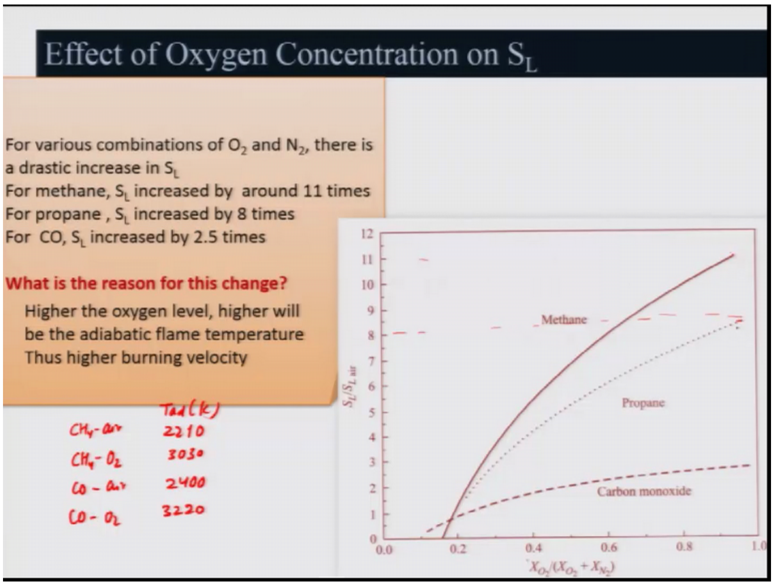
So, one can really explain that C O air mixture also the maxima occurs under fuel rich conditions. And you can explain this thing that for hydrogen air one can say that because with addition of hydrogen air, the molecular weight will be decreasing so that you can get a burning velocity max or the peak burning velocity will be occurring at the rich condition.

But for C O air the peak laminar burning velocity data cannot really be understood so simply, which may be attributed to the chemical complex chemical kinetics which needs to be explored further. So, as I told that that peak laminar burning velocity for hydrogen and C 2 H 2 is your quite different. And it cannot be explained in terms of simple district view of the molecular weight of the mixtures, as we had explain in case of hydrogen air.

So, just to summarise fuel air, mixture of different like we given methane, the burning velocity at equivalence ratio is equal to 1 is 40 around 40 centimetre per second where as

C 2 S 6. That is the 43 centimetre per second C 3 H 845 centimetre per second and C 2 H 2 is around 140 150 centimetre per second. Hydrogen is around 210 centimetres per second.

(Refer Slide Time: 16:13)



Effect of Oxygen Concentration on S_L

For various combinations of O_2 and N_2, there is a drastic increase in S_L
For methane, S_L increased by around 11 times
For propane , S_L increased by 8 times
For CO, S_L increased by 2.5 times

What is the reason for this change?

Higher the oxygen level, higher will be the adiabatic flame temperature
Thus higher burning velocity

	Tad (K)
CH_4 - air	2210
CH_4 - O_2	3030
CO - air	2400
CO - O_2	3220

So, let us look at effect of oxygen concentration on the laminar burning velocity. Here I have taken the data of S L of S L with air, and on the vertical axis, on the horizontal axis. The mole fraction oxygen divided by mole fraction of oxygen and nitrogen that is saying basically, what is the percentage of oxygen on the as a oxidizer in the oxidizer. So, of course, this is very important, because of fact that the people are now bother about the nox mission, and also for efficient combustion system. People are thinking of using oxygen, or they are there trying to replace the nitrogen in the air with oxygen.

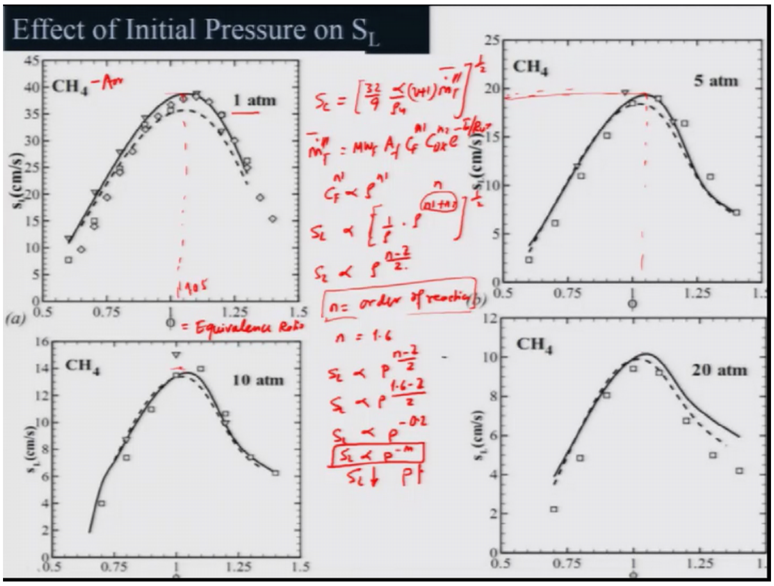
So, if you we have taken the 3 fuel air, one is methane are there is propane and carbon dioxide. You will find that the effect of very much predominant for methane. Because there is there of course, if you look at it is all greater than 1, in this zone whenever there is a more amount of oxygen is being given as compared to the air. And for methane the S L burning velocity is increasing around something 11 times. And whereas for propane the laminar burnings increased around 8 times hear. If you look at something around 8 times or.

And carbon monoxide the laminar velocity increases by around 2.5 times. So, question is what is the reason for this change? And this is because of fact that whenever this nitrogen is replaced by the oxygen, and then there will be a higher adiabatic flame temperature.

And if the flame temperature is higher than naturally have heat release not being consumed by the nitrogen which is inert gas, as a result there will be increased in higher burning velocity. And if you look at really this adiabatic temperature, let me give you some data this is C H 4 air, the adiabatic temperature by kelvin if you look at it will be 2200 2210th, where as if I just use the air oxygen pure oxygen, then I will get 3030 kelvin. And similarly, if I take this carbon monoxide air the temperature will be 2400 kelvin, and C O for oxygen this is 3220 kelvin.

So, there is a lot of difference between the temperatures whenever you replace air with the pure oxygen. As a result, this burning velocity will be increasing. The difference in laminar burning velocity can be attributed to different effective activation energy; because of the chemistry will be different. And also the pre exponential factor of global kinetics between these 2 fuel and oxidizer system that might be the main reason why there is a change in the laminar burning velocity.

(Refer Slide Time: 20:05)



Effect of Initial Pressure on S_L

$S_L = \left[\frac{32}{9}\frac{\alpha}{\rho_u}(\nu+1)\bar{\dot{m}}_F'''\right]^{\frac{1}{2}}$

$\bar{\dot{m}}_F''' = MW_F A_f C_F^{n_1} C_{ox}^{n_2} e^{-E/R_uT}$

$C_F^{n_1} \propto \rho^{n_1}$

$S_L \propto \left[\frac{1}{\rho}\cdot\rho^{\overset{n}{\boxed{n_1+n_2}}}\right]^{\frac{1}{2}}$

$S_L \propto \rho^{\frac{n-2}{2}}$

$\boxed{n = \text{order of reaction}}$

$n = 1.6$

$S_L \propto P^{\frac{n-2}{2}}$

$S_L \propto P^{\frac{1.6-2}{2}}$

$S_L \propto P^{-0.2}$

$\boxed{S_L \propto P^{-m}}$

$S_L \downarrow \quad P \uparrow$

And let us look at the effect of initial pressure. And if you recall that we had seen this data of laminar burning velocity with respect to the equivalence ratio 5 is your equivalence ratio. For one atmosphere and this is for air system, and what will be considering for this methane air system, an increase the pressure, and see what is happening, here if you can look at the peak value of laminar burning velocity is around something 30 right centimetre per second if you look at; this is something 38 and which is occurring around 1.05. And when you increase this pressure to 5 atmospheric, the peak values also occurring at the same location, but, however, it has been reduced so, something around maybe 18 centimetre per second. And when you increase this further, then to 10 atmosphere the curved is similar, but there might be little bit less data here and then nature is little changing, but; however, the pattern of variation of laminar velocity with respect to equivalence ratio or almost same only the peak value is being reduced. If you look at now it is around something maybe one can say around centimetre per second. And if I increased to further 20, then it is not changing my much if you look at twice, I have changed this is around something maybe 10 centimetre per second.

Now, question is why it is happening; that means, with increase in pressure the laminar burning velocity is decreasing. In some cases, you may find that is not really changing much or changing at all. So, that is a different situations or different fuel air system one can think of using.

But let us look at that why there is a why the laminar burning velocity is decrease or change due to the initial change in the initial pressure. We know that laminar burning velocity is basically proportional to the density, and also the concentration we are derived a relationship earlier, that is 32 by 9 alpha by row u, nu plus 1 m f average, this is half. This is basically root. We know that this mass burning rate of the fuel of average can be model per using a single step chemistry; that is, M W f A F, that is pre exponential factor, and C F n 1 C oxidizer n 2 and E by Rut the E is your activation energy.

And we know that C F is basically proportional to if I take n 1 is the density of n 1. So, I can say that then S L is proportional to 1 by row u, row into row n 1 plus n 2 power to the half. So, I can say a S L is proportional to basically row and this I can say as n, this is basically row n minus 2 divided by 2.

So, n is basically the order of reaction, and is n is around let us a 1.6, I can say that S L is proportional to P because row is proportional to P n by divided by 2 is proportional to S L P 1.6 minus 2 divided by 2 is p S L is something around maybe 0.2. So, of course, these values of 0.2 which may be varying, so what is saying that, if P is increasing, then S L has to decrease, and with of course, the co-efficient of the 0.2 or it can be anything.

So, I can say that S L is basically P power to m. So, these values will be different for different cases. And then so that the burning velocity will be decreasing with respect to pressure. Of course, in certain range this n, order of reaction will be changing. So, this is if is order of reaction is changing if it is happening, then the burning velocity will not be affected by the pressure or initial pressure.

Thank you very much. We will stop over here.