

**Fundamentals of Combustion**  
**Prof. V. Raghavan**  
**Department of Mechanical Engineering**  
**Indian Institute of Technology, Madras**

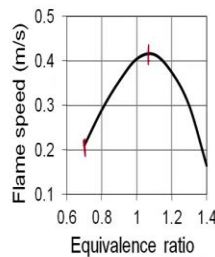
**Lecture - 34**  
**Laminar Premixed Flames – Part 2**  
**Laminar flame speed variation and Structure of premixed flames**

(Refer Slide Time: 00:14)

Laminar Flame Speed Variation



As a result of temperature variation, the laminar flame speed, which strongly depends on the flame temperature, also depicts a similar variation with equivalence ratio. On the richer side, both heat release and flame temperature decreases as the equivalence ratio is increased. Several researchers reported varying values of  $S_L$ ; but,  $S_L$  attains a maximum value when  $\phi$  is in the range of 1.05 to 1.1. (Figure shows the  $S_L$  vs.  $\phi$  for methane – air flames)



Dr. V. Raghavan, IIT Madras



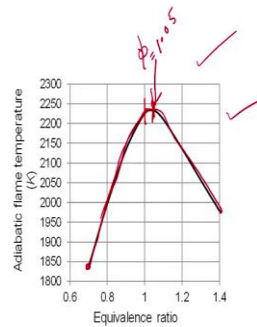
Here, laminar flame speed variation with equivalence ratio is shown. You can see that same methane air flames are considered, equivalence ratio again you can see that 0.7 to 1.4, same range of equivalence ratio. So, this variation of the laminar flame speed with equivalence ratio is typically like the variation of adiabatic flame temperature, where the peak is formed at the richer side.

(Refer Slide Time: 00:39)

## Adiabatic Flame Temperature



Flame temperature, which depends on the heat of reaction, attains a maximum value for a mixture having equivalence ratio slightly greater than unity. There is a shift in the value of equivalence ratio corresponding to maximum heat of combustion and maximum flame temperature due to the dependency of thermal conductivity, specific heat and diffusivity of the gases on temperature. (Figure shows the  $T_{ad}$  vs.  $\phi$  for methane – air flames)



Dr. V. Raghavan, IIT Madras

6



Here also you can see that this is 1 and this is around the same value, almost same value. You will see the peak is formed to the right of  $\Phi = 1$  line. So, as a result of temperature variation, the laminar flame speed which strongly depends on flame temperature also changes, we are going to prove that soon. So, laminar flame speed  $S_L$  strongly depends on the flame temperature.

And due to that, the variation in the  $S_L$ , the laminar flame speed with equivalence ratio is exactly or much similar to the variation of the adiabatic flame temperature with equivalence ratio. So, temperature strongly influences the variation of laminar flame speed. So, this is the variation we get, you can see that very low flame speed about slightly more than 20 cm/s or 0.2 meter per second. For this methane air the maximum is slightly more than 40 cm/s.

So, 40 to 44 cm/s, you are getting that. Then after that it decreases significantly when the equivalence ratio is further increased. So, the leaner side, why it increases because the temperature is increasing so more heat release happens, due to additional supply of fuel. After reaching the maximum why it decreases because on the richer side both heat release and flame temperature decreases.

So, the flame speed decreases, on the richer side both heat release and the flame temperature decrease as the equivalence ratio is increased. As a result of that you get a decreasing trend in the laminar flame speed.

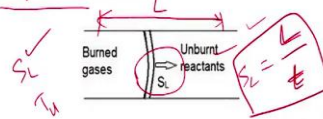
(Refer Slide Time: 02:39)

## Laminar Flame Propagation

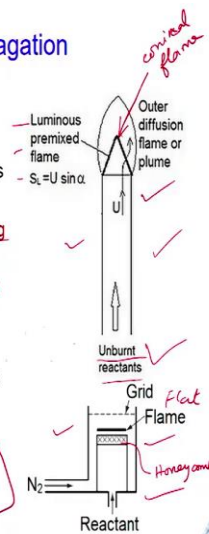


Steady propagation of a flame through a premixed reactant at a subsonic speed is called deflagration. This is also referred to as laminar flame propagation.

The flame is kept stationary by supplying the reactant mixture at a certain rate, such that the magnitude of its velocity component normal to the flame surface is equal to the laminar flame speed. These are shown in figures – Bunsen burner conical flame and a flat premixed flame.



Dr. V. Raghavan, IIT Madras



But please understand that based upon the experimental setup you use, for example, it may be a flat burner it may be this type of propagation. So, when you want to characterize a mixture, premixed reactant mixture, you need to know some characteristics of that. So, one of the important characteristics is the flame speed  $S_L$ . When the unburnt reactant mixture is at a given temperature  $T_u$ .

There is a particular speed at which the flame propagates,  $S_L$ , but, please understand that in the setup if we measure  $S_L$ , you will get one set of values. Go to flat flames and try to measure you will get some set of values go to Bunsen burner you get some values. So, again the values will vary. So, based upon the setup because, you can see that here a curved flame slowly propagates. Here the conical flame stands over the burner rim and there are heat losses and additional factors etcetera which are there in this.

Similarly, the heat loss affects the flat flame at the most. So, the flame stands very close to the burner exit. So, what happens is, it heats the burner itself. So, normally what people do is they cool the burner. And if you cool the burner then we are not measuring the adiabatic flame speed.

See when you want to measure the flame speed it should be almost not influenced by the surroundings. So, you have to isolate that. So, normally make it insulated. So, adiabatic flame speed you are not measuring when you cool the burner and so on. So, lot of other factors are there, due to which the configuration of the setup itself will influence and the laminar flame speed will not have a single value, it will have a range of values.

For example, say 0.8 is its equivalence ratio, several experiments if you want to plot a data you will get the range like this. So, starting from a low value to high value you will

get the range. So, this may be pretty some average value what we can have and we the value plotted here or calculated value will be some averages. So, that means some variations will be there based upon what type of burner they use. So, this variation will be there in this at a given equivalence ratio.

The variation is found due to the variation in the equipment which is used to measure the laminar flame speed. So, several researchers reported varying values of  $S_L$  it is not a constant value like this. So, this means this is not a proper  $S_L$ , because it is not a unique value. It varies with the apparatus, so this is an eigen value.

But all researchers even though they have the variations, they also found the same variations at all the equivalence ratios; however, the maximum value what they found was in the range of 1.05 to 1.1, for methane air mixture. So, this is only for methane air mixture. For methane air mixture, several researchers have reported this range, even though the absolute values may vary for them.

Based upon the equipment they used the maximum value of  $S_L$  was seemed to attain only in a slightly rich range of equivalence ratio in between 1.05 to 1.1 that was guaranteed. But the values had some range. So, which is correct that cannot be determined because, this is based on the equipment.

So, several researchers reported varying values of  $S_L$ , but  $S_L$  was seemed to attain the maximum value, when  $\Phi$  is in between 1.05 to 1.1 for methane air. This is basically for methane air.

So, for other fuels, the  $\Phi$  will vary where the maximum flame speed will attain that  $\Phi$  value will vary, so, that we will see next. So, the main influence of laminar flame speed is by the temperature. And as the temperature varies similar trend is depicted by the variation in the laminar flame speed, adiabatic flame temperature attains a maximum value in a slighter richer composition.

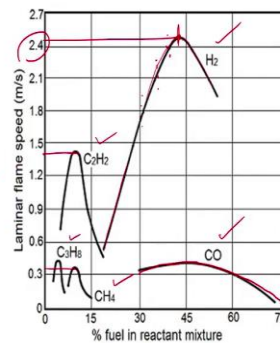
See for example, methane it is around 1.05 something like that here, the  $S_L$ , the flame speed also attains a maximum value in the range of 1.05 to 1.1. So, this thing we have to understand. So, a laminar flame speed varies with equivalence ratio in a typical manner attaining a maximum at slightly richer equivalence ratio. It increases from lean to rich, slightly rich, then it decreases after that. Exactly same as the variation of the adiabatic flame temperature.

(Refer Slide Time: 07:39)

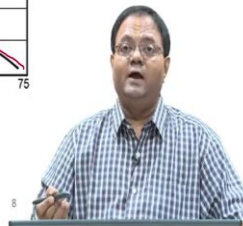
### Laminar Flame Speed Variation



Similar trends are observed in fuels such as acetylene, CO, ethylene, H<sub>2</sub> and propane. However, the equivalence ratio at which the maximum laminar flame speed is obtained is different between these fuels. The laminar flame speeds for several fuels are comparatively shown as a function of percentage fuel in the reactant mixture.



Dr. V. Raghavan, IIT Madras



Now, for several fuels we have shown here you can see that the trend is same, but the values are different see for example, from the lean portion it increases attains a maximum and decreases further. Similarly, hydrogen you can see, this it increases from the lean attains a maximum here and decreases.

So, all positions here you can see this is not the equivalence ratio please understand, the x axis is percentage fuel in the reactant mixture and the laminar flame speed is plotted. This actually compares all the things for example methane, propane, then C<sub>2</sub>H<sub>2</sub> (acetylene), hydrogen, CO everything is present here. So, if you take this the trends are same, that similar trends are observed for other fuels also.

Why the similarity in the trend? From the lean value, lean  $\Phi$  value it increases and attains the maximum value,  $S_L$  attains a maximum value at a richer point, then it decreases. So, this trend is similar. However, the equivalence ratio at which the maximum laminar flame speed is obtained is quite different.

So, that is what you have to understand. Similarly, the laminar flame speeds itself, the maximum value of the laminar flame speed that itself is very different, you can see the highest value in this graph is for hydrogen and so on. So, CO, this graph you have to understand that it is not equivalence ratio. This is percentage fuel in the reactant mixture. So, this comparatively shows the variation of  $S_L$  and the maximum value of  $S_L$  possible for a given fuel air mixture. So, what is the typical range? When we compare to methane which is about 0.42, you can see that for hydrogen it is 2.4. So, 6 times almost 6 times higher than the methane value.

This value itself cannot be absolute as I told you this is done in particular reaction chamber. However, if you vary the equipment or reaction chamber or the conditions, you will see that the variations will be there, the maximum value will be in this range.

So, all these data will have some variation in a given equivalence ratio. So, as I told you the experimental data will be having some spread in its value. So, that is very important to understand; however, we can know the typical range of the maximum  $S_L$  value and the equivalence ratio at which it is attained.

So, that is very important for us to understand. Even though it is an eigen value this is very important information for us to be used in the design of burners. So, the trend is for the air flames.

So, please understand that I am not using pure oxygen here. For any fuel-air a in a typical atmospheric combustion or low to moderate pressure combustion, you can see that there is a variation in trend, from the lean to a slightly richer side the maximum value is attained. And after that the laminar flame speed is decreased as the equivalence ratio is further increased.

(Refer Slide Time: 11:15)

### Laminar Flame Speed Variation



For  $\text{CH}_4$  and  $\text{C}_3\text{H}_8$ , the equivalence ratio at which  $S_L$  becomes a maximum is around 1.08 and for  $\text{C}_2\text{H}_2$ , it is around 1.2.

For  $\text{H}_2$ , it around 1.8 and for  $\text{CO}$ , it is around 2, implying that a richer mixture is required for attaining the maximum flame speed for these fuels.

One important point to note here is that the occurrence of the maximum adiabatic flame temperature for hydrogen-air mixture happens around an equivalence ratio of 1.07, which is almost the same as that of methane. However, the maximum flame speed occurs around an equivalence ratio of 1.8.

This is due to the variation of thermal and mass diffusivities, or their ratio called Lewis number,  $Le$ , with the composition of the reactant mixture.

$\frac{\alpha}{D}$

Dr. V. Raghavan, IIT Madras



So, some typical comments for straight chain alkanes. So,  $\text{CH}_4$   $\text{C}_3\text{H}_8$  etcetera, you can see that the  $S_L$  becomes a maximum around equivalence ratio of 1.08 almost the same, but  $\text{C}_2\text{H}_2$  it becomes maximum at 1.2. This is fine, 1.08 its very close to 1.1, so, 1.2 is fine we can see slight variation. But, for hydrogen the maximum value of  $S_L$  is got at the phi value of 1.8 and for  $\text{CO}$  it is got at 2.

So, this is very important to note here, very important summary. So, when you have straight chain hydrocarbons or unsaturated hydrocarbons, you have a typical variation

say 1.1, 1.2 something, the equivalence ratio value at which the  $S_L$  becomes maximum. And for hydrogen and CO it is 1.8 and 2, respectively, the  $\Phi$  values at which the maximum  $S_L$  value is attained.

So, this means that you can attain the maximum flame temperature only at the rich mixture condition, at richer condition only you can attain the maximum flame speed, then after that it decreases. This is one of the important, that is what I told these are the characteristics, we should know that is a range it may not be exactly 1.8, it may be say 1.7 to 1.85 something like that.

Similarly, here also there will be a small range, this is the typical average value. As we saw for methane, the researchers have reported 1.05 to 1.1. So, 1.08 is a typical value. So, some average value we are reporting here.

But, one more important problem we have to note here is if we take hydrogen air mixture. The adiabatic flame temperature attains a maximum value at 1.07, which is the same as that of methane air mixture. Methane-air mixture also attains, see the  $S_L$  value of methane air mixture attains the maximum at 1.08. So, the adiabatic flame temperature of methane air flames, attains the maximum at around 1.08, something like that.

So, there is a match between the maximum adiabatic flame temperature and the maximum value of  $S_L$ . Almost the same equivalence ratio it is attained for methane-air, but for hydrogen-air the adiabatic flame temperature attains a maximum value at the equivalence ratio of 1.07. But, we have seen that for  $S_L$  to attain its maximum value the equivalence ratio has to be 1.8. So, this is a tremendous difference.

So, this is one of the important thing, you can see that this is due to the variation of thermal and mass diffusivities or what is called the Lewis number. So, this is Lewis number variation, Lewis number variation is what is affecting this. So, due to that, as I told you, the shift itself is due to the dependency of the diffusivities on the temperature.

And since for hydrogen the diffusivities are very high, due to the variation of this diffusivities with temperature, you we have a mismatch between the maximum adiabatic flame temperature. The  $\Phi$  value at which this is attained and the  $S_L$  attaining the maximum value at a different phi value, which is 1.8 compared to 1.07, where the flame adiabatic flame temperature attains the maximum value. The  $S_L$  attains the maximum value at 1.8.

So, this is only the very big deviation we can see in the hydrogen, actually you can see that hydrogen because of very low molecular weight, diffusivities are very high. And

they vary with temperature etcetera. So, due to this the discrepancy which is not felt in the other fuels is got here.

So, these are the important things. So, here in this graph, we have seen the comparison of the maximum values of  $S_L$  and the typical variation of  $S_L$ , where it is attained at what percentage of fuel in the reaction mixture it is attained, etcetera we have seen here. In this case we have quantified some important results like for example, for straight chain hydrocarbons the  $S_L$  attains the maximum value at 1.08 equivalence ratio.

And for  $C_2H_2$  it attains about 1.2. For hydrogen and CO, it is attained at a much richer equivalence ratios like 1.8 and 2. And the discrepancy between the maximum value of adiabatic flame temperature attained at equivalence ratio and that of  $S_L$ , the equivalence ratio at which the  $S_L$  becomes maximum.

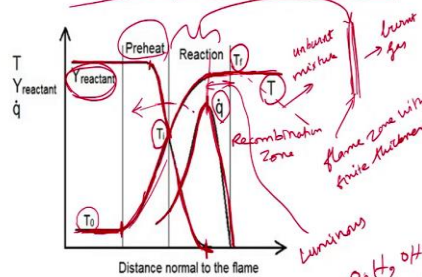
That discrepancy for hydrogen air mixture is given here, 1.07 is the equivalence ratio at which the adiabatic flame temperature of hydrogen-air mixture attains a maximum value, when compared to the  $S_L$  attaining at 1.8 equivalence ratio.

(Refer Slide Time: 16:54)

### Premixed Flame Structure



Premixed reactant approaches the flame in the direction normal to it. Due to the heat transfer from the flame, its temperature increases from the initial value of  $T_0$  to the ignition temperature,  $T_i$ . This zone is called the preheat zone. Reaction zone exists next to it.



Dr. V. Raghavan, IIT Madras

10

Now, the two important characteristics of a premixed flame is adiabatic flame temperature and  $S_L$ , the laminar flame speed. Please understand that adiabatic flame temperature at least has a thermodynamics background, we can calculate with assuming dissociation and so on. But, the flame speed when you want to measure that is actually dependent on the equipment or operators. So, that is not going to be a constant value. So, that we have to understand.

Now, we will move to what is called flame structure. A flame structure is nothing, but description of the variables across the flame. For example, temperature species mass



fraction, heat release etcetera, when you draw the profiles of these quantities across the flame, then what we get is called flame structure. So, there is a flame which is propagating, so, this is flame.

And for example, the flame is stationary and unburnt reactant mixture is here. And this is burnt gas, let us say. So, this is fed and this leaves. So, this is what we are getting here. So, across the flame, how the temperature, species mass fractions, heat release etcetera varies, that is what the flame structure will tell us about.

So, as the unburnt or the reactant mixture approaches the flame zone. So, this is a flame zone, please understand the flame zone has a finite thickness, some small thickness is present in this. So, when the reactant mixture approaches this flame zone, what happens normally is, we will take the components which is normal to this flame.

So, flame zone normal to the direction of the flame surface. The reactant temperature increases. So, the unburnt reactant temperature is  $T_0$ . So, that slowly comes in, once it comes to a particular point it receives heat from the reaction zone. So, this is reaction zone what we are talking about and this is here, that is reaction zone which I call flame.

Now, when this approaches the reactant, this is reactant side, reactant approaches it has a low temperature. And due to the heat from the reaction zone, its temperature increases at a particular point. So, at this point it increases slowly and attains a value of what is called  $T_i$ . This is nothing but the ignition temperature at which the reactant ignites.

So, once it ignites then due to reaction the temperature further increases that is what happens in the reaction zone. Where the temperature increases and reaches a flame temperature value, this is flame temperature  $T_f$ , flame temperature value is reached when the reactions are completed. So, this is the typical temperature profile across the flame.

So, as the reactant mixture approaches the flame, its temperature increases at a particular point due to the heat transfer from the reaction zone to this. So, where the heat transfer starts, the zone called preheat zone, the heat transfer from the reaction zone starts. So, at this point at the starting of the preheat zone, name itself suggests preheat zone, the temperature increases and attains a value of  $T_{\text{ignition}}$  at the end of the preheat zone.

Once the temperature has attained the value of  $T_i$ , the ignition temperature, the reaction zone is said to have started. So, this is starting point of the reaction zone and from this point, the temperature further increases due to the reaction and attains the maximum value called the flame temperature.

Heat release is very low in this zone, there is no reaction etcetera. So, at the middle of the preheat zone some small amount of heat release is happening. But once the reactants are

ignited at the end of the preheat zone or starting of the reaction zone. You can see a sharp increase in the heat release, a sharp increase in the heat release is seen in the reaction zone.

And it attains the maximum value. So, at where it attains the maximum value, you can see that the temperature also reaches almost the flame temperature, that is it. Now, take mass fraction of the reactants, which is higher, a constant value of mass fraction, fresh reactants are coming in towards the flame normal to that. Once it comes to some position it is transported.

Now, some consumption takes place. So, due to the concentration gradient the concentration of reactant is higher here, concentration of reactant is lower elsewhere, downstream it is lower. So, due to the concentration gradient the mass fraction drops. So, after reaching this point they get ignited, the reactants get ignited.

So, this decrease is due to the mass transfer diffusion and after this point its reached, where the temperature also reaches the ignition temperature. The reactant mixture gets ignited. Once the reactant mixture gets ignited, here they are consumed. They are consumed here at a faster rate and I can see that they consume and become 0.

So, at this point you can see that the reactants are entirely consumed. That is the point where the heat release attains the maximum value. As the reactants are fully consumed all the heat is released. Since the reactants are consumed here, the heat release drops sharply.

It drops sharply here and the flame reaches the flame temperature. And I am assuming that after this there is no heat loss so, the temperature remains almost constant. If there is a heat loss further away from the flame, then the temperature can typically decrease after that due to the heat loss.

Now, you can see this is a typical laminar flame structure, where we try to plot the profiles of temperature, reactant mass fractions, heat release etcetera as a function of the distance normal to the flame. Across the flame we are trying to plot. So, premixed reactant approaches the flame in the direction normal to that.

Then, due to heat transfer its temperature increases from the initial value of  $T_0$  to the ignition temperature of  $T_i$ . So, this zone where this increase happens is called preheat zone, then the reaction zone will be just next to it. Once the temperature reaches  $T_i$  the reaction zone starts.

(Refer Slide Time: 24:26)

## Premixed Flame Structure



Reaction zone has a very small thickness; order of a milli-meter.

Usually towards the end of the reaction zone, a bright or luminous zone is present, where the temperature attains a maximum, called the flame temperature,  $T_f$ .

In addition to heat transfer from the reaction zone to the preheat zone, radicals such as H, O, OH and so on, are also transported from the reaction to the preheat zone.

Reactants heated to the ignition temperature, react with these radicals through the chain initiation reactions, and enable the onset of chain propagation and chain branching reactions in the reaction zone.

For lean to stoichiometric mixtures, this causes a reduction in the mass fraction of the reactants and a further rise in the temperature in the reaction zone.

Dr. V. Raghavan, IIT Madras



Now, the reaction zone basically has very small thickness as I indicated here, schematically this is very typical thickness say some 3 mm or 4 mm something like that. It is typically in the order of mm, it will be a very small zone. I have exaggerated in this to show the reaction zone here. So, the reaction zone is very small zone of the order of millimeter. That is the thickness of the reaction zone.

So, usually at the end of the reaction zone a bright. So, once you see here, the heat releases fully there and maximum temperature is attained. Then, in this end of the reaction zone you will see the luminous portion of the flame. So, we have already shown that the luminosity is attached to the flame temperature. So, once the flame temperature is reached, maximum temperature is reached, then the luminosity will occur.

So, that the flame becomes luminous at the end of the reaction zone, where the maximum flame temperature is attained. Towards the end of the reaction zone a bright or luminous zone is present, the temperature attains the maximum value called the flame temperature.

Now, please understand that in this case the heat is supplied.

So, temperature increases and also we can see that in the reaction zone some radicals can be formed. So, like O, H, OH etcetera radicals can be formed these are also transported to this. The radicals are also transported from the reaction zone to the preheat zone, where it may react with the reactants.

So, that also will cause a decrease in the reaction concentration. So, in addition to the heat transfer from the reaction zone to the preheat zone, radicals such as H, O, OH etcetera are also transported from the reaction zone to the preheat zone. Once these radicals come to the preheat zone, they start reacting with the incoming reactants.

So, reactants, they are also heated up slightly, like from the initial temperature to the ignition temperature in the preheat zone. And they react with these radicals which are coming and most of the chain initiation reactions will be completed at the end of the preheat zone.

Now, at the reaction zone which is very small chain propagation, and chain branching reactions which are very fast produce more radicals etcetera, those will take place in the reaction zone. So, the transport of the heat and also the radicals from the reaction zone to the preheat zone, facilitates the initial chain initiation reactions in the end of that preheat zone.

And after that the chain propagation and chain branching reactions of course, the chain termination reaction everything will occur in the reaction zone. So, this is very important. Now, for lean to stoichiometric mixtures, lean mixture to stoichiometric mixture here, this causes a reduction in the mass fraction of the reactants and the rise in the temperature. Because, the reactants are consumed due to the initiation reaction or due to the concentration gradient diffusion takes place, both are the reason for the decreasing trend of the reactants in the preheat zone.

(Refer Slide Time: 28:11)

### Premixed Flame Structure



When the reaction proceeds and the reactants are consumed, the heat release rate rapidly increases and attains a maximum value.

As the major reactant species are consumed at this point, the heat release rate decreases to zero rapidly.

Recombination of the species occurs downstream of the reaction zone. Depending on the initial composition of the reactant mixture, a plume of burned gas or a diffusion flame is present in this zone.

Intermediate species are formed towards the end of preheat zone and are consumed before the end of the reaction zone.

In the case of rich mixtures, the fuel transported out of the reaction zone burns in a diffusion flame mode.



Now, when the reaction proceeds and the reactants are consumed the heat release rate rapidly increases and attains a maximum value, as I told you. So, it attained maximum value around the place, where the reactants are consumed. Now, at that point where it attains the maximum value the major reactant species are consumed.

So, the heat release rate decreases rapidly to 0 value. Now, after the flame reaction zone recombination of species occurs, so, that means, here in this zone to the right of the

reaction zone in this zone we have recombination. So, this is also called recombination zone, preheat zone, then reaction zone, then there is recombination zone.

So, what happens here recombination of species occur. So, for example, some species which are not reacted they will combine or some dissociation would have occurred, they can combine so,  $\text{CO}_2$   $\text{O}_2$  its  $\text{CO}$  plus  $\text{O}_2$  etcetera. So, recombination of species occur downstream that is further away from the reaction zone to the right of the reaction zone.

And now depending upon the initial composition of the reactant mixture; that means, whether it is fuel rich or fuel lean, either a plume of burned gases, if all the fuel are consumed in the reaction zone if this lean to stoichiometric. Then only burned gas will come out and the small recombination reactions will occur.

Now, based upon availability of the air to that recombination zone a diffusion flame will be formed in the recombination zone. Now, intermediate species are formed  $\text{HO}$ ,  $\text{OH}$ ,  $\text{HO}_2$   $\text{H}_2\text{O}_2$  etcetera are formed, towards the end of the preheat zone. We have already seen because as this temperature approaches the ignition temperature, and the small reactions trigger, they form this.

But these intermediate species as the name suggests its intermediate, they are formed and consumed. They are consumed before the end of the reaction zone. So, in the case of rich mixtures fuel transported out of the reaction zone burns as a diffusion flame, this is already what we have discussed.

So, this is the typical structure of a premixed flame, when you understand that physically what is happening we can explain. Quantitatively with the help of the profiles of temperature, reactant mass fraction, heat release and so on. So, this is very important to have any flame. We will be interested in its structure.

That is the quantitative variation of the temperature, species mass fractions, heat release and so on. Several parameters are quantitatively provided across the flame as the function of the distance normal to the flame, if we plot, we get what is called the flame structure.