Combustion in Air Breathing Aero Engines
Dr. Swetaprovo Chaudhuri
Department of Aerospace Engineering
Indian Institute of Science, Bangalore

Lecture - 27
Laminar Premixed Flames VI

Hello. Welcome back to the class. So, in the last classes you see we have discussed quite a lot about laminar pre mixed flames, of course, in an engine you encounter turbulent flames and it can be turbulent pre mixed non premix partially premix flames, but still you understand that the understanding of the laminar structure is very important because we can consider the unit, a unit flame. Let to be essentially building up we can consider a turbulent flame to be essentially and ensemble of these kinds of unit laminar flame. Let us were the inside structure may or may not be disturbed depending on the situation.

So, if to even understand the turbulent flame, it is very important to understand how laminar flame works. How the different physical chemical process is how convection diffusion and reaction are balanced each other inside the inside a laminar flame. Inside a laminar premix flames and in that regard, we have found out we have done analysis to essentially found the find out the laminar flame speed. Whereas, or the laminar burning flux laminar burning flux is essentially the density unbound density times the laminar flames speed. So, we have found out planner laminar flame speed using both simple scaling analysis as well as by using a more detailed mathematical analysis called the Zelda which plans communist analysis.

So, using that we have found out the analytical expression for laminar flame speed about of course, you may have to recognize that even though, it is the laminar flame speed that we have found out this is very important to even describe the global behavior of turbulent flames. Because of the same reason I just discussed that is we can consider the full complete turbulent flamed to be an ensemble of different laminar flame.

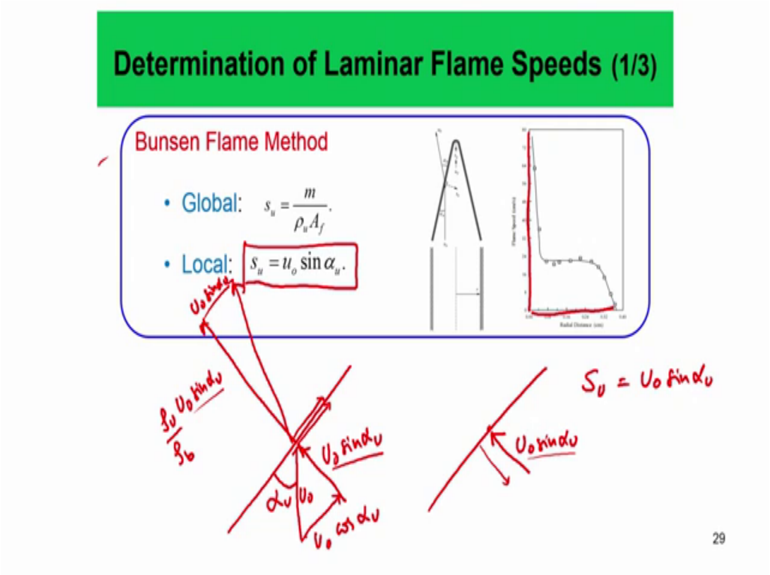
Let us essentially the laminar flame speed equation that we derived that provides a lot of analysis on what needs to be done to even stabilize turbulent flames. Because if the locally the flame behaves like a laminar flame let that the local velocities have to be of the order of the laminar flame speed to make it stabilized, but of course, with there is some more in involved concepts involving like turbulence flames speed which we show in due time that the turbulence flame speed it is much bigger than the laminar flame speed, and as a result you can stabilize the turbulent flame statistically even though you cannot stabilize even though the flow velocities can be much larger than the a laminar flame speed.

So, those things will discuss later, but now I just want to impress upon you that for a laminar for a pre mixed flame laminar turbulent the laminar flame speed is the most important quantity even in the expression of turbulent flames speed, you will see that that which is the global propagation rate of the flame well as laminar flame speed is the essentially the local propagation rate of the flame, and what we have done with is essentially the just a planner laminar flame speed that is even an idealized laminar flame.

So, these things you can connect in 2 different levels with different or increasing orders of complexity. So, I just want to impress upon you that the laminar flame speed is a very important quantity and for is very important quantity in combustion and especially in premix combustion it is the most important quantity.

So, we need to develop tools to understand we have developed these mathematical tools to describe laminar flame speed. And now you will discuss how this laminar flame speed which is such an important quantity can be essentially derived experimentally. So, here we say talk about the different methods.

(Refer Slide Time: 03:45)



Determination of Laminar Flame Speeds (1/3)

Bunsen Flame Method

- Global: $s_u = \frac{m}{\rho_u A_f}$.
- Local: $\boxed{s_u = u_o \sin\alpha_u}$.

So, will see here that we will talk about the determination of laminar flame speed one can essentially determine the laminar flames speed using this Bunsen flame method, where you have this is your Bunsen flame this is the wall and you have this fuel air mixture coming out through this tube. And this is the flame it is essentially a conical flame which is stabilized here, it can be either planner or it can be cylindrical depending on the situation it you can do it both ways actually, and let us consider this is like a planner slot jet which is in 2 dimension that is it is infinitely thick on the plane in into the board and out of the board.

So, there is it is 2 dimensional problem. So, we can estimate the global response of the global flame speed by using this thing, that is if we measure the total mass flow rate coming through this through this tube through this through this tube if you know that, from say your mass flow controller readings or something like that and you know this density of Dunbar mixture, because you know the temperature of that on the pressure of that and you know the cross sectional area if it is a cylindrical tube you can find out the cross sectional area just by a square, if it is slot jth then you find out part per unit thing actually or of course, it cannot we cannot estimate m if it is a fully 2 dimensional fully infinitely thick tube.

So, anyways it is like a suppose if it is a j (Refer Time: 05:10) what is a thickness like this if it is a thickness like this, you can find out m, you can find out af which is the total area like this and so you can find out the idea given that depending on the situation or if it is just (Refer Time: 05:30) you find out the idea by pi r square and then using this thing m by rho uaf you can find out that average flame speed, but of course, you see this average flame speed there at the flame shape is not same everywhere, for example, here it is more or less like a planner it is not planner it is actually cylindrical if you are considering a cylindrical jet and here it is cylindrical barbaras here there is a concave shape. So, then this do may not give you correct results.

So, more refinement would be that and that is shown here, that if we plan the flames if you obtain the flames speed verses radial distance, I will show how to do that it is not same everywhere because the flame structure is different a different places. So, on the other hand you can find out this thing by the following that if you the if you have of flame like this and this is the approach velocity and say the flame is at an angle alpha give it to the approx velocity.

Ten of course, we can resolve this approach velocity which is vertical into 2 components tangential component to the component which is tangential to the flame and the component which is normal to the flame and then we if this is a U 0, then of course, this one is U 0 sine alpha in sine alpha U say this is alpha U and this one is U 0 0 cos alpha U. And this tangential component actually if you just translated to here this vector if you will see that across the flame the tangential component does not change.

So, that there is pure continuity of tangential component across the flame, whereas, the normal component changes because of it release. So, the normal component will change like this and the tangential component does not change. So, the flame the actual flow velocity will be deflected like this.

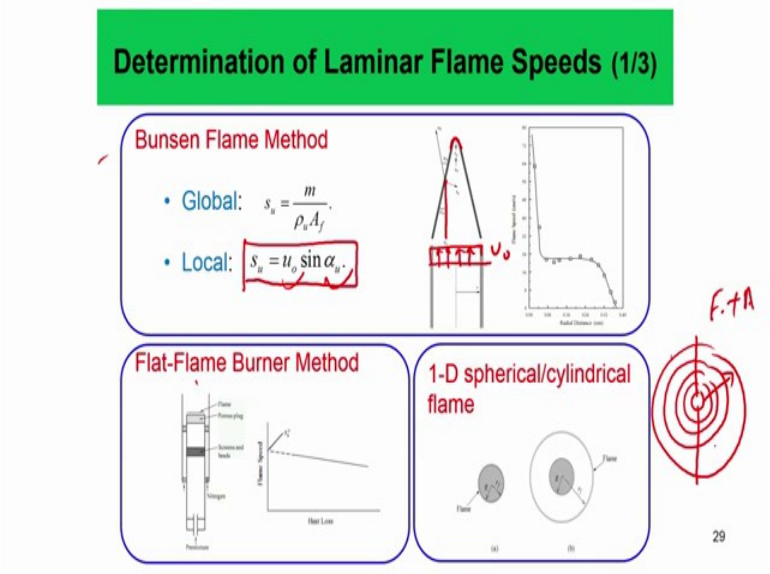
So, this will not change and this will be your basically this normal component will be essentially your U 0 sine alpha U times rho U by rho b, that is it is a because this is rho 0 U 0 sine alpha U. So, this will be U 0 sine alpha U times rho U by rho b because of the fact that your mass has to be conserved because across the flame the mass across has to be has be conserved.

So, and the mass conservation is given by the normal velocity across the surface area. So, that is why you get this relationship whereas, this does not change. So, you see you get still U 0 sine alpha U. And so that is what causes the deflection of this velocity as you see here, but the most importantly the fact is that if this flame is stabilized like this. So, then it means if you are an observer sitting on the reference frame sitting on the flame itself, then it means that then it is the flow is approaching to you at a velocity of U 0 sine alpha U or because the flame is in a stationary state we can consider then the then it is essentially the flame speed, because if this velocity would have been 0 then the flame would have propagated into the sun puck mixer with the same velocity U 0 sign alpha U.

So, then basically the flame speed we can find out s U is equal to U 0 sine alpha U. So, this is what you get here that is a local flame series given by U 0 sine alpha U. So, this is how we can locally you can calculate the local flame speed of Bunsen of Bunsen flame and if you plot this as a radial distance versus flame speed, you will see that this is definitely not here you see that this is definitely not constant, but as it remains constant for a certain radial distance that is up to this region up to this region. Whereas, very near the rim at very near the very near the rim, which is at large radial distance you have heat loss into the walls.

So, that is what the flame speed would reduce as whereas, here the flame speed can change because of the additional curvature effects which we later call a stretch effects.

(Refer Slide Time: 09:38)



Determination of Laminar Flame Speeds (1/3)

Bunsen Flame Method

- Global: $s_u = \frac{m}{\rho_u A_f}$.
- Local: $\boxed{s_u = u_o \sin\alpha_u}$.

Flat-Flame Burner Method

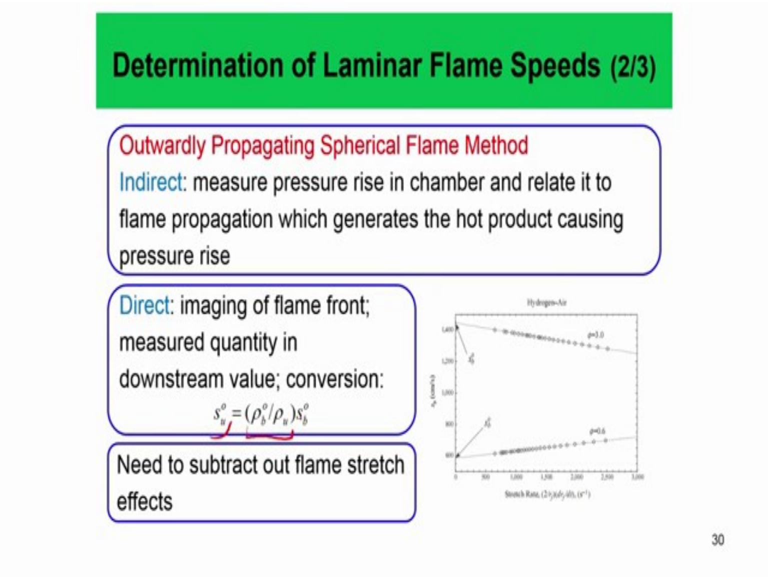
1-D spherical/cylindrical flame

So, because of this the flames it changes, but this at the if you if you estimate this from a photograph of the Bunsen flame you can if you just by estimating the flame angle and the by knowing the mean flow velocity U 0, which of course, has to be uniform at this state otherwise this flame will not be like this, it will be a different kind shape that is if you see that this flow velocity is uniformly going into this then it means that the load which is given by U 0. So, then it means that the flame speed is given by U 0 sine a 5 you should do this on your own to convince this why it is. So, so flames speed is the definition of flames speed there is a speed at which the speed of the flame relative to the local fluid velocity.

So, if the fluid velocity is a play this is a speed or other definition of the local flame series is a is a propagation rate of the flame with respect to the local fluid velocity. So, if the if the local fluid velocity it is at rest of course, the flame propagates into the unbound fluid a mixture at a velocity which is equal to the flame speed on the other hand, if the flight the if the if the fluid velocity is on the other hand of the fluid if the flame is at rest it means to the fluid velocity must be fed at the flame, fed to the flame at a speed equal to the flame speed so that to ensure that the flame is stationary.

So, this is how you estimate the flame speed and of course, you can there are other methods there is this porous plug born on method. So, we can have a porous plug to just stabilize the flame little bit upstream. And then of course, it has some heat loss. So, you can you can do many things just to minimize heat loss well I am not talk in these details, but this is just another method by which you can estimate the flame speed, but this is interesting this x one this spherical and cylindrical flame. So, basically you fill up you fill up a fill up a spherical vessels with the fuel and mixture and fuel plus air mixture and you will inside you ignite at the center with a pair of electrodes and this flame essentially grows like this.

(Refer Slide Time: 11:26)



Determination of Laminar Flame Speeds (2/3)

Outwardly Propagating Spherical Flame Method

Indirect: measure pressure rise in chamber and relate it to flame propagation which generates the hot product causing pressure rise

Direct: imaging of flame front; measured quantity in downstream value; conversion:

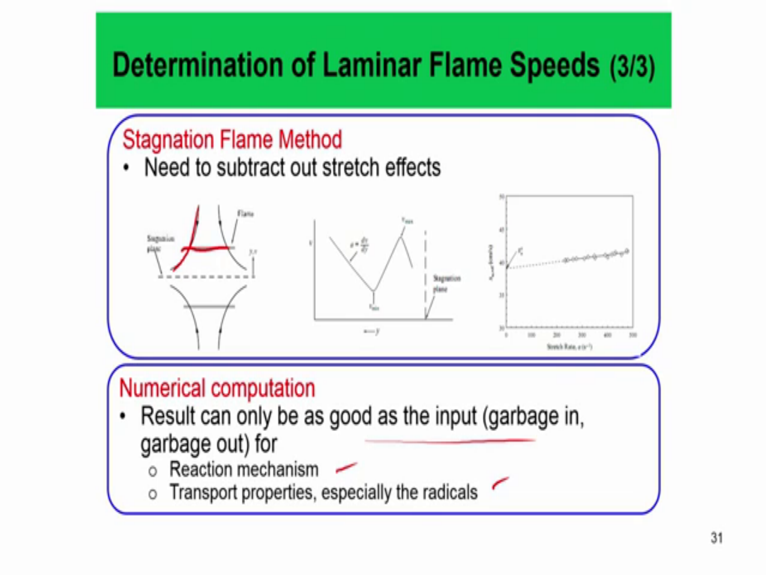
$$s_u^o = (\rho_b^o/\rho_u)s_b^o$$

Need to subtract out flame stretch effects

So, with time it closed like this and of course, by estimating the radius one can find out the radius versus time and then differentiating with respect to time finding dr ftt one can find out the local cody let the local flame speed of course, the indirect ways that one can estimate the pressure rise in the chamber and related to the propagation which generates the hot proto causing the pressure rise, but better is directly made the flame front with a high speed camera and then you measure the quantity in the downstream value and then convert.

So, Si su 0 which basically is rho b 0 times rho b 0 is essentially that a adiabatic bond gas density, divided by U 0 times by v 0 and then you write that you can show that as this sb 0 is essentially, we could be equal to is equal to dr f dt and, but the of course, there is a flame stretch which will discuss later that is a that is surface of the flame is not planner it is stretched because of the curvature effects, and using that we need to essentially subtract the flame speed the flame stretch to arrive at the at the planar laminar flame speed, which is basically the signature value for the given fuel or mixture at a given temperature and pressure upstream temperature and pressure.

(Refer Slide Time: 12:38)



Determination of Laminar Flame Speeds (3/3)

Stagnation Flame Method

- Need to subtract out stretch effects

Numerical computation

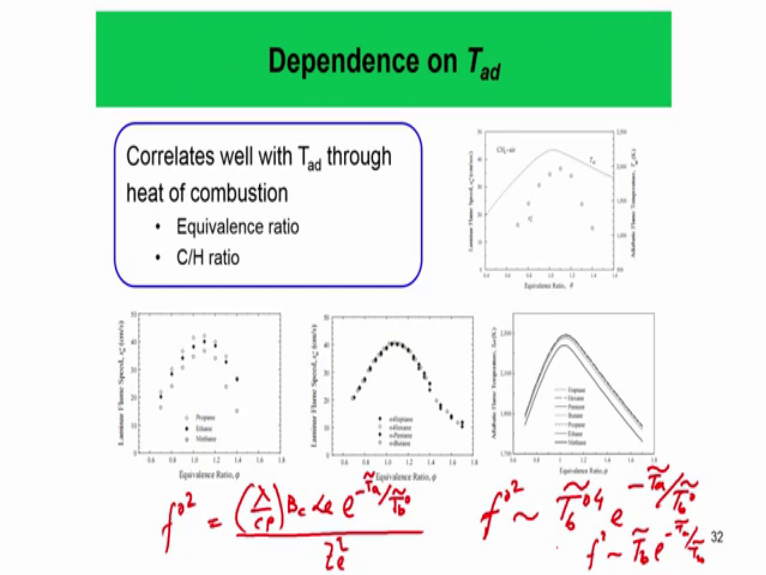
- Result can only be as good as the input (garbage in, garbage out) for
  - Reaction mechanism
  - Transport properties, especially the radicals

So, here also the other methods is that you find out one can do a stagnation flame method of course, the flame is stretched here as well. So, in this stagna in the stagnation flame method what we have is that we have 2 just like this, both are like fuel air mixture which are like a impinging on each other this, just comes like this and this jet comes like this and then pin general stagnation plane and the flame is formed in this engine little upstream and downstream had of the of the stagnation flame respectively as you see here.

So, here is this jet a diverging jet and of course, you see that because of the divergence there is a stretch the flame is stretched and we have to essentially subtract the flame stretch out to get the planar lamina flame speed, which is the parameter of stretcher is the planar laminar flame speed, because it as you see it involves both transport as well as reactions is a very good choice for validating detailed reaction mechanisms. So, that is also one of the reasons why the people have spent a lot of effort in estimating the flame speed or the planar lamina flames speed to at very by different kind of methods with different orders of with different, and try to improve the accuracy of this different methods by which flame speed which could be estimated for to for time.

And, nowadays where people either use this sprinkle flame method, or these stretch flame methods to stretch flame more; this count of flames to estimate the planar laminar flame speed. So, as I was saying that the results can be it is used for validating the reaction mechanisms and for transfer properties especially the radicals.

(Refer Slide Time: 14:20)



Dependence on T_{ad}

Correlates well with T_{ad} through heat of combustion

- Equivalence ratio
- C/H ratio

$$f^{o2} = \frac{\left(\frac{\lambda}{c_p}\right) B_c\, Le\, e^{-\tilde{T}_a/\tilde{T}_b^o}}{\tilde{l}_e^2}$$

$$f^{o2} \sim \tilde{T}_b^{o4}\, e^{-\tilde{T}_a/\tilde{T}_b^o}$$

$$f^o \sim \tilde{T}_b\, e^{-\tilde{T}_a/\tilde{T}_b}$$

So, now next question is that. So, it flames speed is such an important quantity which why flame speed is really such an important quantity, which characterize is the flame both the with the propagation behavior of the flame and also and that comes out because of certain unique structure of the flame unique structure of the of the diffusion region of the reaction region.

Then what does this really depend on and of course, it is a practical interest because you have a you feel a per tube with the a with the flame exterior fuel and mixture and you ignite at the end and of course, the speed the flame will propagate from one end to another end, and it is a practical interest to know what would that speed be because of course, as we I discuss later previously that in a premixed gas turbine combustor locally the flame will be stabilized only at that point where the local flames speed this is equal to the local normal flow velocity.

So, it is inspired in a in designing combustors, also if you are designing our nearly premix combustion one must have a very clear knowledge about what the flame speed of the mixture you are working with otherwise you cannot stabilize the flame.

So, flames speed is really important in that respect and well. So, we need to really understand what does the flames speed depend on. So, if you remember the flame speed we discussed was a was a was obtained like this that is the sender which frank communist k analysis kept me at the flame speed to be like f 0 square is equal to lambda by Cp times Bc times Lewis number times e to the power of minus T a tilde by T b tilde. This was your eta minus activation energy at activation temperature by the bond gas temperature, and this was equal to the minus of r ns number and followed by this delta which number squared.

So, now Zelda which number, if you remember Zelda which number involves Zelda which number involves this thing that is Ta tilde. I feel I can tilde terms that is T be 0 square tilde. And this was Tb tilde minus Ta tilde which is equal to 1. So, if you remember that.

Now, T a tilde if we consider it as constant you say Zelda which number is essentially proportional to Tb 0 square. So, if you see that you can write this as this f 0 square is essentially f 0 square is essentially your T be 0 tilde to the power of 4, because of this Zelda which number square keeping the T activation energy constant times T a tilde Yt Tb 0 tilde. So, you see that the to the leading order and of course, we can write this for any mixture actually f 0 square, f square later that is any bound gas bond lamina burning flux is essentially is equal to Tb tilde which is can be any bound gas temperature need not bad hebetic also the minus Ta tilde by Tb tilde.

So, you see the fact of the matter is that the f 0 that is the burning flux has a very strong dependence on temperature. So, this thing there is the bonding flux having a very strong dependence on temperature says is actually shows up in the experiments or in the simulations also, which tells that and we expect that the burning flux will have a very strong temperature or the or the adiabatic flame temperature or the or the bond gas flame temperature dependence. And we find that an experiments that is if you see that we see that the burning flux to the leading order of the laminar flame speed to the leading order is actually governed most strongly by the adiabatic flame temperature.

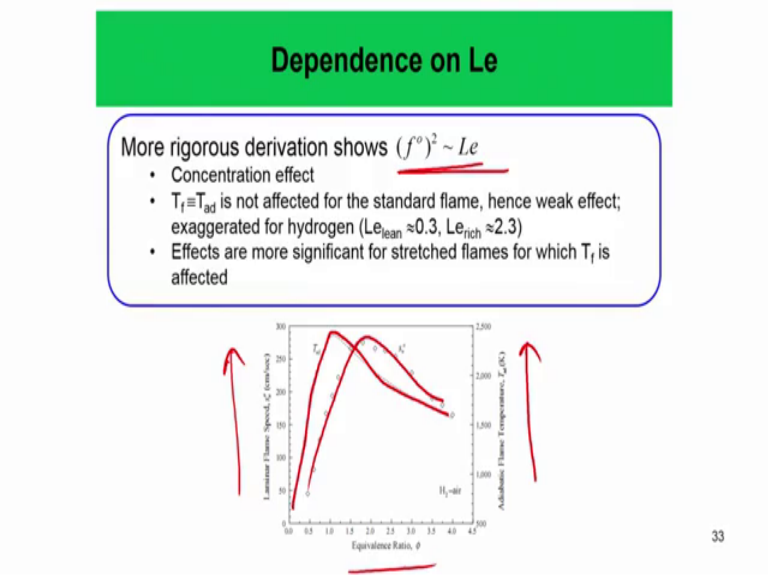
And this is a testimony to that fact, that if we plot laminar flame if you plot laminar flame speed on the y axis and the and the equivalence ratio on the x axis for a methanol mixture and this adiabatic flame temperature on the on the other y axis, if this is your adiabatic flame temperature you see that this is your essentially the your flame speed plot. So, the flame speed mimics almost a adiabatic flame temperature of course, it can shift slightly on the right hand side and left hand side because it has got the other dependent through Lewis number etcetera.

Now that is also has a very important effect in this things. So, you see that if we consider this all this alkanes like all the way from methane propane methane ethane propane to butane pentane hexane and heptane. You see that the flame speed the laminar flame speed of methane is smallest at a given equivalence ratio, then it increases to some extent for a ethane and then it increases slightly for propane. And then when we go here you see that all this laminar flame speeds of butane pentane hexane heptane all same, why is reason the reason is actually the adiabatic flame temperature you see go to the go to this plot, and you plot a adiabatic flame temperature you see that yes in the methane has the lowest adiabatic flame temperature which is correct and, but then ethane increases slightly.

And then this adiabatic flame temperature does not increase at all from propane butane pentane hexane and heptane at a given equivalent ratio very small it changes. So, that is why this flame suite also because the flame speed to the leading order depends on a adiabatic flame temperature it does not change at all for the it does not change at all between butane to heptane and this is called the fuel similarity.

So, butane to n butane to n heptane the flame speed does not changes, and there is fuel only the fact that your adiabatic flame temperature also does not change.

(Refer Slide Time: 20:12)



Dependence on Le

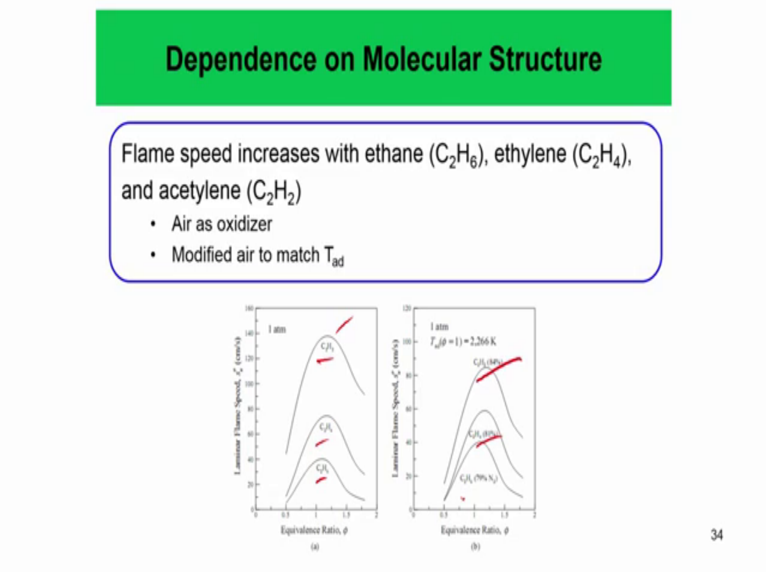
More rigorous derivation shows $(f^o)^2 \sim Le$

- Concentration effect
- $T_f \equiv T_{ad}$ is not affected for the standard flame, hence weak effect; exaggerated for hydrogen ($Le_{lean} \approx 0.3$, $Le_{rich} \approx 2.3$)
- Effects are more significant for stretched flames for which T_f is affected

And now what happens with hydrogen with hydrogen it is little bit little tricky, but though the behavior holds more or less you see that here if you plot that our laminar flame speed on this axis y one axis and the adiabatic flame temperature on the y 2 axis as a function of equivalence ratio this is your adiabatic flame temperature when this is your laminar flame speed. So, yes it changes it has a bearing to that what you see here this plank cum nurse can noise is also says that the f 0 square will be proportional to Lewis number. And this effect is really exaggerated for hydrogen because hydrogen is a very small molecule. So, it is diffusivity is very large. So, which is why in the lean sides the this Lewis number is very small, it is molecule because it is large and on the richer side that is where the effective Lewis number is obtained by that of hydrogen oxygen.

So, this Lewis number is 2.3. So, because of the strong changes in Lewis number this f 0 square. So, so little bit deviated behavior from this adiabatic flame temperature. And this we will see that later these effects are most significant for essentially the stretch clamps. So, this shifting of the flame speed in the flame speeds will actually have a strong impact on the on the stretch rates. And that will be controlled by this Lewis number that we will see later.

(Refer Slide Time: 21:45)



Dependence on Molecular Structure

Flame speed increases with ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2)

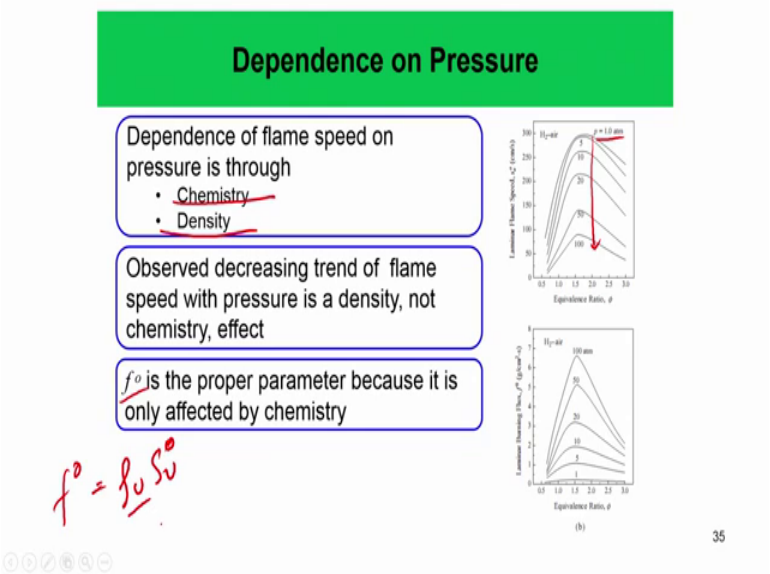
- Air as oxidizer
- Modified air to match T_{ad}

For now will just focus on the planar lamina flame speed because then that is why this f this f 0. So, the planar lamina flames speed once again you will see that the dependence on the molecular structure, how does it depend on the molecules. So, we see that if you plot with like from C2H6 that is ethane to ethylene to acetylene.

So, we see which increases at one atmosphere, but is it increasing due to the adiabatic flame temperature because your ethylene adiabatic flame temperature is large. So, what we can do is that we can we can choose the oxidizers in such a way or we can dilute the oxygen with such an inert in such a way. So, that the adiabatic flame temperature is constant at different cases. And then also we see the acetylene wins over our ethylene and ethane.

So, it is a acetylene despite. So, here the fuel structure also some effect through put on the on the flame speed and that cannot be solely captured by a adiabatic flame temperature. So yes, indeed adiabatic flame temperature is very important, but it is not the only factor that controls the flames will behavior; so that is what is the lesson of this thing.

(Refer Slide Time: 22:53)



Dependence on Pressure

Dependence of flame speed on pressure is through
- Chemistry
- Density

Observed decreasing trend of flame speed with pressure is a density, not chemistry, effect

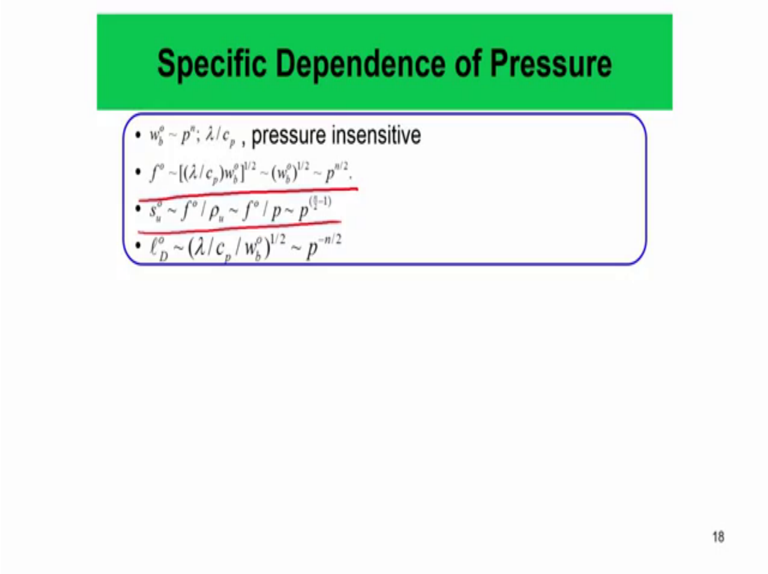
f^o is the proper parameter because it is only affected by chemistry

$f^0 = \rho_u S_u^0$

So, one very important thing is the dependence and pressure. Why because you see engines operate at the high pressure both the car engines as well as the gas turbine engines say gas turbine engines our editor pressure of 30 atmosphere 30 or 40 atmosphere. So, we need to know only knowing what how the flame behaves in one sphere is not good enough.

So, we need to know how the flame here is at 30 or 40 atmosphere or 50 atmosphere. So, what we see is that that if you remember that we obtained this in previous classes you obtain this relationship that, how much does f 0 one what should the f 0 depend on yes this is the thing.

(Refer Slide Time: 23:34)



Specific Dependence of Pressure

- $w_b^o \sim p^n; \lambda / c_p$, pressure insensitive
- $f^o \sim [(\lambda / c_p) w_b^o]^{1/2} \sim (w_b^o)^{1/2} \sim p^{n/2}$.
- $s_u^o \sim f^o / \rho_u \sim f^o / p \sim p^{(\frac{n}{2}-1)}$
- $\ell_D^o \sim (\lambda / c_p / w_b^o)^{1/2} \sim p^{-n/2}$

So, it was shown that that f 0 is going to depend in going to increase with pressure to p to the power of n by 2. And n is the order of the reaction, but as s which is f 0 that is the burning flux normalized by density that should behave in a manner p, to the one n by 2 minus one. So, depending on the order of reaction of course, f 0 must always increase with pressure divided the irrespective of the order of the reaction because the burning flux must increase the pressure, and that comes from the fact that the whole reaction rate is increasing at a high pressure because coalition is act, but s because the density also decreases this is not guaranteed.

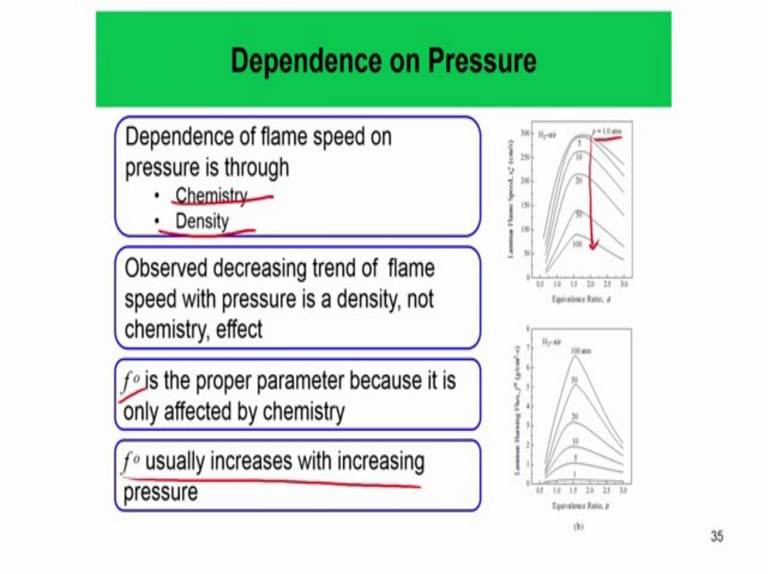
So, depending on the order the pressure can actually the ss actually can increase or decrease with pressure. So, here will see what is happening for actual fuels. So, you see that with pressure as we have seen that the dependence on pressure comes from the flame speed through 2 things, that is it comes to chemistry it comes to density the chemistry part is in the when you say f 0 is essentially this burning flux is proportional to w reaction rate to the power of half. And then the reaction rate we can correlate with pressure so, but then as a su that is flame speed that also contains that also contains your density. So, the density is the density effect is essentially comes the density effect is also can take away some of the chemistry effects on the when it comes to dependence on pressure.

So, we see that that s here if you consider hydrogen inflames at a different equivalence ratios we and at different pressure we see that this highest is for one atmosphere and then it reduces with increasing pressure. So, the flames speed essentially reduces with pressure and the reason is because the density is actually reducing. So, with a density is actually increasing with pressure. So, as a density increases you have more gas to heat up. So, and that is why the flame speed is retarded at high pressure.

So, it is an it is an effect of density it is not a chemistry. Whereas, if you really under I want to understand how the flame speed depends on pressure the better quantity to look at is this burning flux which is f 0 is equal to rho U times su 0. So, this quantity because it accounts to the density waits at the flame speed essentially a density waits at flame speed. So, f 0 is the proper parameter because it is only affected by chemistry and not affected by density.

So, we find that this if we consider the same thing, and if you plot the laminar burning flux with equivalence ratio, we see that with increasing pressure the laminar burning flux at a given equivalence ratio monotonically increases. And that is the pure effect of chemistry which we just discussed.

(Refer Slide Time: 26:25)



Dependence on Pressure

Dependence of flame speed on pressure is through
- Chemistry
- Density

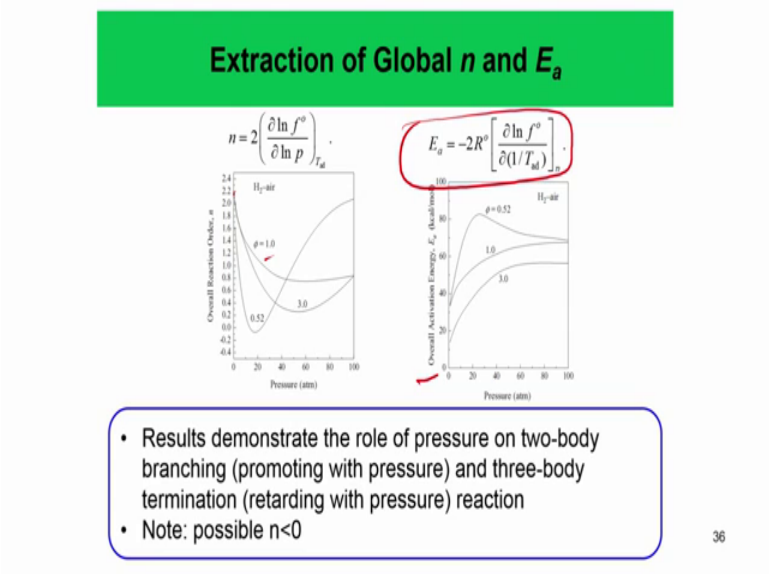
Observed decreasing trend of flame speed with pressure is a density, not chemistry, effect

f^o is the proper parameter because it is only affected by chemistry

f^o usually increases with increasing pressure

So, as you said that f 0 usually increases with increasing pressure and the flame speed actually decreases with increasing pressure. So, that is one important thing you have to keep in mind.

(Refer Slide Time: 26:36)



Extraction of Global n and E_a

$$n = 2\left(\frac{\partial \ln f^o}{\partial \ln p}\right)_{T_{ad}}.$$

$$\boxed{E_a = -2R^o\left[\frac{\partial \ln f^o}{\partial (1/T_{ad})}\right]_n}.$$

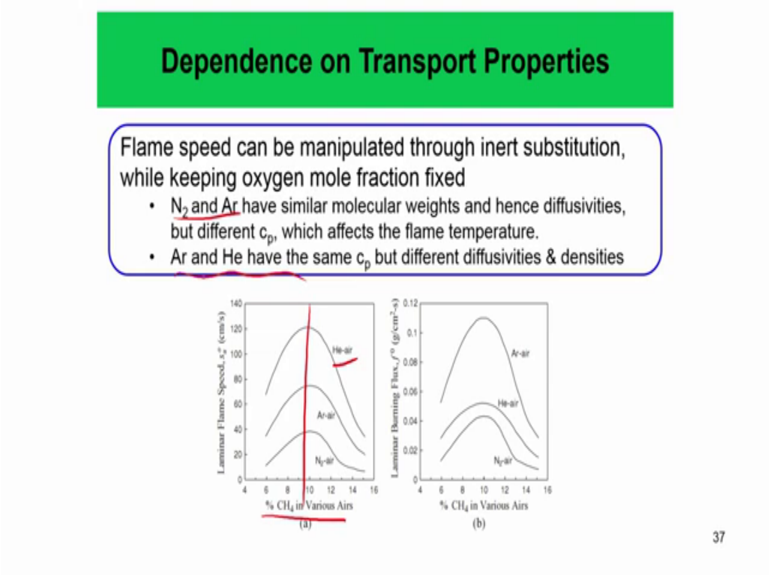
- Results demonstrate the role of pressure on two-body branching (promoting with pressure) and three-body termination (retarding with pressure) reaction
- Note: possible n<0

So, now using that you can these entails the relationship, that without we can find out the global order of the reaction and we see that the global order of the hydrogen air reaction. Of course, as you have seen that hydrogen air combustion involves at least 9 species and 19 21 90 reactions. And this whole thing can be just simplified into one reaction order using this burning flux and the pressure dependence. So, if you plot that we see that the that the this is how for different equivalence ratio is the global order depend on it starts from somewhere near to for larger equivalence ratio cases. And then it drops and then it can again increase. So, that is right because it is less than 2 it is actually mostly it is less than 2 we have basically the flame speed decreasing with pressure.

Now, we can find out the over an activation energy also the global activation energy for the whole hydrogen reaction using this formula as well. So, this results this results demonstrate the role of the pressure on the 2 body reaction and the 3 body reaction. And it is not possible within less than 0 also. So, because the role of 2 body branching reaction is the role of pressure of the we see that the 2 body branching reactions are promoted with pressure and the 3 body non branching reactions terminations. The reactions are not promoted lesser the flames behavior is promoted or retarded with pressure and this is not possible with n 0, but of course, this is the fact on the burning flux whereas, the actual behavior comes from the fact that.

Of course, reaction rate increases with pressure which causes the increase in the burning flux whereas, the flame speed reduces with pressure and that is a purely an effective density and is not an effect of reactions.

(Refer Slide Time: 28:27)



Dependence on Transport Properties

Flame speed can be manipulated through inert substitution, while keeping oxygen mole fraction fixed

- N_2 and Ar have similar molecular weights and hence diffusivities, but different c_p, which affects the flame temperature.
- Ar and He have the same c_p but different diffusivities & densities

So, the fact that the you know another parameter, that has left being left is essentially this is this transfer properties. We have talked about at very flame temperature we have talked about molecular structure we have talked about pressure we have not talked about transferred properties so, but as you see that your m 0 square has proportional to lambda y Cp and all other proper parameters are constant. So, there are how the transfer property effects and the planes it can be easily found out the experiments, where the nitrogen can be replaced with argon and because they have similar molecular weights and diffusivities, but different Cp the flame temperature that adiabatic flame temperature is actually changed..

So, flame speed we just manipulate flame speed using this property. We can manipulate flame speed with different in our substitution. As you see that because the Cp is are changing with different innards though the though there diffusivities us are similar at least for nitrogen and argon they the with nitrogen and argon as the Cp is changing it your flame speed is actually increasing with argon air, and it increases for that with heal (Refer Time: 29:52) air because you have a less your the Cp is less you have less energy to be spent to heat that gas up right.

So, the flame speed is actually is higher to in this cases. So, this is CH4 in very smart this is of course, considers all to be the equivalent ratio, but will what to be equal to 1 behavior here we get. So, similarly with CH4 in different CH4 percentage in different years we see that this is the laminar flame speed. And this is the bar this is the burning flux and of course, the density also plays at rho also, what still the nitrogen has the least burning flacks one by helium air because helium is very light, and your then it goes up increases to argon air.

So, this is what we get.