Advanced Thermodynamics and Combustion
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Module - VIII
Combustion and Flames
Lecture - 28
Laminar Premixed Flame (Part I)

Dear learners, greetings from IIT Guwahati. We are in this course Advanced Thermodynamics and Combustions. Today, we are going to start the last module of this course that is module 8, Combustion and Flames. In this module, on an average 5 lectures are planned.

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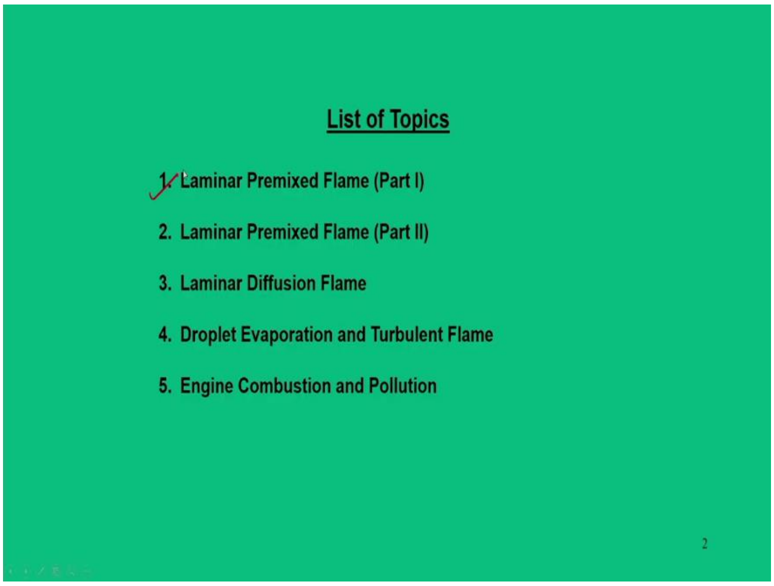

List of Topics

1. ✓ Laminar Premixed Flame (Part I)
2. Laminar Premixed Flame (Part II)
3. Laminar Diffusion Flame
4. Droplet Evaporation and Turbulent Flame
5. Engine Combustion and Pollution

The first two lectures we will be discussing about laminar premixed flame. It will be followed by laminar diffusion flame, then we will enter into the fundamental aspects of droplet evaporations and turbulent flame. And, the last we will try to see the engine combustions and pollution. And in fact, this particular lecture will be fully dedicated to the actual phenomenon that happens in the engines.

And, due to the combustions in the engines and the combustions products that comes out to the exhaust, how it reacts with atmospheric air and that leads to the pollution. So, this is overall picture of this module. So, let us start the first lecture Laminar Premixed Flame Part I.

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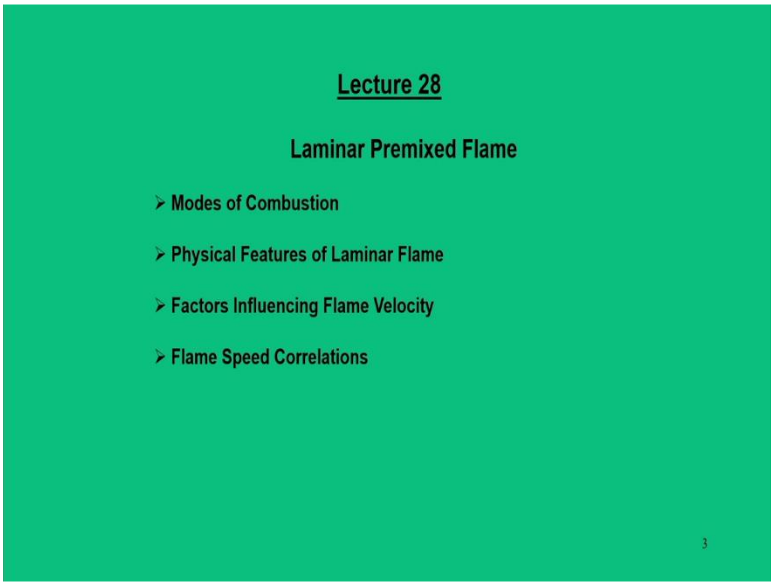

Lecture 28

Laminar Premixed Flame

- Modes of Combustion
- Physical Features of Laminar Flame
- Factors Influencing Flame Velocity
- Flame Speed Correlations

So, in this lecture that is lecture number 28 laminar premixed flame, we will cover the topics such as modes of combustions, physical features of a laminar flame, the factors that influences the laminar velocity and flame speed correlations. So, typically when you talk about flame, it is the flame speed that essentially decides how the reaction should proceed.

If the flame extinguishes means that it is not a self-sustained flame. So, in order to achieve a self-sustained flame, we need to have a desired flame velocity. So, in a laminar premixed flame, the flame velocity plays a critical role and of course, the temperatures, pressures, equivalence ratio they have all have adequate roles that influences the flame velocities.

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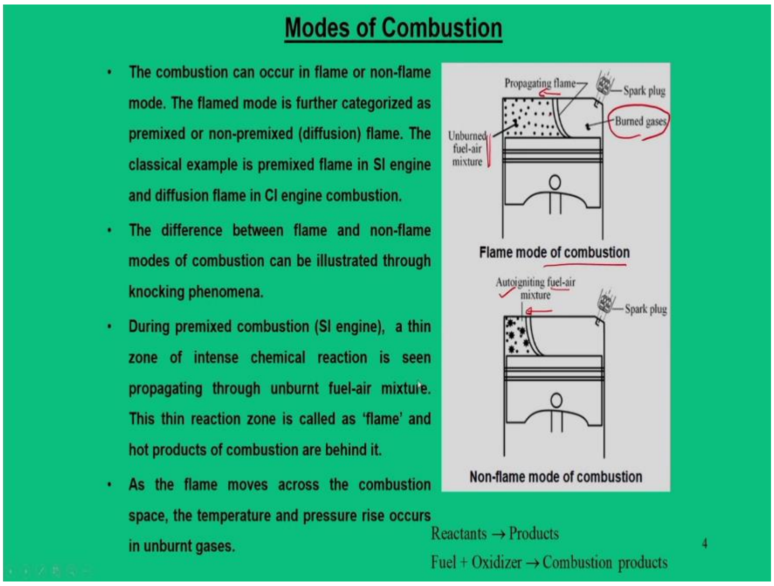

Modes of Combustion

- The combustion can occur in flame or non-flame mode. The flamed mode is further categorized as premixed or non-premixed (diffusion) flame. The classical example is premixed flame in SI engine and diffusion flame in CI engine combustion.
- The difference between flame and non-flame modes of combustion can be illustrated through knocking phenomena.
- During premixed combustion (SI engine), a thin zone of intense chemical reaction is seen propagating through unburnt fuel-air mixture. This thin reaction zone is called as 'flame' and hot products of combustion are behind it.
- As the flame moves across the combustion space, the temperature and pressure rise occurs in unburnt gases.

Flame mode of combustion

Non-flame mode of combustion

Reactants → Products

Fuel + Oxidizer → Combustion products

So, we will discuss them one by one. So, let me start the first I mean to introduce the flame, let us go back to very basics of combustions which we started much earlier in our previous lectures. One point of time we discussed the modes of combustions and to some extent we all know that combustion phenomena take place in spark ignition engines and compression ignition engines.

So, in a spark ignition engine, the fuel and air they mix before the charge enters into the engines. So, it is a premixed combustions and in a compression ignition engine, the fuel and air they are separate entities and they mix as and they meet or admit at some interface in the combustion chamber. So, this is the very basic difference that makes the nature of the flame. So, the combustion can occur in two types of modes; one is flame mode, other is non-flame mode. Typically, in SI and CI engines they are flame mode.

So, the flame mode is further categorized as premixed or non-premixed, non-premixed flames are known as diffusion flame. So, mainly in SI engines the combustion is initiated through premixed flame and typically mixed as well as non-mixed diffusion flames are part of CI engines, we will discuss about that. And, if you broadly look at the flame and non-flame mode combustions, they are detected by knocking phenomena.

For example, if you take an instant that in a premixed combustion in SI engines, there is a thin zone of intense chemical reactions that seem to be propagated in the unburnt air fuel mixtures. So, if you look at this particular figure, in a flame mode of combustion in SI engines, there is a propagating flame. And when the flame propagates; that means, reactants and oxidizers, they already have reacted and it has created. As the flame propagates in from left to right the reactants and products they mix together and they form burnt gases.

Whereas, in the other side of the flame we have unburnt fuel air mixtures, but still and slowly they get reacted as and when the flame enters into their zone. Similarly, in a CI engine when the flame moves there is a region where auto ignition takes place for the fuel and air mixtures, that is mainly because the fuel and air they are considered as a separate entity and they come and mix locally at one particular positions in the engine cylinders. So, that is the basic difference.

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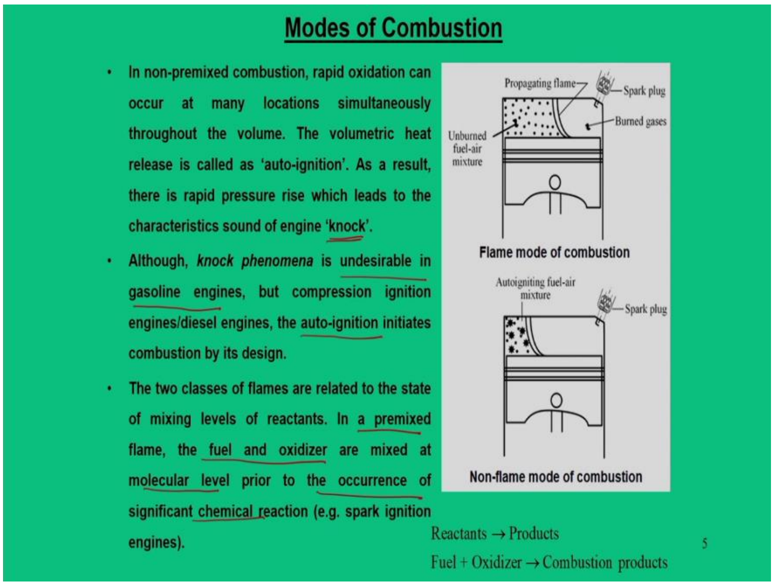

Modes of Combustion

- In non-premixed combustion, rapid oxidation can occur at many locations simultaneously throughout the volume. The volumetric heat release is called as 'auto-ignition'. As a result, there is rapid pressure rise which leads to the characteristics sound of engine 'knock'.
- Although, *knock phenomena* is undesirable in gasoline engines, but compression ignition engines/diesel engines, the auto-ignition initiates combustion by its design.
- The two classes of flames are related to the state of mixing levels of reactants. In a premixed flame, the fuel and oxidizer are mixed at molecular level prior to the occurrence of significant chemical reaction (e.g. spark ignition engines).

Flame mode of combustion

Non-flame mode of combustion

Reactants → Products

Fuel + Oxidizer → Combustion products

Moving further with respect to knocking; so, knocking is a very common phenomenon that leads to the sudden rise in the pressure in the engine cylinder due to the chemical reactions. And in fact, we all know that this knocking is undesirable in diesel engines, but we cannot avoid this knocking in compression ignition engines; because the auto ignition itself creates sudden rise in the pressure in the engine cylinders.

So, with this viewpoint, if you take two classes of flames; one is premixed flame where fuel and oxidizer they are mixed at molecular level prior to the occurrence of chemical reactions that is the very basic definitions when you talk about premixed flames. And, the mixing takes place at molecular levels and this mixture is nothing but a homogeneous mixture.

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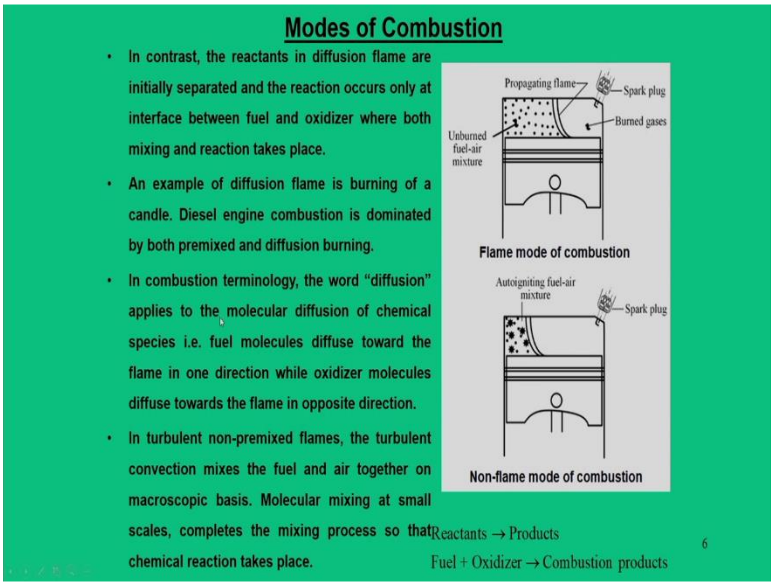

Modes of Combustion

- In contrast, the reactants in diffusion flame are initially separated and the reaction occurs only at interface between fuel and oxidizer where both mixing and reaction takes place.
- An example of diffusion flame is burning of a candle. Diesel engine combustion is dominated by both premixed and diffusion burning.
- In combustion terminology, the word "diffusion" applies to the molecular diffusion of chemical species i.e. fuel molecules diffuse toward the flame in one direction while oxidizer molecules diffuse towards the flame in opposite direction.
- In turbulent non-premixed flames, the turbulent convection mixes the fuel and air together on macroscopic basis. Molecular mixing at small scales, completes the mixing process so that chemical reaction takes place.

Flame mode of combustion

Non-flame mode of combustion

$$\text{Reactants} \rightarrow \text{Products}$$

$$\text{Fuel} + \text{Oxidizer} \rightarrow \text{Combustion products}$$

But, in contrast when if you look at diffusion flames, they are initially separated and the reaction occurs only at the interface between the fuel and oxidizers where actual mixing happens and reaction takes place. An example of diffusion flame is burning of a candle. Diesel engine combustion is mainly dominated by premixed as well as diffusion burning. So, we cannot exactly say it is a diffusion flame, it is a combination of both, but; however, SI engine it is purely dominated by premixed flame.

But, by definition if you go back to cumbersome terminology, the way we define the premix plane that mixing takes place at molecular level and mixture is homogeneous. In the similar context, we say that diffusion to the molecular level is achieved when the fuel molecules diffuse towards the flame in one direction, while oxidizer molecules diffuse to the flame in the opposite directions.

So, basically, we have fuel and air molecules and they come as a separate entity and when the reaction takes place at the location of the flame locations, we say that fuel molecules diffuse towards the flame in one direction and oxidant molecules diffuse to the flame in the opposite directions.

This is the very basic definition for diffusion flame. And, moving further there is another concept of turbulent flames and in turbulent non-premixed flame, the turbulent convection mixes the fuel and air together at microscopic basis. And, in a molecular level or in the small molecular scales, the mixing process occurs in a very small domain or thickness and where the chemical reaction takes place.

In fact, in most of the engine combustions, turbulence was created intentionally so, that we need to have a proper mixing of fuel and air and in particular that is in diesel engines. So, having said the very basic introductory part of the flame, we will now focus on to laminar flame.

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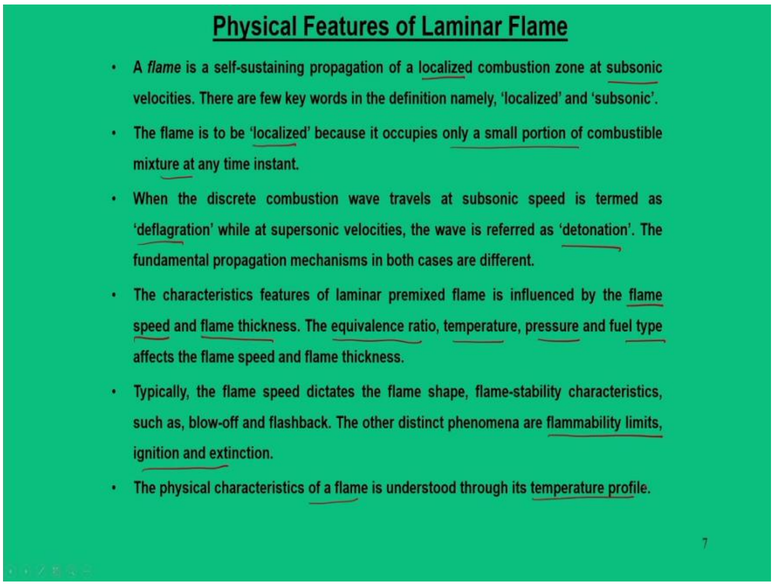

Physical Features of Laminar Flame

- A *flame* is a self-sustaining propagation of a localized combustion zone at subsonic velocities. There are few key words in the definition namely, 'localized' and 'subsonic'.
- The flame is to be 'localized' because it occupies only a small portion of combustible mixture at any time instant.
- When the discrete combustion wave travels at subsonic speed is termed as 'deflagration' while at supersonic velocities, the wave is referred as 'detonation'. The fundamental propagation mechanisms in both cases are different.
- The characteristics features of laminar premixed flame is influenced by the flame speed and flame thickness. The equivalence ratio, temperature, pressure and fuel type affects the flame speed and flame thickness.
- Typically, the flame speed dictates the flame shape, flame-stability characteristics, such as, blow-off and flashback. The other distinct phenomena are flammability limits, ignition and extinction.
- The physical characteristics of a flame is understood through its temperature profile.

So, before we go for the laminar flame, let us understands how this laminar flame look like or what is the basic definition of the flame. So, a flame is nothing but a self-sustaining propagation of localized combustion zone at subsonic speed. So, there are keywords like localized and subsonic. Of course, why the word subsonic? Because, at advanced version of combustion, we can have supersonic mode of combustion where air and fuel movement are treated at supersonic speeds.

But however, that is not part of this course, but to understand a particular features of laminar flame, let us see that why this flame has to be localized; because it occupies small portion of combustible mixture at any time instant. If a flame exists, then it must contain the combustible mixture of fuel and air at any time instance. Now, there are two categories that we can have deflagration or detonations.

So, here deflagration occurs when discrete combustion waves, they travel at subsonic speed. But, when these waves travel at supersonic velocities, we call this as a detonation. So, our main focus will be the combustion phenomenon at subsonic speeds and we are trying to look into the characteristic features of this premixed flame. So, the dominant factors that is influenced for the existence of a laminar flame are its flame, speed and flame thickness.

And, for this existence of this flame speed and flame thickness, we require appropriate environment; means for a self-sustaining flame we require adequate equivalence ratio, temperatures and pressures, fuel types, all conditions need to be satisfied. And in fact, the flame speed, they effectively detect the flame shape, stability such as blow up and flashback, blow up flash back something like either it can create an explosion or flame will be out of the domain or flame will not exist.

And, all the other parameters like we also require the flammability limits, ignitions, extinction; that means, for a self-sustaining flame we need to put appropriate amount of energy, we call this as ignition energy. And, the flame to be terminated we require flame extinction. So, all these things we are going to discuss for a laminar flame. So, before you do that, let us understand the characteristics features of a flame and that is decided through its temperature profile.

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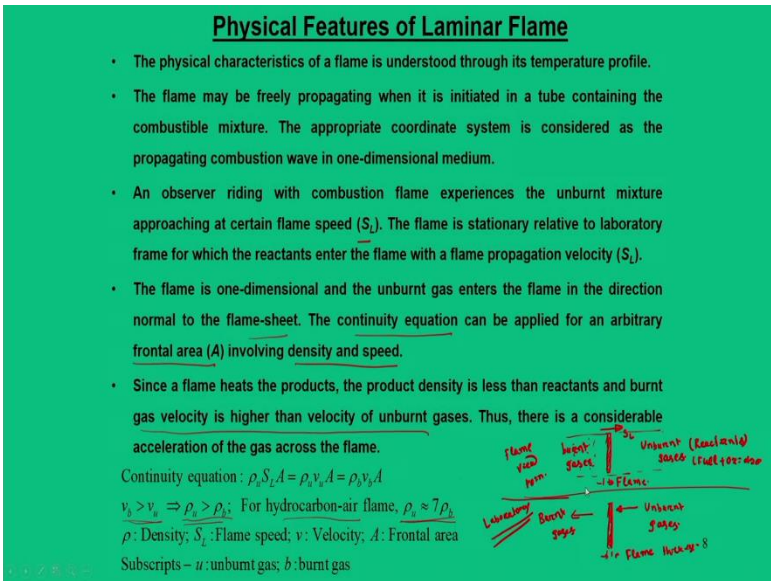

Physical Features of Laminar Flame

- The physical characteristics of a flame is understood through its temperature profile.
- The flame may be freely propagating when it is initiated in a tube containing the combustible mixture. The appropriate coordinate system is considered as the propagating combustion wave in one-dimensional medium.
- An observer riding with combustion flame experiences the unburnt mixture approaching at certain flame speed (S_L). The flame is stationary relative to laboratory frame for which the reactants enter the flame with a flame propagation velocity (S_L).
- The flame is one-dimensional and the unburnt gas enters the flame in the direction normal to the flame-sheet. The continuity equation can be applied for an arbitrary frontal area (A) involving density and speed.
- Since a flame heats the products, the product density is less than reactants and burnt gas velocity is higher than velocity of unburnt gases. Thus, there is a considerable acceleration of the gas across the flame.

Continuity equation : $\rho_u S_L A = \rho_u v_u A = \rho_b v_b A$

$v_b > v_u \Rightarrow \rho_u > \rho_b$; For hydrocarbon-air flame, $\rho_u \approx 7\rho_b$

ρ: Density; S_L :Flame speed; v: Velocity; A: Frontal area

Subscripts – u :unburnt gas; b :burnt gas

We will come back to the temperature profile later, but let us understands that if you want to extinguish a flame, what should happen. The flame may be freely propagating when it is initiated in a tube in a combustible mixtures, the appropriate coordinate system must be considered. So, basically if you consider a flame to exist, normally by definition we say in a one-dimensional framework, if the flame has to exist it has a very small thickness and within this thickness we have reactants, products and actual reaction that takes place.

So, if you see that there is some flame it is travelling at certain speed. So, let us say if it is flame speed is S_L and it is travelling at certain speed. Then, what we see is if you say this is a flame and when you take the coordinate systems such that you are sitting on the flame and in a one-dimensional framework, you try to see where is reactants and where is products. So, if you take this domain, you can see just before this flame, we will see that we will have burnt gases which means flame has already propagated in these regions.

And, in the other side we have unburnt gases, which means it is a mixture of reactants or reactants that is fuel plus oxidizer means that this flame has not entered to the unburnt regions. And, when the flame crosses this burnt regions, already the burnt gases has very high velocities. So, this we see when we are sitting on the flame; with respect to laboratory viewpoint, you assume that you arrest this flame; try to see where is the unburnt gases and where is the burnt gases.

So, in a sense that if the flame is considered to be stationary right now, we can say that this unburnt products or unburnt gases they enter at certain speed and they come as burnt gases. And, entire event that happens in this small thickness, which is nothing but the flame thickness; so, this viewpoint we call this as laboratory viewpoint analysis and this is with respect to flame viewpoint.

So, this is what we have explained here that observer riding on this combustion flame experiences unburnt gases approaching at certain speed. And, the flame is stationary relative to the laboratory frame for which reactants enter the flame with a flame propagation velocity of S_L. And, in a certain flame sheet of certain thickness 1 mm let us say, we can see a one-dimensional zone in which we can apply this continuity equations for a frontal area A, that involves density as well as the speed.

Now, the flame heats the products and when we can write these continuity equations, $\rho_u S_L A = \rho_u v_u A = \rho_b v_b A$. So, A is your frontal area which will get cancelled. But, what remains is that ρ is the density, subscripts u and b stands for burnt and unburnt gases and we have flame speed S_L, v stands for velocity.

So, this equation says that $v_b > v_u$, why? Because, we can say that since the flame heats the products, the product density is less than reactants and the burnt gas velocity is higher than the velocity of the unburnt gases.

So, $v_b > v_u \Rightarrow \rho_u > \rho_b$. Typically, in a hydrocarbon air flame, this is about 7 times higher. So, this particular equation gives considerable acceleration of gas within the flame and all these analyses are done with respect to one-dimensional framework.

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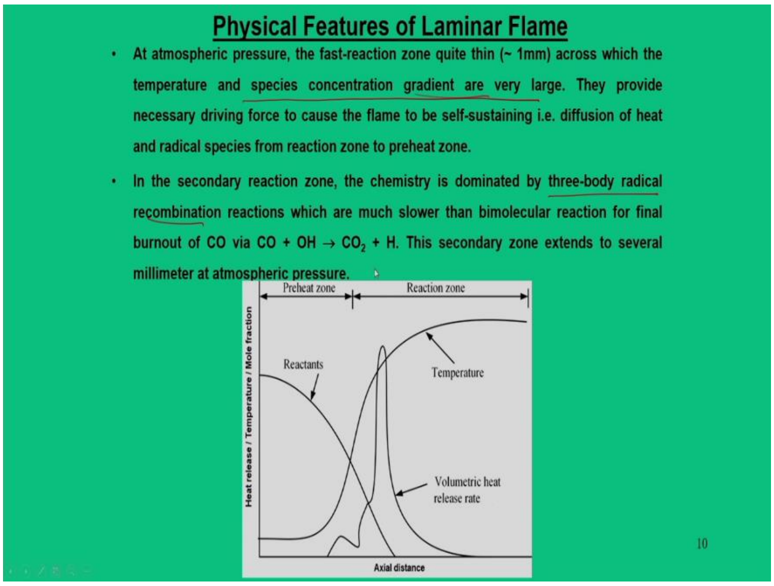

Physical Features of Laminar Flame

- At atmospheric pressure, the fast-reaction zone quite thin (~ 1mm) across which the temperature and species concentration gradient are very large. They provide necessary driving force to cause the flame to be self-sustaining i.e. diffusion of heat and radical species from reaction zone to preheat zone.
- In the secondary reaction zone, the chemistry is dominated by three-body radical recombination reactions which are much slower than bimolecular reaction for final burnout of CO via CO + OH → CO_2 + H. This secondary zone extends to several millimeter at atmospheric pressure.

Now, let us understand another clear picture. So, this is a generic figure that represents what happens in the flame. So, a flame is considered to have two distinct zones. One is preheat zone, other is reaction zone. So, the preheat zone is where the little heat is released and reaction is the zone is where the bulk amount of chemical energy is released.

So, if you look at this particular figure, we are looking at this axial distance versus heat release or temperature and mole fractions. So, as we go in the axial direction; obviously, the concentration or mole fraction for the reactants drops. And, when the reaction keeps on happening temperature shoots up. And, if you look, the temperature shoots very fast rate and the temperature also shoots up and at the same time there is an enough heat release. So, we call this as a volumetric heat release and this heat release is very instantaneous and it takes a shape of a impulsive nature.

So, it is like an impulsive heat load. So, what we see here is that if you divide this entire phenomena in two zones; one is preheat zone, other is reaction zone. So, during the preheat zone not much of information we get about heat release or temperatures but, maximum reactions or changes that takes place in the reaction zone.

And, typically entire event that happens in a flame thickness, which is nearly about 1 mm and, further and if you are very particular about reaction zone, it is further divided into thin regions which involves fast reactions or fast chemistry as well as the slow chemistry.

For examples, the destruction of fuel molecules and creation of intermediate species occur in the fast region chemistries and in fact, they are dominated in a bimolecular reaction. Now, again in the fast reaction zones where, temperature and species concentrations are very large; and to keep this flame in a self-sustaining mode, this temperature and species concentration should be high and because they provide necessary driving force.

Hence, we can say diffusion of heat and radical species from reaction zone to preheat zone can produce a self-sustaining flame. And, another kind of reactions also gets dominated even that is in the secondary zone or reaction zone in which the reaction is dominated by three-body radical recombination. What we discussed earlier they are bimolecular reactions. Now, there are other possibilities that there are radical combinations of the secondary reaction zone where, we can have the three-body radical recombination.

So, when the word recombination takes place, it normally slows down the reaction process. So, as a result the formation of products gets the dominance. One such example we can say that when CO and OH radicals they mix in the reaction zone, they form CO_2. Once CO_2 is formed it automatically slows down because again further dissociation is not initiated. So, the three-body radical zones are normally considered as a recombination reaction, it slows down the bimolecular reactions.

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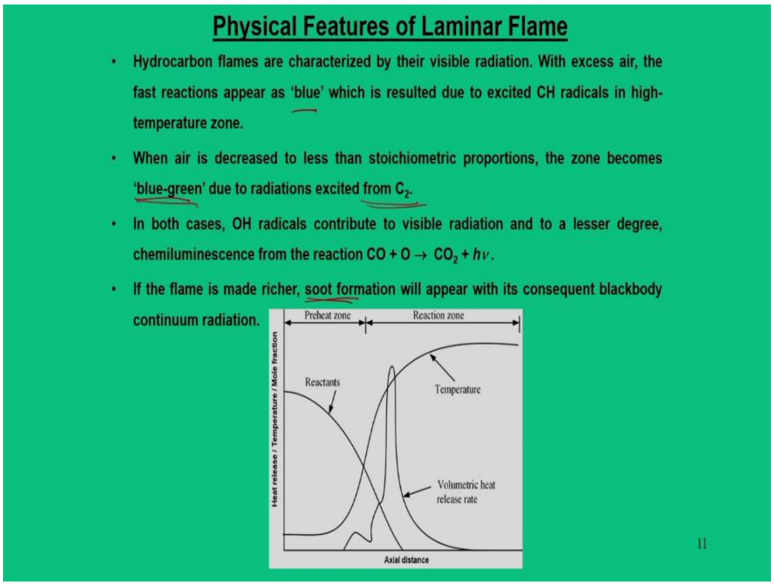

Physical Features of Laminar Flame

- Hydrocarbon flames are characterized by their visible radiation. With excess air, the fast reactions appear as ‘blue’ which is resulted due to excited CH radicals in high-temperature zone.
- When air is decreased to less than stoichiometric proportions, the zone becomes ‘blue-green’ due to radiations excited from C_2.
- In both cases, OH radicals contribute to visible radiation and to a lesser degree, chemiluminescence from the reaction $CO + O \rightarrow CO_2 + h\nu$.
- If the flame is made richer, soot formation will appear with its consequent blackbody continuum radiation.

Another kind of study people have done is that for hydrocarbon flames, when you look at hydrocarbon flames and we try to see what happens in this reaction zone, we find that during excess air reactions or in a lean mixtures, we see the flame to appear as a blue and that is due to the presence of radical CH and that happens in the high temperature zone.

Now, when we come back or reduce the excess air; that means, we come back to stoichiometric or we are entering into the fuel less region, the colour becomes blue-green. So, this is mainly due to the carbon atoms or C_2 and in both the cases we get an effect called as chemiluminescence which means $CO + O \rightarrow CO2 + h\nu$, h is the Planck's constant and ν is the frequency of radiations.

So, these frequency talks about, which colour gets dominated during the reaction process; further, when you enter into richer zone; that means, when the flame gets more and more richer, it is obvious that we will have soot formations. And, this soot formation that we have already analysed that, when we are rich mixtures, soot formation is a very common effect.

And, all these things again when we analyze this soot formations, we analyze through the viewpoint of chemical reactions. Here, we are going to look into the view point of flame. Now, let us understands some mathematical background of how a flame looks like.

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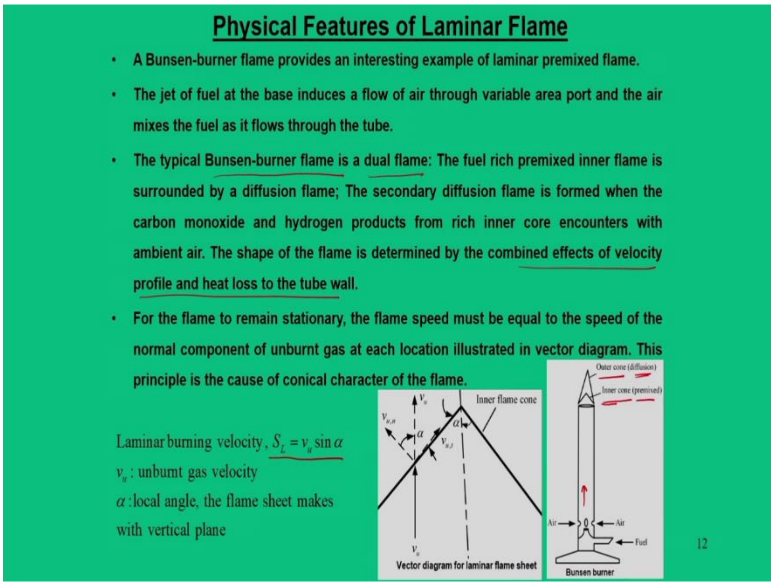

Physical Features of Laminar Flame

- A Bunsen-burner flame provides an interesting example of laminar premixed flame.
- The jet of fuel at the base induces a flow of air through variable area port and the air mixes the fuel as it flows through the tube.
- The typical Bunsen-burner flame is a dual flame: The fuel rich premixed inner flame is surrounded by a diffusion flame; The secondary diffusion flame is formed when the carbon monoxide and hydrogen products from rich inner core encounters with ambient air. The shape of the flame is determined by the combined effects of velocity profile and heat loss to the tube wall.
- For the flame to remain stationary, the flame speed must be equal to the speed of the normal component of unburnt gas at each location illustrated in vector diagram. This principle is the cause of conical character of the flame.

Laminar burning velocity, $S_L = v_u \sin\alpha$

v_u : unburnt gas velocity

α :local angle, the flame sheet makes with vertical plane

Vector diagram for laminar flame sheet

Bunsen burner

A standard example we can say is a Bunsen burner flame which consists of a dual flame. So, if you look at a Bunsen burner flame, the entire idea is that we have slots, we have a tube and in the bottom of the tube there are slots where air enters and also there is a passage of fuel. And, both mix and travel towards the upper regions and what we see in the top is flame consists of two mixed cones. One is inner cone, other is outer cone. So, inner cone is typically premixed whereas, outer cone is diffusion.

So, what does this mean? That the fuel premixed inner flame is surrounded by a diffusion flame. The secondary diffusion flame is formed, because carbon monoxide and hydrogen products from richer cone encounters the ambient air. So, the shape of the plane is further determined by the combined effect of velocity profile and heat loss to the tube wall. Now, for the flame to remain stationary, the flame speed must be equal to the speed of normal component of unburned gases at each location which can be illustrated in the following vector diagrams.

So, let us see this particular figure. We have this inner cone and in this inner cone geometrically, we can say we can define an angle α which is the local angle of the flame sheet that makes with a vertical plane. We have the unburnt gas velocity which is defined V_u vector which comes from the bottom.

Then, we can define two components, one is the normal component, other is the tangential component with respect to this flame sheet. And, based on this we can define laminar velocity $S_L = v_u \sin\alpha$. So, this is the basic definition of laminar burning velocity.

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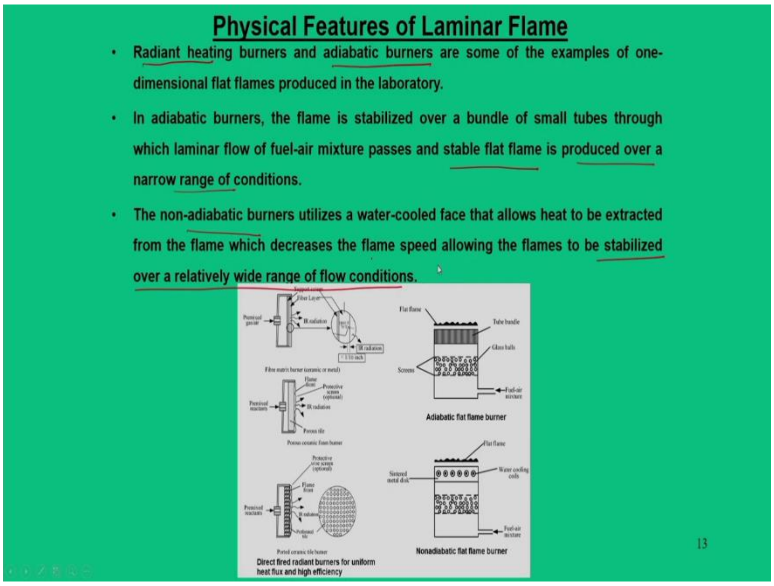

Physical Features of Laminar Flame

- Radiant heating burners and adiabatic burners are some of the examples of one-dimensional flat flames produced in the laboratory.
- In adiabatic burners, the flame is stabilized over a bundle of small tubes through which laminar flow of fuel-air mixture passes and stable flat flame is produced over a narrow range of conditions.
- The non-adiabatic burners utilizes a water-cooled face that allows heat to be extracted from the flame which decreases the flame speed allowing the flames to be stabilized over a relatively wide range of flow conditions.

Direct fired radiant burners for uniform heat flux and high efficiency

Adiabatic flat flame burner

Nonadiabatic flat flame burner

Now, moving further there are the consideration of the flames is normally adopted in various types of burners. And, in the market we have radiant burners, we have adiabatic burners. And what they produce? They produce laminar flames and in the adiabatic burners we get stable flat flames and in non-adiabatic burners we get stable flame, but very narrow regions.

And, in non-adiabatic flame we get same flame, but we get it over a wide range of flow conditions. So, typically depending on the requirement of the burners, we decide what should be the nature of the flame. And, all of these things is decided whether we are retaining this flame speed or not or or self-sustaining flame or not.

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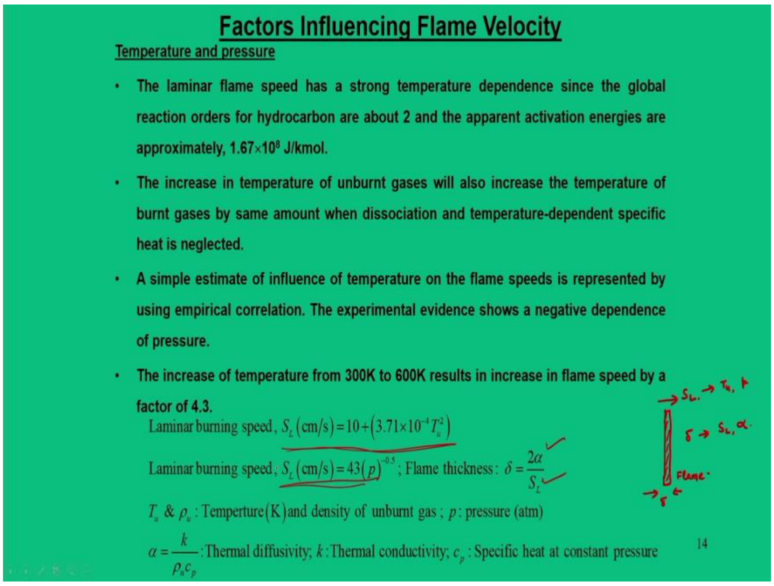

Factors Influencing Flame Velocity

Temperature and pressure

- The laminar flame speed has a strong temperature dependence since the global reaction orders for hydrocarbon are about 2 and the apparent activation energies are approximately, 1.67×10^8 J/kmol.
- The increase in temperature of unburnt gases will also increase the temperature of burnt gases by same amount when dissociation and temperature-dependent specific heat is neglected.
- A simple estimate of influence of temperature on the flame speeds is represented by using empirical correlation. The experimental evidence shows a negative dependence of pressure.
- The increase of temperature from 300K to 600K results in increase in flame speed by a factor of 4.3.

Laminar burning speed, $S_L\,(\text{cm/s}) = 10 + \left(3.71 \times 10^{-4} T_u^2\right)$

Laminar burning speed, $S_L\,(\text{cm/s}) = 43\,(p)^{-0.5}$; Flame thickness: $\delta = \dfrac{2\alpha}{S_L}$

T_u & ρ_u : Temperture(K) and density of unburnt gas ; p: pressure (atm)

$\alpha = \dfrac{k}{\rho_u c_p}$:Thermal diffusivity; k :Thermal conductivity; c_p : Specific heat at constant pressure

$\rightarrow S_L \rightarrow T_u, P$

$\delta \rightarrow S_L, \alpha$

Flame

δ

The next topic of discussion is factors that influences the flame velocity. So, the first two factors are; obviously, temperature and pressures. Laminar flame speed has a strong temperature dependence, because the global reaction orders for the hydrocarbons is about 2. So, it is a kind of second order reaction and for which the activation energy is quite high, it is about 1.67 X 10^8 joule per kilomole.

The increase of temperature of bond gases also increases the temperature of on-board gases by the same amount when dissociation and temperature dependent specifics are neglected. So, this is the role of temperatures and when you think about what is the temperature dependence with respect to flame speed, the laminar speed is with respect to temperatures is given by this expression which says that burning speed is proportional to the square root of temperature of unburnt gases.

And these relations are empirical in natures and of course, and this holds good for most of the temperature ranges from 300 to may be close to 1000 kelvin. Another, dependence of pressure we can say that laminar speed is inversely related to pressures. And, also the film thickness is related to thermal diffusivity and the flame speed.

So, basically if you look at a flame, it has certain thickness δ, it has a characteristic speed S_L. So, S_L depends on temperature of unburnt gases and pressure and δ depends on flame speed and thermal diffusivity. So, these simple relations are given through empirical correlations as shown in these equations.

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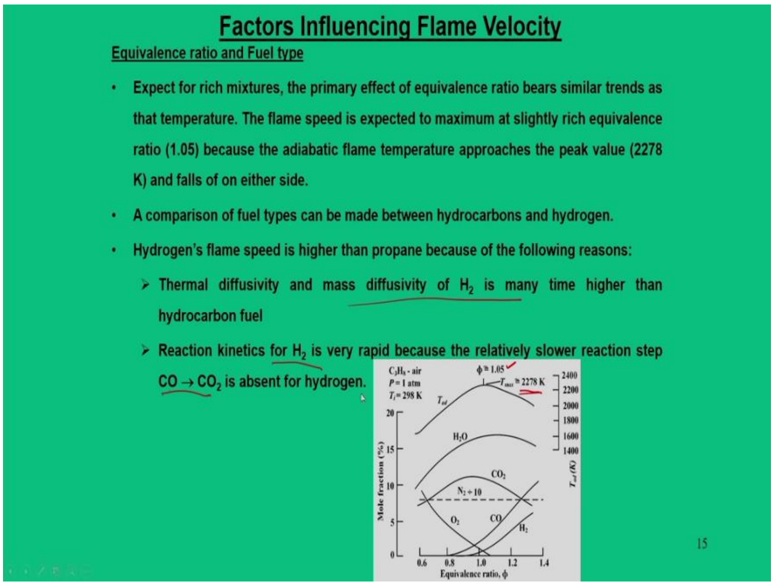

Factors Influencing Flame Velocity

Equivalence ratio and Fuel type

- Expect for rich mixtures, the primary effect of equivalence ratio bears similar trends as that temperature. The flame speed is expected to maximum at slightly rich equivalence ratio (1.05) because the adiabatic flame temperature approaches the peak value (2278 K) and falls of on either side.
- A comparison of fuel types can be made between hydrocarbons and hydrogen.
- Hydrogen's flame speed is higher than propane because of the following reasons:
  - Thermal diffusivity and mass diffusivity of H_2 is many time higher than hydrocarbon fuel
  - Reaction kinetics for H_2 is very rapid because the relatively slower reaction step $CO \rightarrow CO_2$ is absent for hydrogen.

The next dependence factor that influences the flame velocity are equivalence ratio and fuel type. So, if you recall our earlier one of the figures which says that how the temperature changes during a reaction process with respect to equivalence ratio. If you talk about adiabatic flame temperatures, we have seen that for a propane air mixture, the maximum adiabatic temperature is reached about 2278 K at slightly rich mixture, that is closely $\phi = 1.05$.

So, in same philosophy we can say equivalence ratio plays major role as that of temperatures. So, the flame speed is expected to be maximum at slight rich equivalence ratio, because the adiabatic flame approaches peak value and it falls on either side and this logic also is true with respect to equivalence ratio.

Another type of comparison with respect to fuel type, we can make some distinction that hydrogen is considered to be one of the green fuel. And whereas, hydrocarbon fuels are also considered which are being used as a conventional fuels.

And, if you look at hydrogen, in a hydrogen combustion environment, hydrogen flame speed is higher than that of a propane or any hydrocarbon that is mainly because thermal diffusivity and mass diffusivity of hydrogen is much more higher than the hydrocarbon fuels, that is one thing. Second is reaction kinetics for hydrogen is very rapid because the relative slower reaction that is conversion of CO to CO_2 is absent.

That means, one of the reaction process there is a step where carbon monoxide changes to carbon dioxide. And this is nothing but a slow reaction and these slow reactions of course, affects the chemical kinetics. And, which is absent in hydrogen because hydrogen is a green fuel and for which you can say the reaction kinetics of H_2 is much higher.

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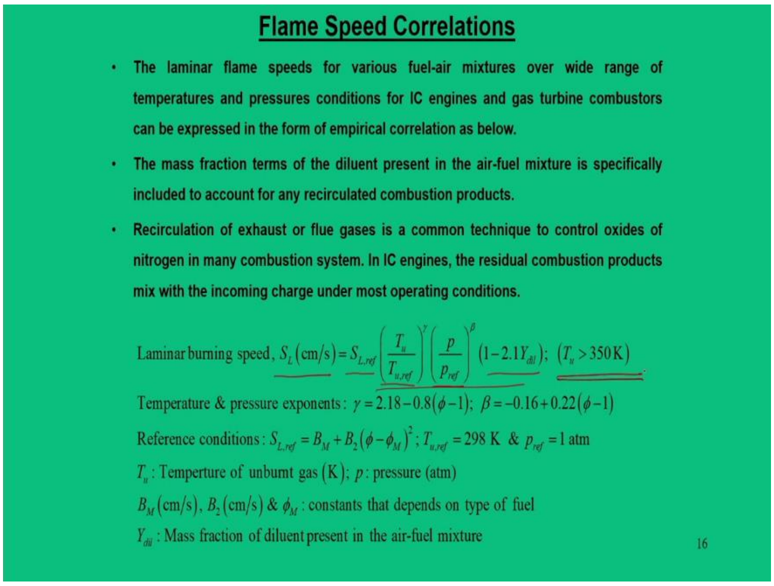

Flame Speed Correlations

- The laminar flame speeds for various fuel-air mixtures over wide range of temperatures and pressures conditions for IC engines and gas turbine combustors can be expressed in the form of empirical correlation as below.
- The mass fraction terms of the diluent present in the air-fuel mixture is specifically included to account for any recirculated combustion products.
- Recirculation of exhaust or flue gases is a common technique to control oxides of nitrogen in many combustion system. In IC engines, the residual combustion products mix with the incoming charge under most operating conditions.

$$\text{Laminar burning speed, } \underline{S_L(\text{cm/s})} = \underline{S_{L,ref}}\underline{\left(\frac{T_u}{T_{u,ref}}\right)^{\gamma}\left(\frac{p}{p_{ref}}\right)^{\beta}(1-2.1Y_{dil})};\ \underline{\underline{(T_u > 350\,\text{K})}}$$

$$\text{Temperature \& pressure exponents: } \gamma = 2.18 - 0.8(\phi - 1);\ \beta = -0.16 + 0.22(\phi - 1)$$

$$\text{Reference conditions: } S_{L,ref} = B_M + B_2(\phi - \phi_M)^2;\ T_{u,ref} = 298\ \text{K}\ \&\ p_{ref} = 1\ \text{atm}$$

T_u : Temperture of unburnt gas (K); p : pressure (atm)

B_M (cm/s), B_2 (cm/s) & ϕ_M : constants that depends on type of fuel

Y_{dil} : Mass fraction of diluent present in the air-fuel mixture

A workable model for flame speed correlation has been developed for laminar speeds. So, here we are going to discuss the laminar speed correlations with respect to pressure, temperatures and some dilutants. One thing I need to emphasize, while developing this correlations, this correlations is with respect to particular fuel with certain reference conditions. And the expressions deal with some pressure and temperature exponents and all these data sheets or data for the fuel types, that can be available in the text books. What it says is that if you look at this particular expressions, the calculation of laminar flame speed depends on three factors that is flame speed at reference conditions, the effect of temperatures of unburned gases, effect of pressures and the effect of dilute. That means, in many IC engines what you do is, you circulate the exhaust gas again into the engines.

So, it affects the engine equivalence ratio, in turn it has a negative effect with respect to flame speed; that means, flame speed reduces with the presence of dilutants. So, this means that the recirculation of exhaust or flu gases mix with incoming charge in most of the operating conditions, this reduces the flame speed. So, as you can see in this figure. And in fact, this particular lessons holds good for temperature much above than 350 kelvin.

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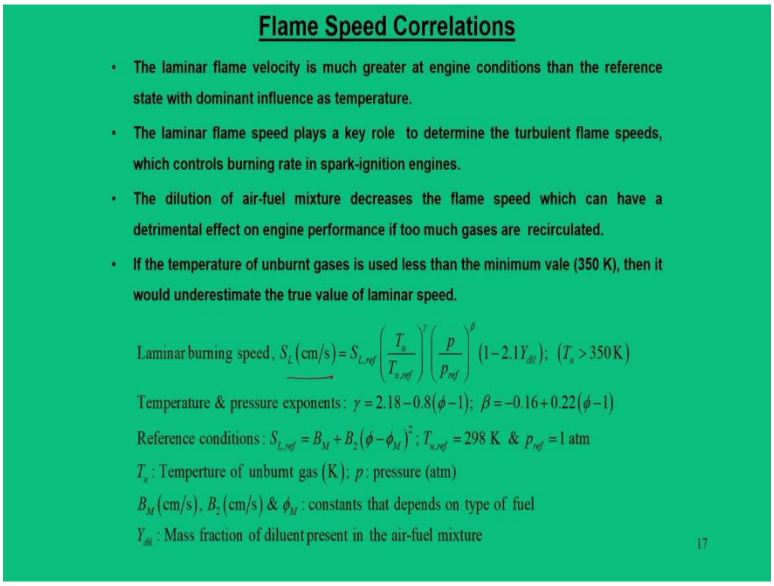

Flame Speed Correlations

- The laminar flame velocity is much greater at engine conditions than the reference state with dominant influence as temperature.
- The laminar flame speed plays a key role to determine the turbulent flame speeds, which controls burning rate in spark-ignition engines.
- The dilution of air-fuel mixture decreases the flame speed which can have a detrimental effect on engine performance if too much gases are recirculated.
- If the temperature of unburnt gases is used less than the minimum vale (350 K), then it would underestimate the true value of laminar speed.

$$\text{Laminar burning speed, } \underrightarrow{S_L\left(\text{cm/s}\right)} = S_{L,ref}\left(\frac{T_u}{T_{u,ref}}\right)^{\gamma}\left(\frac{p}{p_{ref}}\right)^{\beta}\left(1-2.1Y_{dil}\right);\ \left(T_u > 350\,\text{K}\right)$$

$$\text{Temperature \& pressure exponents: } \gamma = 2.18 - 0.8\left(\phi - 1\right);\ \beta = -0.16 + 0.22\left(\phi - 1\right)$$

$$\text{Reference conditions: } S_{L,ref} = B_M + B_2\left(\phi - \phi_M\right)^2;\ T_{u,ref} = 298\ \text{K}\ \&\ p_{ref} = 1\ \text{atm}$$

T_u: Temperture of unburnt gas (K); p: pressure (atm)

B_M(cm/s), B_2(cm/s) & ϕ_M: constants that depends on type of fuel

Y_{dil}: Mass fraction of diluent present in the air-fuel mixture

And, if you use this formula for less than 350 kelvin, we get an underestimate value with respect to flame speed. And, for our study we can say this laminar speed correlations is a very strong relations which can be used for solving many numerical problems of the combustion studies.

Of course, this particular relation has dominant influence we can say with respect to temperature as well as pressures. And, in particular while dealing with the turbulent flame analysis, the estimate of laminar flame speed plays a key role. So, this thing is very vital in the study.

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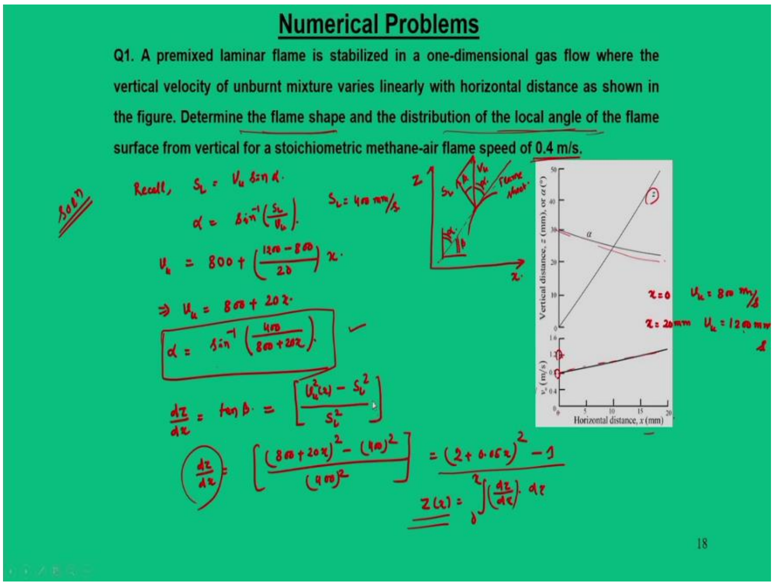

Numerical Problems

Q1. A premixed laminar flame is stabilized in a one-dimensional gas flow where the vertical velocity of unburnt mixture varies linearly with horizontal distance as shown in the figure. Determine the flame shape and the distribution of the local angle of the flame surface from vertical for a stoichiometric methane-air flame speed of 0.4 m/s.

Soln

Recall, $S_L = V_u \sin\alpha$.

$\alpha = \sin^{-1}\left(\frac{S_L}{V_u}\right)$. $S_L = 400\ mm/s$

$V_u = 800 + \left(\frac{1200-800}{20}\right)x$.

$\Rightarrow V_u = 800 + 20x$.

$\boxed{\alpha = \sin^{-1}\left(\frac{400}{800+20x}\right)}$ ✓

$\frac{dz}{dx} = \tan\beta = \left[\frac{V_u^2(x) - S_L^2}{S_L^2}\right]$

$\frac{dz}{dx} = \left[\frac{(800+20x)^2 - (400)^2}{(400)^2}\right] = (2+0.05x)^2 - 1$

$z(x) = \int_0^x \left(\frac{dz}{dx}\right) dx$

$x = 0$ $V_u = 800\ m/s$

$x = 20\ mm$ $V_u = 1200\ mm/s$

So, with this we completed the today’s lecture parts, the second component we are going to discuss is to solve some numerical problems based on our discussion. So, the first problem talks about a situation, where we are considering a premixed laminar flow in a one-dimensional gas flow where the vertical velocity of unburnt gases varies linearly with horizontal distance as shown in this figure.

So, we are supposed to find what is the flame speed, flame shape, distribution of local angle and flame surface from the vertical for a stoichiometric methane air flame speed of 0.4 m/s. So, basically the problem is nothing but we need to recall our study where we say that if you say we have a flame front which is plotted in a z - x coordinate.

And, if you take a flame sheet which is propagating and we can draw one vertical which is nothing but your flame speed S_L and unburnt gases which can go as Vu. And, if you take the angle point of reference, then you can say this angle is nothing but your α and this angle is nothing but β.

And, at one particular point on this flame sheet, we draw a tangent and configure this geometrical information. And, what the question is asked? We need to find what is this flame shape first thing and distribution of local angle, local angle means how alpha varies with the distance.

What is the data given? Data given is referred with respect to figure. Your vertical unburnt velocity that varies in a distance 0 to 20 mm and speed varies from 0.8 to 1.2 m/s. So, and this variation is linear. So, this relation is given. So, we recall that laminar flame speed $S_L = v_u \sin\alpha\,; \alpha = \sin^{-1}\frac{S_L}{v_u}$. S_L is given as 0.4 m/s, we will write 400 mm/s.

$$@x = 0, v_u = 800\frac{mm}{s}\ ; @x = 20mm, v_u = 1200\frac{mm}{s}$$

$$v_u = 800 + \left(\frac{1200 - 800}{20}\right)x = 800 + 20x$$

$$\alpha = \sin^{-1}\frac{400}{800 + 20x}$$

To find the flame speed we need to find the z versus x. So, from this figure we can find what is $\frac{dz}{dx}$.

$$\frac{dz}{dx} = tan\beta = \frac{v_u^2 - S_L^2}{S_L^2} = \frac{(800 + 2x)^2 - 400^2}{400^2} = (2 + 0.05x)^2; z(x) = \int_0^x \left(\frac{dz}{dx}\right)dx$$

So, these equations can be integrated to get the flame shape. So, this is a very simple problem which we can be attempted. And, this figure that takes about that how z varies with x, typically we are going to get it and how alpha varies with x that also you can see it is plotted here. So, ultimately what those plots we come here that is represented through this equation.

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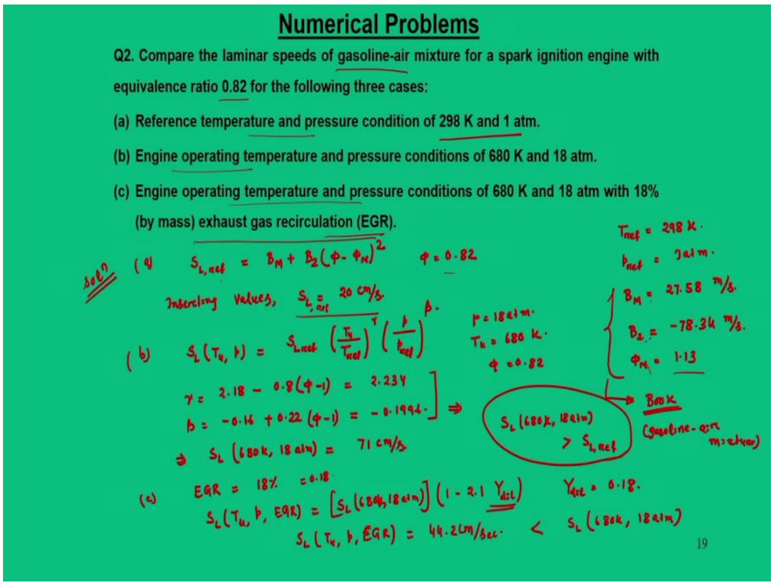

Numerical Problems

Q2. Compare the laminar speeds of gasoline-air mixture for a spark ignition engine with equivalence ratio 0.82 for the following three cases:

(a) Reference temperature and pressure condition of 298 K and 1 atm.

(b) Engine operating temperature and pressure conditions of 680 K and 18 atm.

(c) Engine operating temperature and pressure conditions of 680 K and 18 atm with 18% (by mass) exhaust gas recirculation (EGR).

Sol^n

(a) $S_{L,ref} = B_M + B_2(\phi - \phi_M)^2$ $\phi = 0.82$

Inserting values, $S_{L,ref} = 20$ cm/s.

$T_{ref} = 298$ K.

$p_{ref} = 1$ atm.

$B_M = 27.58$ m/s.

$B_2 = -78.34$ m/s.

$\phi_M = 1.13$

Book (gasoline-air mixture)

(b) $S_L(T_u, p) = S_{L,ref}\left(\frac{T_u}{T_{ref}}\right)^{\gamma}\left(\frac{p}{p_{ref}}\right)^{\beta}$. $p = 18$ atm. $T_u = 680$ K. $\phi = 0.82$

$\gamma = 2.18 - 0.8(\phi - 1) = 2.234$

$\beta = -0.16 + 0.22(\phi - 1) = -0.1996$. $\Rightarrow$ $S_L(680K, 18 atm) > S_{L,ref}$

$\Rightarrow S_L(680K, 18 atm) = 71$ cm/s

(c) EGR = 18% = 0.18

$S_L(T_u, p, EGR) = [S_L(680K, 18 atm)](1 - 2.1\, Y_{dil})$ $Y_{dil} = 0.18$.

$S_L(T_u, p, EGR) = 44.2$ cm/sec. $< S_L(680K, 18 atm)$

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The 2nd problem which we are going to discuss is about the comparison of laminar speeds of gasoline air mixture in a spark ignition engine at equivalence ratio (ϕ) of 0.82 in three case. One is temperature pressure conditions at reference situations, engine operating conditions and engine operating conditions with an EGR.

So, what is the data given? Data are T reference, normally this T reference is 298 K which is already written in our previous slides, p reference is 1 atmosphere that is your reference conditions. And, fuel parameters at reference conditions are required as $B_M = 27.58 \frac{m}{s}; B_2 = -78.34 \frac{m}{s}; \phi_M = 1.13$.

So, this data we obtained from the book and this data was taken for gasoline air mixture. $S_{L,ref} = B_M + B_2(\phi - \phi_M)^2$. So, inserting the value, we can directly get S_L as 20 centimetre per seconds.

The second part is we have to find with this S_L reference data, we are going to get the flame speed at engine operating conditions.

$$S_L\left(\frac{\text{cm}}{\text{s}}\right) = S_{L,ref}\left(\frac{T_u}{T_{u,ref}}\right)^{\gamma}\left(\frac{p}{p_{ref}}\right)^{\beta}; T \quad = 680K, p \quad = 18\, atm$$

$$\gamma = 2.18 - 0.8(\phi - 1) = 2.234; \beta = -0.16 + 0.22(\phi - 1) = -0.1996$$

So, this will give you S_L as 71 centimetre per second. So, you can see that S_L at 680 kelvin, 18 atmosphere is greater than S_L reference. This is the first conclusion we say. Last part, the same operating conditions, but with exhaust gas recirculation;

$$S_L(T, p, EGR) = S_L(T, p)(1 - 2.1Y_{dil}); Y_{dil} = 0.18$$

So, this number when you calculate that $S_L(T, p, EGR)$ that value is 44.2 cm/s, this means that is less than $S_L(T, p)$.

What it says that exhaust gas recirculation decreases the flame speed and higher circulation of EGR will have a great consequence in terms of flame speed, because it can arrest the flame to almost 0 velocity. So, there are limited situations that exhaust gas can be initiated with certain level. So, with this I conclude the discussions for today.

Thank you for your attention.