Fundamentals of Combustion for Propulsion

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Lecture - 30

Summary - premixed flames

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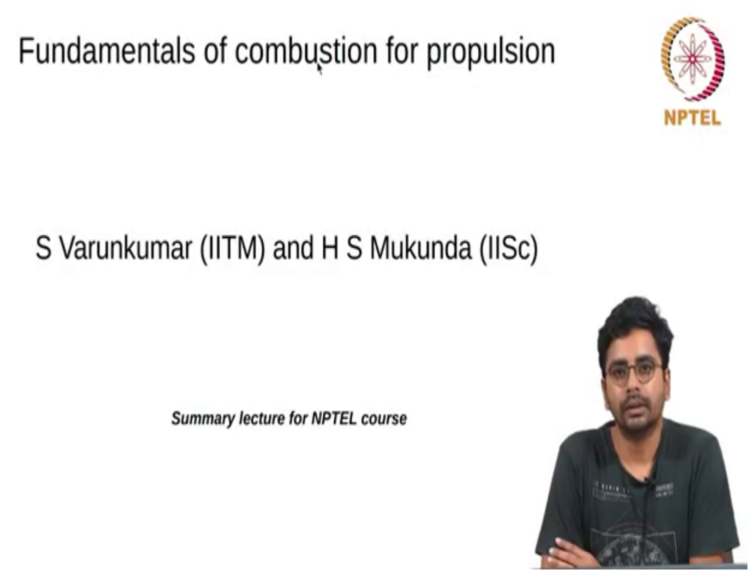

Fundamentals of combustion for propulsion

NPTEL

S Varunkumar (IITM) and H S Mukunda (IISc)

Summary lecture for NPTEL course

Hello everyone, hope you have been enjoying the lectures of this course titled Fundamentals of Combustion for Propulsion. This will be the last lecture in this course and what we have attempted to do here is to very briefly summarize the topics that we have covered in this course.

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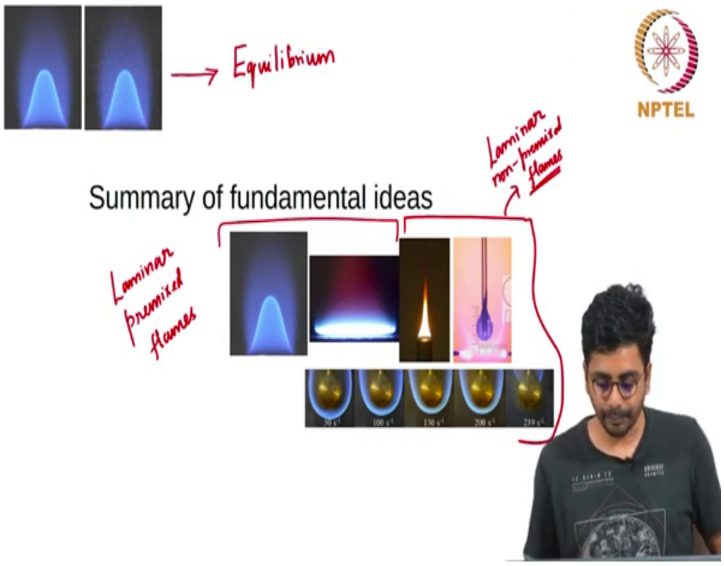

Summary of fundamental ideas

And what is what has been attempted in this particular lecture is to try and convey as much as possible, the key ideas through set of pictures. That were used as a part of the course and I will try to summarize the lectures using these pictures. And, what you see in this particular slide is collage of all the pictures flame pictures that was flame pictures that were used during the first part of the course where we discussed the fundamental ideas.

So, a quick summary of the fundamental ideas. In this slide, I have shown all the pictures that were used in the course to explain some fundamental ideas about flames, both premixed and non-premixed flames. In addition to the idea of a equilibrium. So, these two pictures were used to describe equilibrium. These two pictures were used to explain the key ideas about laminar premixed flames. These two plus the picture at the bottom were used to bring out key ideas about laminar non-premixed flames ok. I will use the same pictures in the following slides to bring out the key ideas.

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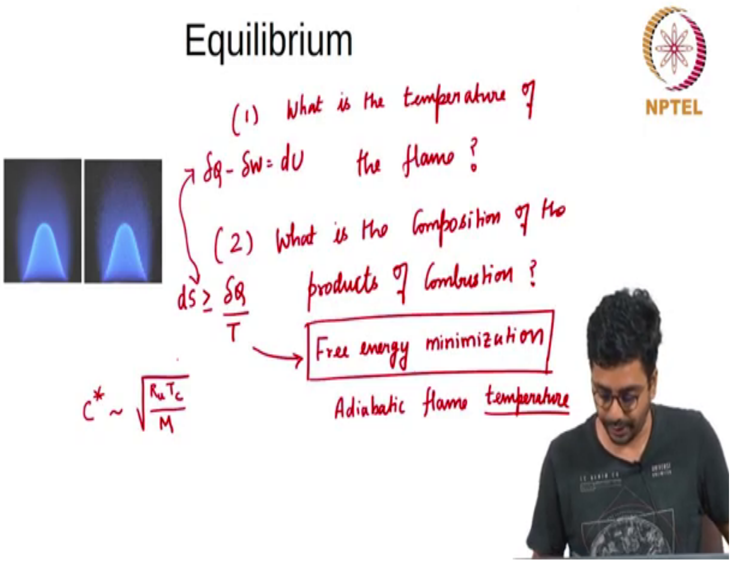

Equilibrium

(1) What is the temperature of the flame ?

$\delta Q - \delta W = dU$

(2) What is the Composition of the products of Combustion ?

$dS \geq \frac{\delta Q}{T}$

$\boxed{\text{Free energy minimization}}$

Adiabatic flame temperature

$C^* \sim \sqrt{\frac{R_u T_c}{M}}$

We saw, we discussed in one of the earlier lectures that as seen as a whole this premixed flame cannot be considered to be a system at thermal equilibrium. But when the when the domain is divided into a large number of small volumes then it is possible to actually treat the conditions inside each one of these volumes as being in thermodynamic equilibrium.

And the natural question is, how small can the volumes be and then we saw that the lower limit for it is should be subset that the continuum assumption is not violated and the upper limit of it is the flame thickness ok. And therefore, when we have a volume that is sufficiently larger such that the continuum assumption is valid and sufficiently smaller. So, that we have a good resolution of the flame thickness. The following meaningful questions can be asked and answered using thermodynamic principles of thermodynamic analysis.

First question is, what is the temperature of the flame? The key question is what is the temperature of the flame. Second question is what is the composition of the products of of combustion. These two questions were can be answered by using together, the first and the second principle of thermodynamics; dU the first law of thermodynamics plus second law which is d s delta Q by T ok.

So, these are the two principles when combined together when combined together leads to a new property, thermodynamic property called free energy which could be the gibbs free energy for constant pressure constant temperature system. The helmholtz free energy for the constant volume, constant temperature system leads to the definition of free energy and the important principle that the state of equilibrium is a state of minimum free energy. So, these two principles combine to give us the free energy minimization principle which is what is used in all equilibrium calculation codes to calculate the equilibrium states ok.

So, the temperature at the equilibrium state is called the adiabatic flame temperature and important fundamental property of a given fuel oxidizer mixture and the initial temperature and pressure ok. Of course, the other fundamental outcome of the equilibrium analysis is the product composition which we saw is important in calculating the characteristic velocity of a propellant combination which we saw is proportional to square root of the universal gas constant multiplied by the flame temperature which we also denoted as the chamber temperature, because this is used in the context of rocket motor divided by the molecular weight of the products ok.

This important quantity called the characteristic velocity can be determined simply from the equilibrium analysis by calculating the adiabatic flame temperature of a given fuel oxidizer mixture and the molecular weight of the products. As you can see it is directly proportional to the square root of the temperature, but inversely proportional to the square root of the molecular weight. And this is the reason why the maximum C star which is a desirable we would like for a given propellant combination we would like to operate the rocket at maximum C star, because that is the condition that leads to maximum specific impulse.

We saw in the case of, in the case of a hydrocarbon oxygen mixtures. Typically the maximum flame temperature and maximum C star points will occur close to stoichiometry, but there are important exceptions for example, liquid oxygen and liquid hydrogen systems are hydrogen oxygen cryogenic rocket systems.

The maximum flame temperature point does not coincide with the maximum characteristic velocity point. Because the molecular weight of hydrogen being much smaller compared to that of oxygen. The maximum C star point occurs on the (Refer Time: 07:50) side ok. So, these are some important conclusions that can simply be drawn by looking at equilibrium analysis for a given propellant combination or a given fuel oxidizer combination.

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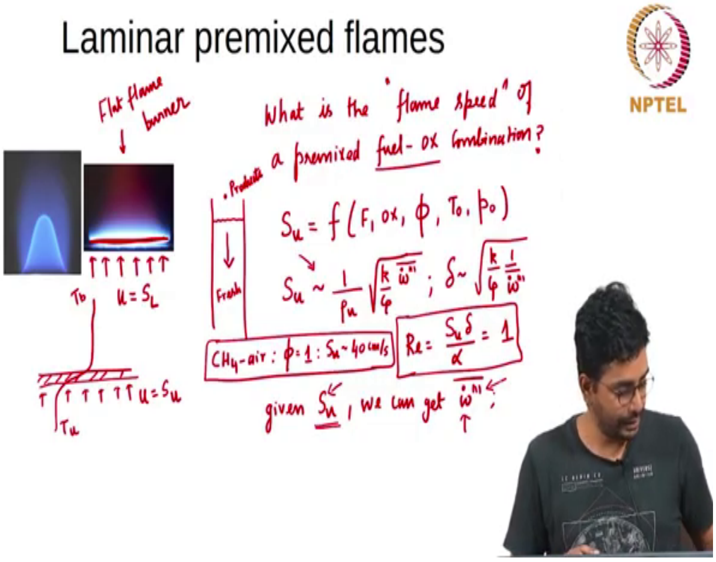

Laminar premixed flames

What is the "flame speed" of a premixed fuel-ox combination?

$S_u = f(F, ox, \phi, T_0, p_0)$

$S_u \sim \frac{1}{\rho_u}\sqrt{\frac{k}{c_p}\overline{\dot{\omega}'''}}$; $\delta \sim \sqrt{\frac{k}{c_p}\frac{1}{\overline{\dot{\omega}'''}}}$

$\boxed{CH_4\text{-air} : \phi = 1 : S_u \sim 40\ cm/s}$ $\boxed{Re = \frac{S_u \delta}{\alpha} = 1}$

given S_u, we can get $\overline{\dot{\omega}'''}$

That I would like to move on to the next key idea that we discussed. It is a laminar premixed flames and we saw the important question in the context of laminar premixed flames is. What is the flame speed of a premixed fuel oxidizer combination? If you go back to the lecture on laminar premixed flames, you will recall a video which showed a tube like this filled with a premixed LPG air mixture ignited at the top which creates a flame front and that flame front propagates into the unburnt mixture this is the fresh mixture this is the products.

So, a laminar premixed flame separates the unburnt mixture from the products and the flame propagates normal to itself in the into the unburnt mixture and it propagates with the characteristic velocity which is best characterized under adiabatic, laminar, one dimensional or as it called unstretched conditions denoted as S u ok.

It is the speed with which a one dimensional adiabatic unstretched flame front propagates into the unburnt mixture. And this again is a characteristic property of the fuel oxidizer combination at a given initial pressure and given initial temperature. Is a function of the fuel oxidizer the equivalence ratio or the ratio in which it is mixed the initial temperature and pressure ok.

We found that this is a characteristic property and the there are several ways of measuring it and one simple way is to use what is called a flat flame burner, this is a flat flame burner where a laminar premixed flame has been a flat laminar premixed flame has been stabilized over the burner. This is the flat laminar premixed flame ok.

And since the flame is stationary, the flame velocity is simply equal to the velocity of the unburnt mixture ok. Remember that flame velocity is the speed with which the flame propagates into the un into a stationary unburnt mixture. But in a frame of reference in which the flame is fixed, the flame is stationary. The unburnt mixtures will move towards the flame at the flame speed and such a flame is what is created in a flat flame burner. The flame is stationary because the unburnt mixture is pushed towards the flame at exactly the flame speed. And therefore, it is straight forward to say that u is equal to S L u is equal to S L.

And what happens across the flame? Fresh fuel oxidizer mixture comes towards the flame and then it is temperature increases ok. This is the flame, this is T unburnt, this is T burnt the gases are moving the unburnt mixture is moving towards a stationary flame at a velocity that is exactly equal to the flame speed this u is exactly equal to S u ok

So, for this for this structure of the flame, we performed a a mass balance analysis and an energy balance when these two equations simple equations, integral equations are put together we we could derive a simple expression for the flame speed and the flame thickness. We saw that s u goes as 1 by rho u square root of the thermal conductivity divided by the specific heat multiplied by the average reaction rate ok. Square root of this, square root of k by c p omega dot triple dash averaged is the reaction rate and the flame thickness goes as k by c p, 1 over omega dot triple dash 1 bar ok. And you can also easily show from here that s u delta by alpha which we can think of as a frame Reynolds number is equal to 1.

So, the flame speed is a direct measure of the reactivity of the mixture. Higher the flame speed higher is the reactivity. Typical values of flame speed are methane air stoichiometric mixture, stoichiometric mixture S u is about 40 centimeters per second ok. That is a good number to remember. Hydrogen air mixture will be much higher than this about a few meters per second, hydrogen oxygen will be much more that because simply because hydrogen air is more reactive than methane air and hydrogen oxygen hyd a mixture of stoichiometric mixture of hydrogen and pure oxygen is much more reactive than hydrogen air mixtures.

And we saw that a more useful form in which these this idea is used is not so much in calculating flame speed given an average reaction rate. In fact, the usefulness is when it is used in reverse; that is given S u we can get omega dot triple dash bar. In fact, this is the idea that was that was used in the heterogeneous quasi 1 D modeling for composite solid propellants that we discussed in the course where we used the burn rate of ammonium perchlorate and the homogeneous ammonium perchlorate H T P B mixtures. The burn rate is nothing but the density of the propellant times the burn rate is equal to the density of the gases times the flame speed.

So, given the burn rate, we can get the flame speed and from the flame speed we actually calculate it the average reaction rate ok. Because it is easier and we can obtain S u or the burn rate of a propellant much more accurately than reaction rate. In some modeling frame works, it is easier to use the burn rate or the flame speed an input and calculate the average reaction rate as an output which can in turn be used for other calculations ok. So, these are the key ideas as far as laminar premixed flame is concerned.

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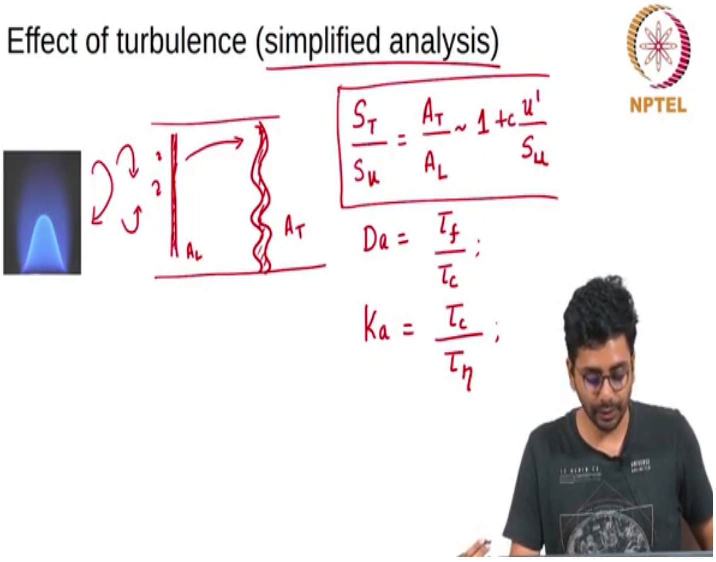

Effect of turbulence (simplified analysis)

$$\boxed{\frac{S_T}{S_u} = \frac{A_T}{A_L} \sim 1 + c\frac{u'}{S_u}}$$

$$Da = \frac{\tau_f}{\tau_c};$$

$$Ka = \frac{\tau_c}{\tau_\eta};$$

Let us move onto a quick analysis of what happens when a laminar premixed flame or when a premixed flame is subjected to turbulence ok. I will not go into too much details, I will only present a very simple analysis. So, consider a laminar flame, a laminar premixed flame ok. Remember the turbulence is a chaotic motion of the flow and it is a special kind of chaos because it has a very specific spatial and temporal structure ok. These spatial structures called the eddies of different sizes can wrinkle premixed flame.

So, because of turbulence, unstretched laminar premixed flame can become a very wrinkled stretched laminar stretched premixed flame ok. You can quickly see that when this happens for a given cross section for a given cross section, the flame surface area has now increased here we had a certain area let us call it A L, here we have a larger area let us call it A T, T for turbulent.

So, one simple way of looking at the effect of turbulence on premixed flame is to quantify the increase in the, increase in the consumption rate of the fuel air mixture in terms of the increase in the surface area. So, one simple way to show this is the flame speed in the presence of turbulence is enhanced from the laminar value, because of the increase in the flame surface area. And the increase is typically proportional to the intensity of turbulence usually some constant here.

In the simplest form; let me remove this equal and say, in the simplest in a simplified analysis of the effect of turbulence the best way to see the effect of turbulence is that it increases the surface area for the same cross section. Thereby increasing the consumption rate of the fuel oxidizer which effectively reflects as an increase in the flame speed. So, the turbulent flame speed is equal to 1 plus a constant times u dash by S u ok.

Of course, keep in mind that this is a very simplified picture in the in the course we characterized the effect of turbulence on premixed flames using two non dimensional numbers; one is called the damkohler number which is the flow timescale based on the integral scale to the chemical timescale. And another non dimensional number called the karlovitz number which is the chemical timescale to the flow timescale based on the Kolmogorov length scale ok.

We will not go into the details here you can refer to the appropriate lecture. But I will move on with this simplified picture of the effect of turbulence on premixed flames.