Fundamentals of Combustion (Part 2)
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Lecture - 44
Introduction to Laminar Premixed Flame

Let us start this lecture with a thought process, life is a marathon; not a race. So, if we recall that in the last lecture, we basically derived a relationship known as Rankine-Hugoniot for a one-dimensional combustion wave which covers both the deflagration and detonation. And, we also discussed various regimes of the Rankine-Hugoniot curve and in which we pointed out that this weak deflagration and weak detonation are possible, where as the strong detonation or strong deflagrations are not possible in nature.

Therefore, we will be basically restricting our discussion to the weak detonation and deflagration. In this course, we will be not discussing about the detonation as such rather we will be talking about deflagration. Before venturing into the deflagration, I would like to take an example on this detonation that is basically will have to determine the pressure.

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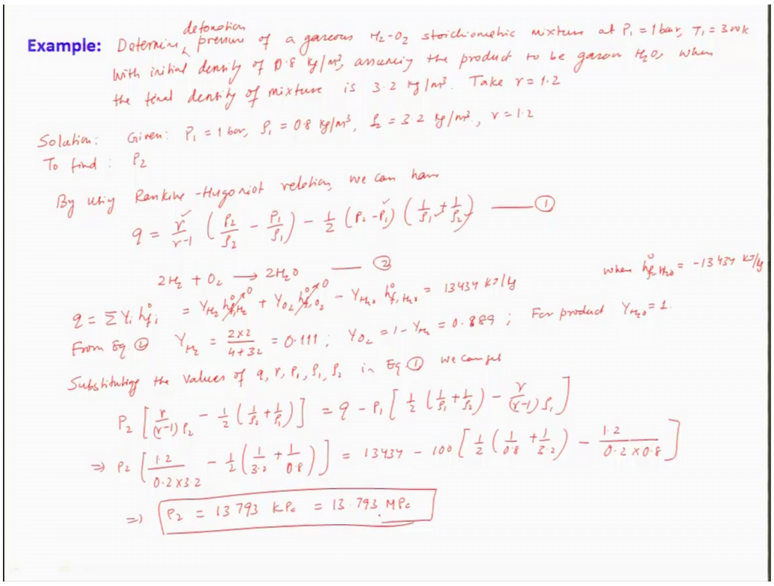

Example: Determine detonation pressure of a gaseous H_2-O_2 stoichiometric mixture at $P_1 = 1$ bar, $T_1 = 300$ K with initial density of 0.8 kg/m³, assuming the product to be gaseous H_2O, when the final density of mixture is 3.2 kg/m³. Take $\gamma = 1.2$

Solution: Given: $P_1 = 1$ bar, $\rho_1 = 0.8$ kg/m³, $\rho_2 = 3.2$ kg/m³, $\gamma = 1.2$

To find: P_2

By using Rankine-Hugoniot relation, we can have

$$q = \frac{\gamma}{\gamma-1}\left(\frac{P_2}{\rho_2} - \frac{P_1}{\rho_1}\right) - \frac{1}{2}(P_2 - P_1)\left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right) \quad \text{——} ①$$

$$2H_2 + O_2 \longrightarrow 2H_2O \quad \text{——} ②$$

when $h^0_{f,H_2O} = -13434$ kJ/kg

$$q = \sum Y_i h^0_{f_i} = Y_{H_2} \cancel{h^0_{f,H_2}}^{0} + Y_{O_2} \cancel{h^0_{f,O_2}}^{0} - Y_{H_2O} h^0_{f,H_2O} = 13434 \text{ kJ/kg}$$

For product $Y_{H_2O} = 1$.

From Eq ② $Y_{H_2} = \frac{2 \times 2}{4 + 32} = 0.111$; $Y_{O_2} = 1 - Y_{H_2} = 0.889$;

Substituting the values of $q, \gamma, P_1, \rho_1, \rho_2$ in Eq ① we can get

$$P_2\left[\frac{\gamma}{(\gamma-1)\rho_2} - \frac{1}{2}\left(\frac{1}{\rho_2} + \frac{1}{\rho_1}\right)\right] = q - P_1\left[\frac{1}{2}\left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right) - \frac{\gamma}{(\gamma-1)\rho_1}\right]$$

$$\Rightarrow P_2\left[\frac{1.2}{0.2 \times 3.2} - \frac{1}{2}\left(\frac{1}{3.2} + \frac{1}{0.8}\right)\right] = 13434 - 100\left[\frac{1}{2}\left(\frac{1}{0.8} + \frac{1}{3.2}\right) - \frac{1.2}{0.2 \times 0.8}\right]$$

$$\Rightarrow \boxed{P_2 = 13793 \text{ kPa} = 13.793 \text{ MPa}}$$

Determine the pressure of a gaseous stoichiometric hydrogen, oxygen stoichiometric mixture at initial pressure of P1 1 bar and temperature T1 you can say 300 Kelvin with the density of 0.8 kg per meter cube and assuming the product to be gaseous hydrogen only, right When the fluid density, when the rather mixture when the final density of mixture is 3.2 kg per meter cube and you can take gamma as 1.2, so basically we will have to look at the pressure of the mixture. This detonation, this will be detonation pressure, right.

That means, it is basically P2 and in these we need to basically find out P2 and what are the things are given is, P1 is given 1 bar and rho 1 is given 0.8 kg per meter cube and rho 2 is given 3.2 kg per meter cube. If you look at we will be using basically Rankine-Hugoniot relationship by using, we can have q is equal to gamma gamma minus 1 P2 by rho 2 minus P1 rho 1 half P2 minus P1 1 by rho 1 plus 1 by rho 2. This is the relationship what we had derived earlier.

Now, if you look at what is given you know like P1 is given, the rho 1 like this is given, rho 1 rho 2 is given, gamma is given, right, these are values are given. Gamma is 1.2. Now, you do not know P2, you do not know the q, right; q is basically how much of heat being released. However, it is given the stoichiometric mixture. That means like 2 hydrogen is reacting with O2 going to water, right.

So, I need to find out basically q; q is y i h f i naught which is equal to y h 2 h f h 2 naught plus y oxygen h f o 2 naught minus y water h f water, right. So, that means I need to evaluate the mass fraction of hydrogen, mass fraction of oxygen and mass fraction of water which is from this you know if I say this is the equation 1, this is equation 2, I can find out the mass fraction of the hydrogen, y of hydrogen. What it would be? It would be basically 2 into 2, right.

The molecular weight of hydrogen divided by 4 plus 32; right 2 moles of hydrogen and 1 mole of oxygen, right. These reactions given in equation 2 are balanced. So, therefore what it would be? It will be 0.111, right. What will be then oxygen? This is on the reactant side, right. What will be oxygen? Then, this will be 1 minus that 1 minus y as to that will give me 0.089. Isn't it and what will be the product side? For product, the mass fraction of water will be 1. Only water is there.

So, you can find it out and then, if I substitute these values and you will have to also get this heat of formation for hydrogen, oxygen and water from the thermo dynamic table or thermo chemical table, right and the hydrogen at the standard state, it will be 0, right.

This will be 0 and this will be also 0, oxygen and where as the h f where h f water happens to be something 13434 kilo joule per kg, right because if get mole basically in mole and then, divide by the molecular weight, you will get basically in terms of kg. If I put this thing here, this will be 13434 kilo joule per kg, right. Then what you do? You basically substitute these values in equation 1.

So, substituting the values of q and gamma and P1 rho 1 rho 2 in equation 1, we can get basically P2. I can write down this expression in terms of P2 P2 gamma gamma minus 1 rho 2 minus half 1 by rho 2 plus rho 1, right. I am just taking you know using this expression 1 and is equal to and is equal to q minus P1 half 1 by rho 1 plus rho 2 minus gamma gamma minus 1 rho 1. So, I will just substitute these values and what I can get that is P2 into this is 1.2 divided by 0.2 into 3.2 rho. 2 is 3.2 minus 1 by 2 1 by rho 2 3.2 plus 1 by rho 1.08 is equal to q q is 13434 kilo joule per kg minus P1 is 1 bar. 1 bar means you can say it is basically 100 Pascal's 100 kilo Pascal.

So, half 1 by rho 1 is 0.8 plus 1 by 3.2 minus 1.2 divide by 0.2 in to rho 1 into 0.8. So, if you calculate you will find that P2 is 13793 Pascal is equal to 13.793 mega Pascal which is a very you know high value as compared to P1. We had seen that in a table I had shown you that what will be the pressure ratio I, right. Pressure ratio will be very high in this case. It is a much higher like P2 by P1. Of course, these are very ideal case what you are considering, but in real situation it will be order of something you know 20-30 kind of things like kind of P2 by P1.

So, in this case it happens to be something 130 right times kind of. So, what we will do now? We will be basically now looking at the deflagration side, particularly the premix flame. So, we will be considering laminar premix flame because it is very simple to handle. That is one thing and also it is being used particularly part domestic burners, where in a other application where you do not need to have a very high heat release rate. So, therefore, we will be using it and it is quite fundamental to even handling the turbulent premix flame. Let us look at like this premix flame which was basically invented by Robert Bunsen in 1855 and he developed basically Bunsen Burner.

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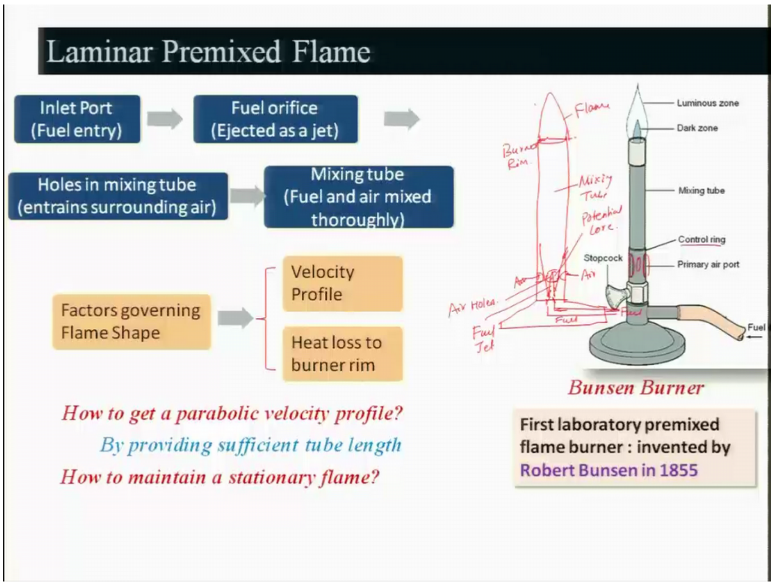

Laminar Premixed Flame

Inlet Port (Fuel entry) → Fuel orifice (Ejected as a jet) →

Holes in mixing tube (entrains surrounding air) → Mixing tube (Fuel and air mixed thoroughly)

Factors governing Flame Shape → Velocity Profile; Heat loss to burner rim

How to get a parabolic velocity profile?

By providing sufficient tube length

How to maintain a stationary flame?

Bunsen Burner

First laboratory premixed flame burner : invented by Robert Bunsen in 1855

Bunsen Burner if you see that the fuel is entering into this zone here and there is of course a stopcock; you can say it can on and off, alright. That it will be making it off and on for the safety purposes and there is what you call primary airport here and there is a tube which is you call it as a mixing tube and once you let the fuel to flow through these and it will be mixing with the air which will be entering into these mixing gamber through the primary airport and then, you ignite, you will get flame.

Of course, it will be having some dark zone and then, luminous zone, but question arises why the air from the atmosphere will be entering into the mixing tubet, right. It is because unless the fuel and oxidizer are mixed, you cannot get premix flame. For example, if I close this air port by this controlling ring, you might have use a Bunsen Burner, you can change like that thing and controlling ring you can close the air, then what you will get is, you will get basically a yellow flame which is nothing, but a diffusion flame right.

So, let us see what is happening in this simple devise which is help in mixing the fuel into air. When the fuel is to enter into this file through this, the tube it will be creating a jet. Jet means there is a small RFs will be there through which you will be pushing the fuel. In this case I, at a higher pressure, right and as a result it will be moving the fluid at a very high velocity, right. So, the fuel orifice will be there and if I consider this as a tube, right let say this is a tube and this is close and then, you know what happened like you are there will be a jet. This is the fuel which will be entering and this is having the jet will be there. So, as a result what will happen there will be a jet which will be having this is known as basically the potential core and this jet will be having, now of course, this will be having a hole. These are air will be entering in to this air and this is air holes, right and this is fuel which is entering is fuel and this is fuel jet. Now, when it is entering these, what will happen as it is having a potential core, so this portion is known as basically potential core.

What is the meaning of that? Meaning of that is whatever the velocity is coming from the orifice, right it will be remaining same. It will not be affected by the air and environment. Why the air will be because this will be having a large momentum and it will be trying to drag the fluid which will be nearby, right. If the air is around because there is a hole and the air will be there, so that will be dragging the fluid along within, like in the similar way you know leader in a society always drag the people along within ideas. In similar manner, the fuel jet in the case of Bunsen burner will be dragging the air along with duty. It is higher momentum as a dissolve the fuel air will be getting mixed and these are the holes if you look at these are air ports, these are the air ports.

Of course, there will be some air ports here through which air will moving. Once it mix and this is your mixing tube right. Of course, you will get a flame. So, holes in the mixing tube and trend the surrounding air and the fuel air mix thoroughly in this mixing tube because as it moves, it will be having some momentum. It will be mixing well and it has given enough residence time for the fuel air to be get properly mixed at the exit of this outlet of this Bunsen burner and once you of course ignite the mixtures, then the flame will be established. Keep in mind that similar mixing set of or mixing process occurs in case of your LPG burner. Did you see that there will be some holes, the jet will be there and this jet diameter orifice and also pressure will be basically affecting the mixing process, right.

So, what are the factors that govern the flame shape is basically the velocity profile at the exit of the Bunsen burner, right. It can be one dimensional profile, right. It can be parabolic profile. Generally whenever you use a tube, it will be parabolic profile and under what condition I can get a parabolic profile provided the flow is fully developed right, but however in this case you will be getting a semi-parabolic profile. Generally the tube is given such that it will be getting air where also as the flame is near by the tube, then there will be some heat losses right from the this thing because the heat, the flame will be anchoring and heat loss to the burner heat rim. This is known as burner rim, right. It will be having some fine air thickness. It is given as the line, but there will be some thickness.

So, how to get a parabolic profile? I have already told you that is by providing sufficient tube length, it is use you know like particularly for laminar kind of flow situation. Laminar flow you will have to give something order of something 100 you know diameter of the tube which is much higher which you cannot offer to give incase of Bunsen burner or of LPG stove burner, but however you will give sufficient. So, that profile, some certain profile will be developed.

How to maintain a stationary flame? Basically you will have to keep this, maintain the fuel flow rate constant. The flame will be stationary. Of course, in this case even though the fuel you will be changing little bit, but it would not change, but once you goes at beyond certain fuel flow rate or in other words, the velocity right, the flame will blow out and if in case of the fuel flow is less, you know rate, then what will happen the flame will get into the burner and then, it is known as flashback. We will be discussing about that, about the blow out and then, flashback little later on.

So, with this we will stop over here and in the next lecture, we will be discussing about the laminar premixing flame premix flame, laminar premix flame.

Thank you very much.