Turbulent Combustion: Theory and Modelling
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Lecture – 25
Laminar Non-Premixed Flames (cont…)

Welcome back, so let us finish the discussion on internal combustion system where we are doing the SI and CI engine discussion.

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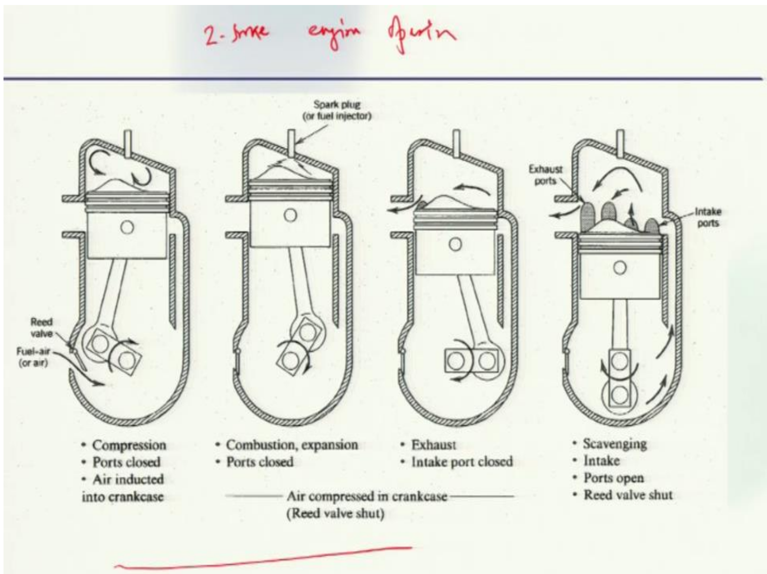

So, we stopped looking at this 2 stroke engine. This is the 2 stroke engine operating cycle. So, this is a 2 stroke SI engine operating cycle. So, there are essentially, primarily 2 strokes, 1 is the there are different components this is a schematic every engine has its design, but essentially it operates on 2 stroke and 1 is the comparison stroke and other one is that expansion of the power stroke.

So, what it does that in the comparison strokes actually starts by closing the intake inlet and the exhaust port and then compresses the cylinder contents and draws fresh charge into crankcase and this happens once the piston approaches toward the top center and at the same time the spark plug ignites it and the combustion is initiated. Now in the second stroke or is your power and expansion stroke it is similar to that you are 4 stoke to cycle and that happens until your piston approaches to BC when the first and exhaust port and then the intake ports are uncovered.

Now, here all the burnt gases or rather most of the burnt gases exit cylinder and in an exit blowdown process. So this what happens and when the inlet ports are uncovered fresh charge which has been compressed in crankcase flows into the cylinder so, that is how this process actually continues.

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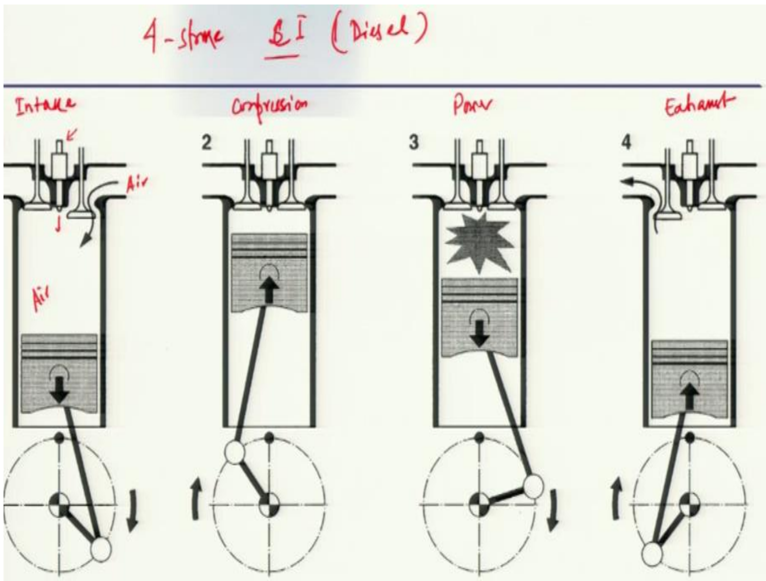

Now, this schematic is your 4 stroke CI engine or diesel engine cycle. First one is your intake, second one is your compression, third one is your power and this is exhaust. So, these are the again the 4 stroke like your SI engine. So, this is the operating cycle, this is a piston head connected with the crankshaft and here this is your essentially fuel injector, intake valve, exhaust valve and all these are there.

So, operating principle is pretty much similar to your 4 stroke SI engine, but here your fuel is injected from here and fresh air comes in so cylinder only contents here. So, this is what air comes in. So, intake air comes in then compression takes place where actually their reaction is initiated and then finally expansion and this goes off. So, this is how the different cycle things works.

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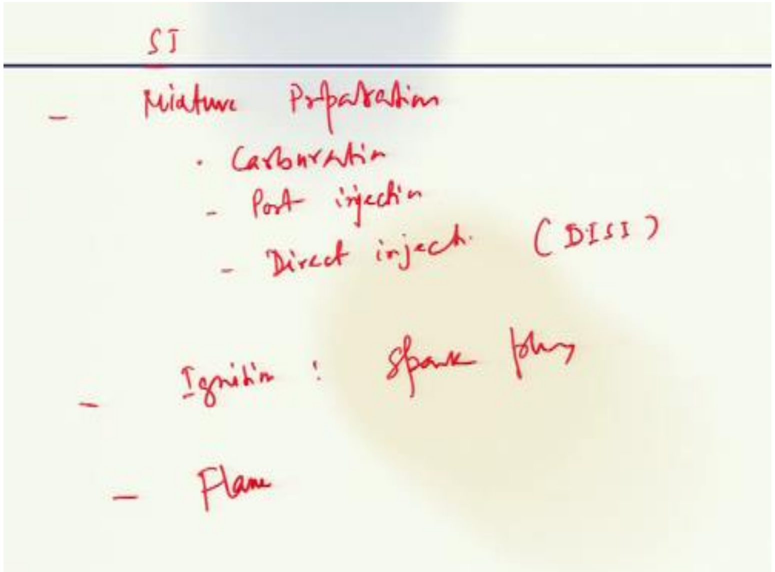

Now, if you look at this combustion in SI engine there would be one is the mixture preparation. This requires carburetion which is no longer used in pretty much in the North American market then your port injection were fuel is split into the air steam just before the inlet valve, then here we could have a direct injection system to a cylinder. So, this is your DISI direct injection system.

Then you have ignition which is through spark plug and then the flame which is the flame carnal will develop and there would flame proposition.

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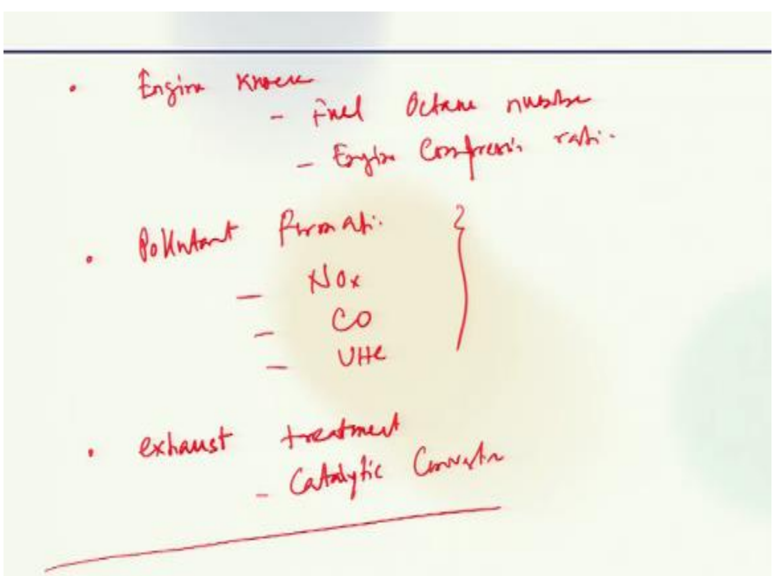

Then you will have some parameter for quantification one is engine knock so, that is because of your fuel octane number, engine compression ratio. Then you have pollutant formation one is the NOx, CO, UHC. So, these are now finally your exhaust treatment which is your catalytic converter and all these things. Now, there are also now the recent development that is the hybrid vehicle.

So, that means, now that has opened up and another area of research where these hybrid vehicles are gaining more popularity and then you can avoid a lot of these issues of your pollution and all these things and also then you may not need to use either gasoline or diesel that kind of fuel or hydrocarbon fuel. So, in a hybrid, it would be more powered by the battery and that is where your fuel cell technology these things they are becoming quite popular, but obviously, one issue is that the sustainable of that fuel cell is how long it can sustain how much power production it can give you all these things are there.

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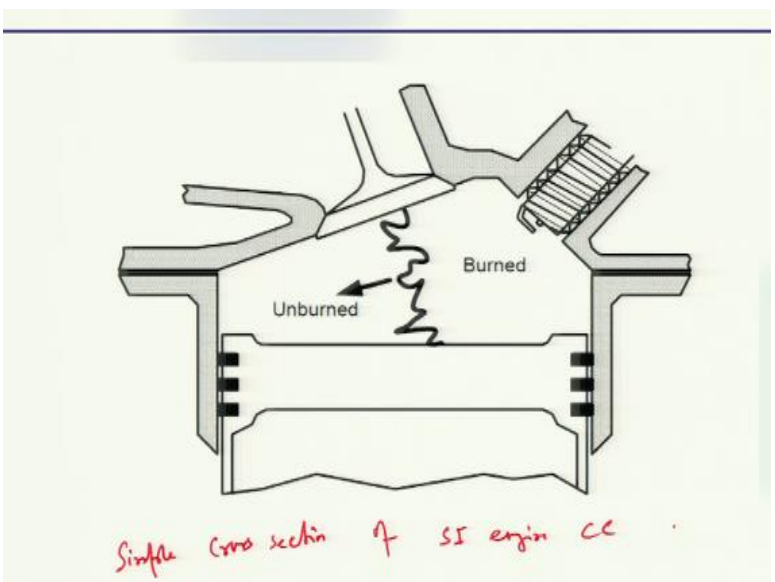

So, this is we have already seen that this is an simple cross section of a SI engine, SI engine combustion chamber so, that is an simple cross section of that.

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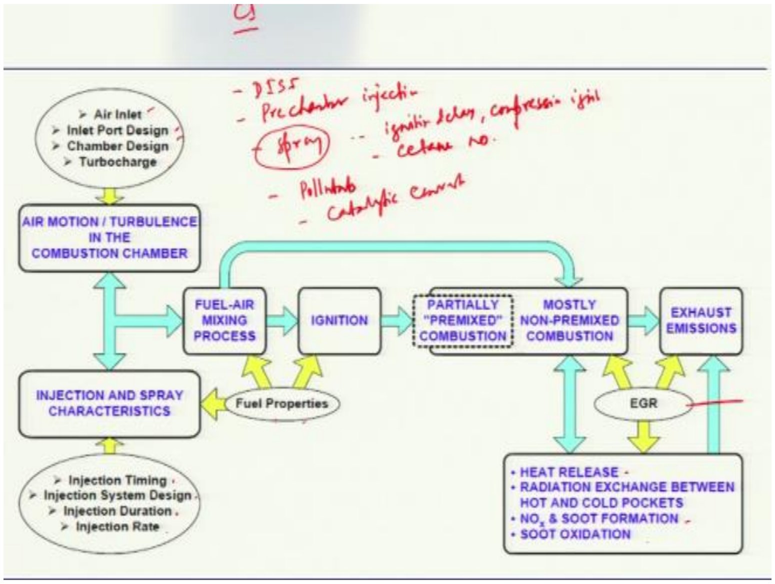

Now, if you see the diesel engine operation now, this is how the diesel engine operation takes place. Now in your CI engine, compression ignition engine, the operation takes place in this many processes are there. So when you look at the CI operation so there is a direct in cylinder injection DC for large engine. So, there could be pre-chamber injection also, then you have spray which is compression ignition or ignition delay.

So, issue is that ignition delay, compression ignition all these are there. Then fuel Cetane number obviously pollutant formation are there, pollutants they are NOx, CO, SCO your catalytic converters all these are your important component of that these are your CI engine components. And operation wise if you look at it here you have air inlet, inlet port design, chamber design, turbocharger so that will dictate your air motion or the turbulence in the combustion chamber.

Now, and the other side you have the spray characteristics and all these things. So, that will basically the fuel properties which will directly impact the ignition, failure mixing process. Now this when you have injection and the injection timing is one important thing, then injector system design is another important thing, injection duration is another injection rate. So, these will actually determine these pre characteristics and all these things. Because this will tell you that what kind of spray you are going to have it and that has the direct impact on the combustion characteristics inside the cylinder.

When that happens, basically that goes to the mixing process. Obviously mixing is indirectly also impacted by the sum of the fuel properties. So, this is mostly non-premixed combustion or partially premixed combustion. So once the combustion takes place you have a heat release which is obvious, then the radiation effect on the wall polluted formation, soot and all these things. Then either you can send it to exhaust or you recycle through EGR and send something back to the chamber.

And again EGR is another advantages technology which allows you to improve the thermal efficiency of the system it injects back some of these exhaust gases to the fresh mixture. So the heating of the fresh mixture or their temperatures, so EGR allows you to control the temperature of the incoming mixture there are the reaction temperature also to remain under some control, where you are pollutant formation are not that high.

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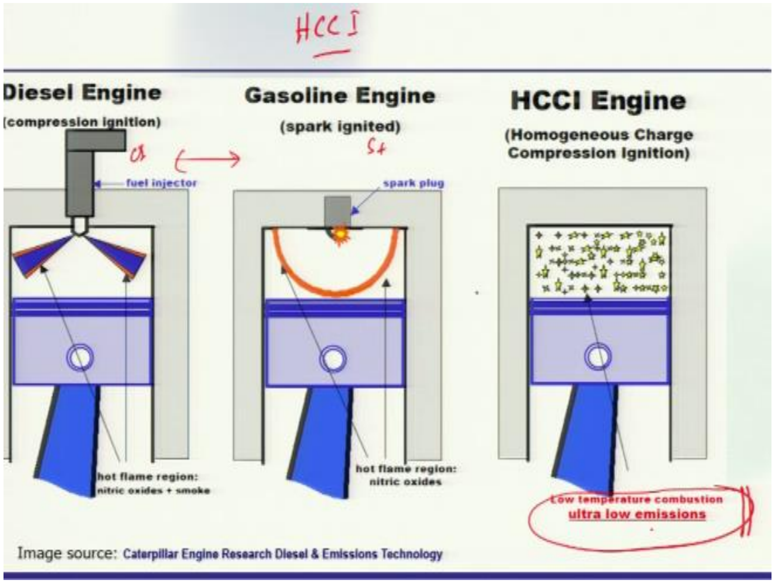

So, these are lastly, we can look at this it is an HCCI system where your diesel engine is a compression ignition engine, this is the fuel injector, this is the system or gasoline engine is this spark ignited where pre-mixed mixture gas or sitting there these are the 2 which we have already discussed because this is CI, this is SI and this is a HCCI which is homogeneous charged compression ignition.

That means this allows you to have ultra-low emissions, so that is one of the technologies where the industry people are really looking forward and if this comes in place that would be a huge advantage from pollutant emission side. But as I mentioned already, there is already a huge trust in the western country to come up with the hybrid vehicle. So that you can avoid these things, the pollutants and all these things as long as you do not burn the hydrocarbon fuel.

But again, that hybrid vehicle is supposed to be more sustainable and these things. Now, that’s pretty much what we want to discuss about the combustion system. Now, another area that comes under the basics that will discuss before we move to the tablets.

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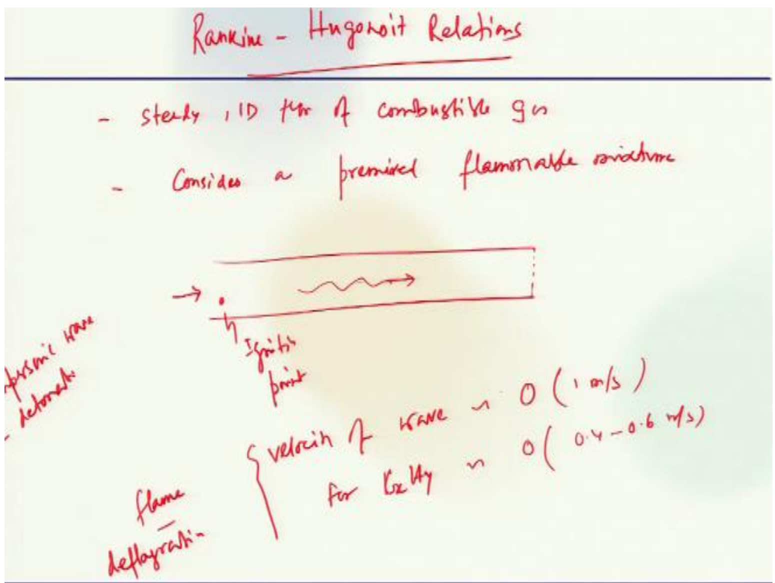

So that is Rankine Hugonoit relations so, that is what we do. Now, this is for steady 1D flow of combustible gas that burns to completion. So, we look at the equations relating to initial and final condition and we can derive them from the conservation equation. Now, let us consider a premixed flammable mixture. So, you have a long tube inside that you have a mixture which is coming pre mixture from one end.

Now obviously, if you have that, the combustion will travel down to the other end if this is the ignition point if this is the ignition point from the ignition point that will travel to the other side. Now both the ends are open to atmosphere then the velocity of this combustion wave would be order of one meter per second. But for most hydrocarbon mixture these typically for hydrocarbon C_xH_y this is order of 0.4 to 0.6 meter per second.

So, how is it controlled? Essentially the velocity of this wave is primarily controlled by the diffusion of heat and active radicals so, this is what normally called as flame. Now, once we are talking about the flow property we call it the deflagration. Now, other case is the tube closed from the one end and then it is ignited at the other end then the propagating wave will go from transition from subsonic to supersonic speed under the right conditions and if that happens that supersonic wave this is called detonation. Now, in the detonation heat or radical diffusion do not control the velocity.

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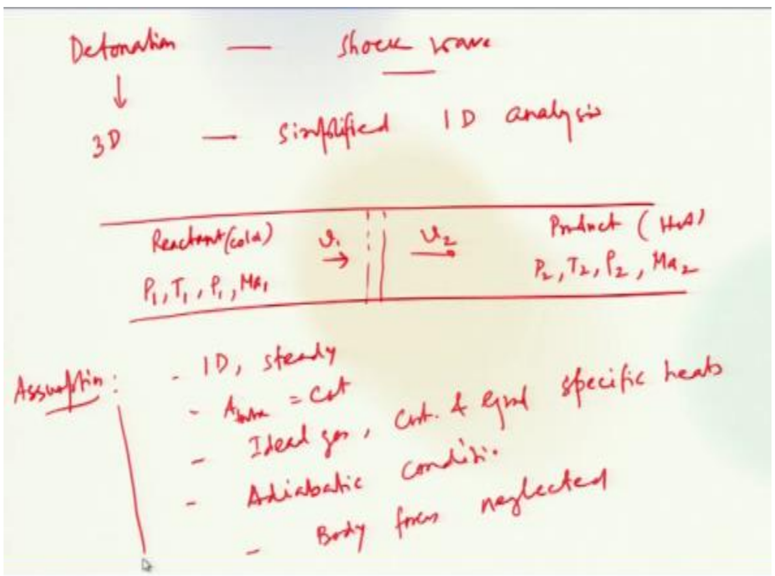

So in detonation, so it is more controlled by the shockwave structure of the supersonic wave. So, that will control the temperature, pressure and all these things though the detonation wave is always 3 dimensional but, we can do a simplified analysis simplified 1 D analysis of the cell. So we can do that, so that is what we wanted to do it. Now let us put a tube like this and in between there is an these things this is let us say v_1, this is v_2 this is product that means hot gas P_2, T_2, ρ_2, Mach 2 and this is reactant there is also cold gas.

So, let's say it is P_1, T_1, ρ_1, Mach 1. Some assumptions which are there associated with this one dimensional analysis is that 1 D steady that is number 1. Area of the tube constant that is number 2, number 3 ideal gas constant and equal specific heats. Then adiabatic conditions that means there is no heat loss to the wall of the tube and obviously any external forces like body forces these are neglected. So, these are the assumption behind this one dimensional analysis.

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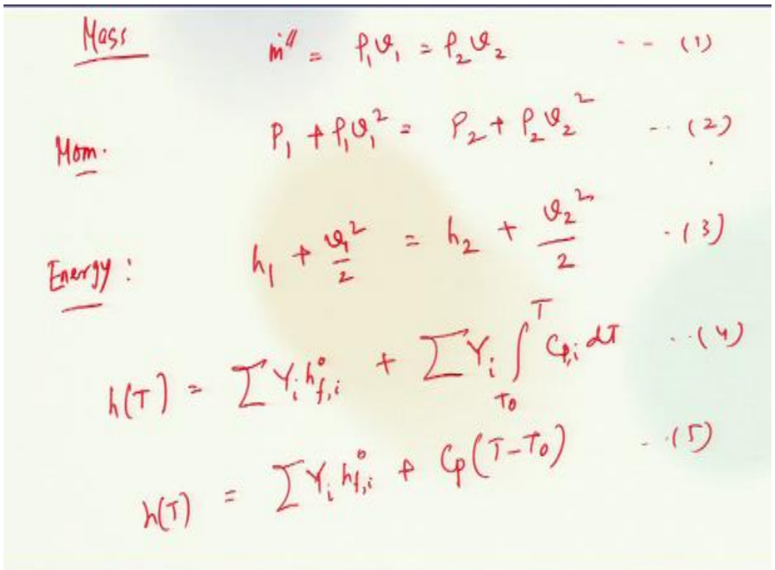

So, first thing that one would like the mass conservation. So, the mass conservation you get:

$$\dot{m}'' = \rho_1 v_1 = \rho_2 v_2$$

Now, second is the momentum conservation only force acting on the control volume is the pressure. So, we will take:

$$P_1 + \rho_1 v_1^2 = P_2 + \rho_2 v_2^2$$

Which is second equation and I can write energy conservation equation which is:

$$h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2}$$

So, this is again further into this conditions, this is my control volume and one stands for the reactant side. Now if we split the total enthalpy into 2 components, one is the sensible enthalpy and other is the η formation, we get:

$$h(T) = \sum Y_i h_{f,i}^0 + \sum Y_i \int_{T_0}^{T} C_{P,i} dT$$

So that is what now since we have made an assumption like it is constant an equal specific heat, so this equation can be written as:

$$h(T) = \sum Y_i h_{f,i}^0 + C_P(T - T_0)$$

So, this is what I will get my enthalpy. Now I will put this 5 into 3 in the energy equation.

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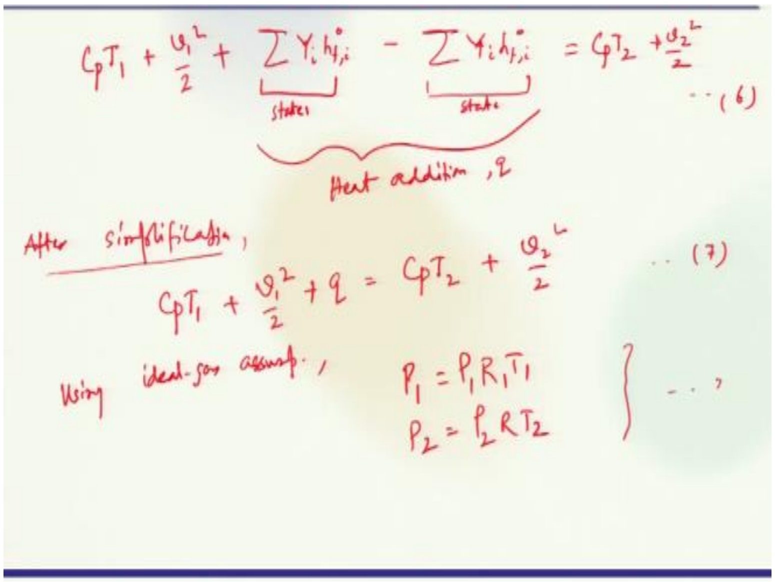

So once I do that, what I get:

$$C_P T_1 + \frac{v_1^2}{2} + \sum Y_i h_{f,i}^0 - \sum Y_i h_{f,i}^0 = C_P T_2 + \frac{v_2^2}{2}$$

So, this is you can think about state 1, this is state 2 and this is in total you think about heat addition which is q that is my equation number 6. Now, if you simplify this then the energy equation get simplified too. So, after simplification what do we get:

$$C_P T_1 + \frac{v_1^2}{2} + q = C_P T_2 + \frac{v_2^2}{2}$$

Now, we have made one more assumption is the ideal gas assumption. So, once we incorporate that ideal gas assumption, so using ideal gas assumption what we get that:

$$P_1 = \rho_1 R T_1$$

$$P_2 = \rho_2 R T_2$$

So this is what we can write.

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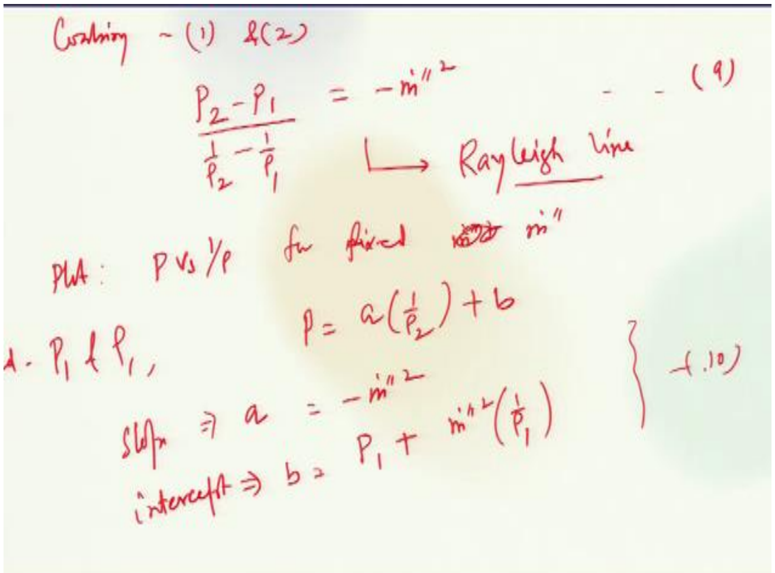

Then, now combining equations 1 and 2, we get:

$$\frac{P_2 - P_1}{\frac{1}{\rho_2} - \frac{1}{\rho_1}} = -\dot{m}''^2$$

This is my equation number 9 and that actually gives you equation for Rayleigh line so this is an equation for the Rayleigh. Now, we can actually plot P versus $1/\rho$ for fixed mass flow rate so this will give you Rayleigh. Let us say for fixed P_1 and ρ_1 we get:

$$P = a\left(\frac{1}{\rho_2}\right) + b$$

This is for fixed P_1 and ρ_1 where slope a is $-\dot{m}''^2$ and intercept b is $\left[P_1 + \dot{m}''^2\left(\frac{1}{\rho_1}\right)\right]$ so this is what we get.

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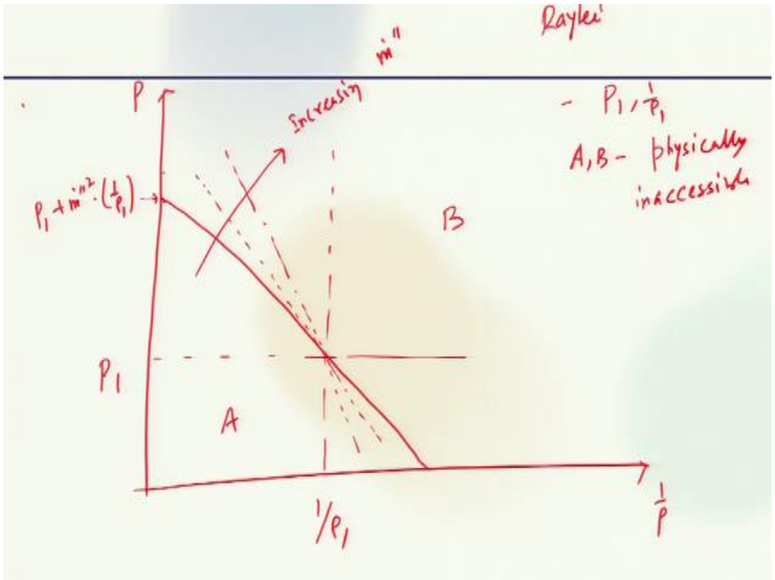

If you plot this is the axis, this is $\left(1/\rho_1\right)$ this goes to $\left[P_1 + \dot{m}''^2\left(\frac{1}{\rho_1}\right)\right]$. So, sincerely this is for P axis. Now, we can get a curve like this, this is A, this is B and this would be P_1 and this slope is intercept is $\left[P_1 + \dot{m}''^2\left(\frac{1}{\rho_1}\right)\right]$. So that is my intercept. So now, what you can have, you can have different mass flow rate and you can see the lines would be like this so this is the increasing $\dot{m}''$.

So, the increasing $\dot{m}''$ you get different Rayleigh line. Now, these are division so, here your for state one Rayleigh for state 1 is $\left(\frac{P_1}{\rho_1}\right)$ which is fixed. So, once we increase the mass flow rate the lines become much stiffer then, one can see that the limit of infinite mass flux then Rayleigh would be particle like this, this is infinite mass flux while at the opposite limit of 0 flux it is horizontal so this is what you get.

Now, there are 2 quadrants which are level A and B. So, these are essentially A and B, these quadrants are physically inaccessible so, this figure will let us used to decide what final states are possible for the detonations. So, that will do or rather use this one for the later stage to decide that thing now, Rankine Huguenot, this is a Rayleigh line plot.

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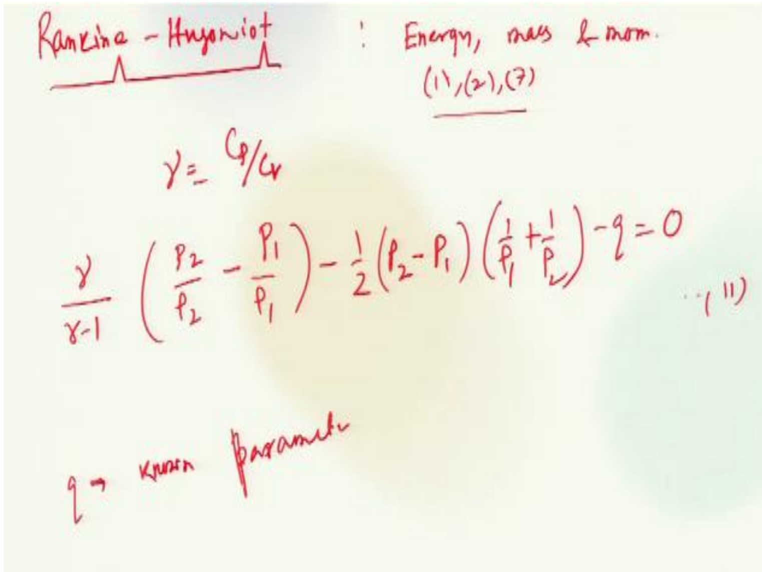

Now, the Rankine Huguenot curve we can obtained from the energy equation. So this we can obtain from the energy equation along with the mass and momentum conservation. So which, we have here at one to mass and momentum conservation and the energy equation at 7, so that is essentially equation 1, 2 and 7 and where you can also ideal gas relation:

$$\gamma = {}^{C_P}/_{C_v}$$

So if you do that and combining these, we can get the expression like:

$$\frac{\gamma}{\gamma - 1}\left(\frac{P_2}{\rho_2} - \frac{P_1}{\rho_1}\right) - \frac{1}{2}(P_2 - P_1)\left(\frac{1}{\rho_2} + \frac{1}{\rho_1}\right) - q = 0$$

So here, we further assume that q is a known parameter and then we will fix the value of the $\left(\frac{P_1}{\rho_1}\right)$ and look at the other parameter and so we will stop here and take it up from here in the subsequent lecture. Thank you.