Introduction to Airbreathing Propulsion
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Lecture – 19
Piston Engines and Propellers (Contd.,)

Okay. So welcome back and let us continue the discussion on the piston and propeller engine. And we have talked about what the basic engine type and their arrangements and all these. So we just started taking the assumption for reciprocating engine and now we look at the thermodynamic analysis of those engines.

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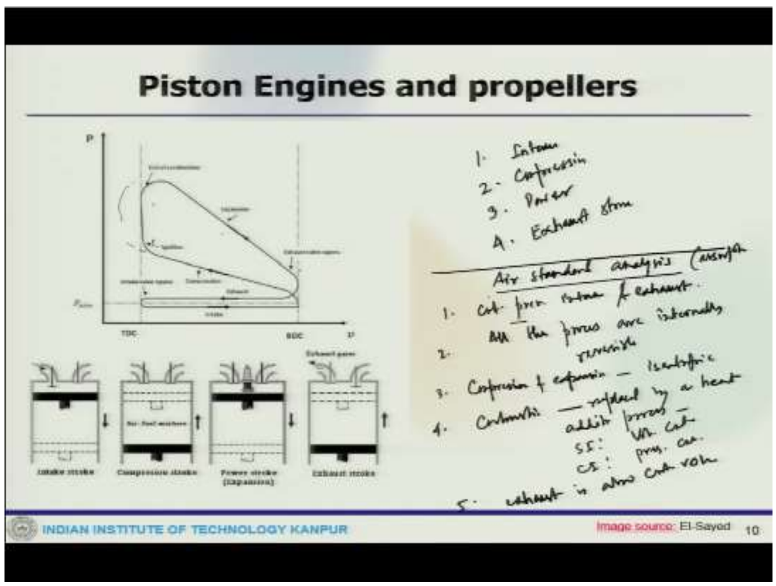

So this is what we have talked about this air standard for air standard analysis the assumption and things like that.

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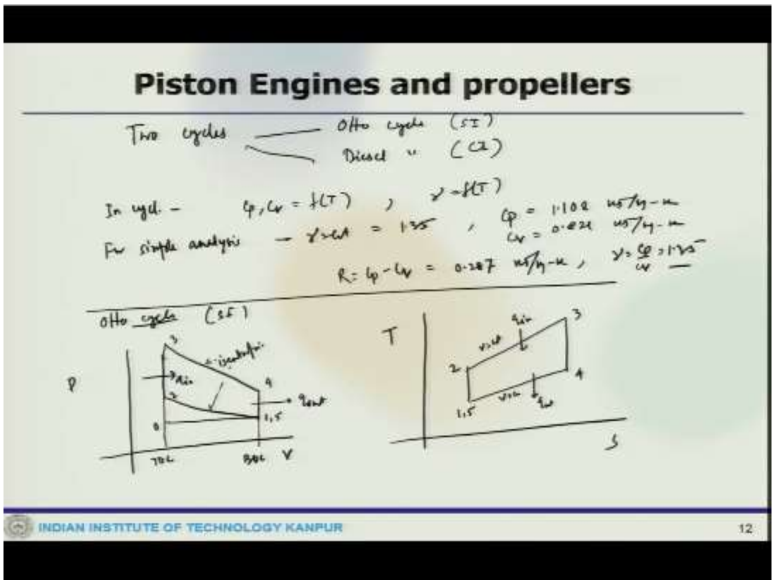

And then what we will do we will talk about two cycles here one is the Otto cycle and other one is the Diesel cycle. So Otto cycle is for spark ignition engine and this one for the compression ignition analysis. Now there are specific heat of air or function of actual temperature like C_P and C_V and the temperature within the cylinders actually vary a lot so; and also the ratio of the specific heat is gamma which is; so the; to simplify the analysis what we will do.

So that means in cylinder in realistically C_P C_V they are function of temperature so gamma also becomes function of temperature or something like that. But to make it simple for simple analysis we will say gamma to be constant and we will use some average value of 1.35 and something like that. And also we will use the constant

$$C_p = 1.108\,\frac{kJ}{kgK}$$

$$C_v = 0.821\,\frac{kJ}{kgK}$$

So R would be

$$R = C_p - C_v = 0.28\,\frac{kJ}{kgK}$$

and

$$\gamma = \frac{C_p}{C_v} = 1.35$$

So these are what we are going to use.

So let us start with the Otto cycle and first this is a cycle for the spark ignition engine, so this was named in after Nikolaus Otto who built 1876 I think a four-stroke engine and successfully in Germany. In most spark ignition engine as we saying the piston executes four-complex stroke to mechanical within the cylinder and the crankshaft completes two revolutions. So these are called four-stroke internal combustion engine.

So the typical PV diagram, so let us say this is a state from where it goes here that is state 0 or TDC then from here this goes like this then this then like this and comes like that, so this is 1, 5, 2, 3, 4 so this is where heat is out, combustion in, then this process is isentropic and that is same for this guy also and this is the bottom dead center, okay. And then same thing if you put back in the TS diagram; this is 2 3 4 like this so 1 5 2 3 4. So this is V constant process where Q in, V constant process Q out. So this is the PV and TS diagram.

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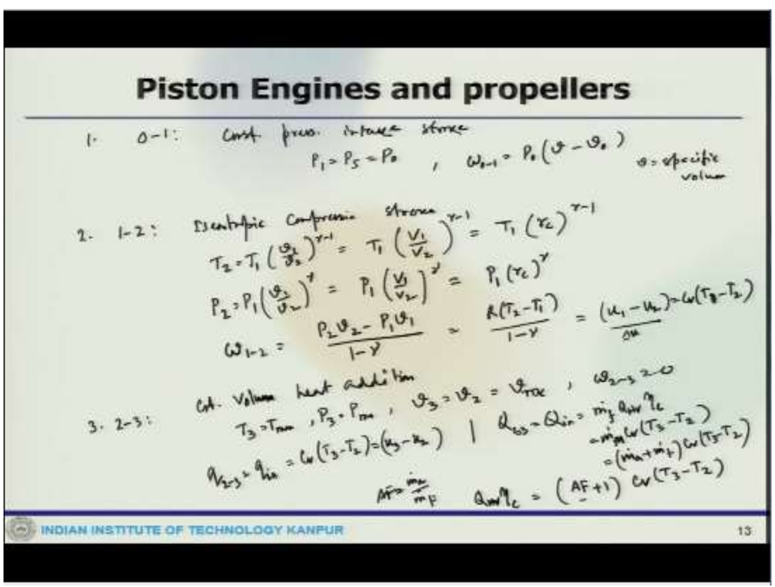

Now first between 0-1 process, so this is a constant pressure intake stroke so; and the pressure at the intake takes place at p_0 with the intake valve open and exhaust valve closed the piston makes an intake stroke to draw a face charge. And it could be a mixture of fuel and air for SI engine into the cylinder. So what it gives p_1 would be p_0 so let us say

$$W_{0-1} = p_0(v_1 - v_0)$$

Here the, this one is the v is specific volume, okay.

So now move to process 1 to 2 that is isentropic compression stroke. So with both the valves closed the piston undergoes a compression stroke and raising the temperature and pressure of the charge, so this requires an input from the piston to the cylinder so what happens

$$T_2 = T_1 \left(\frac{v_1}{v_2}\right)^{\gamma-1} = T_1 \left(\frac{V_1}{V_2}\right)^{\gamma-1} = T_1 (r_c)^{\gamma-1}$$

$$p_2 = p_1 \left(\frac{v_1}{v_2}\right)^{\gamma} = p_1 \left(\frac{V_1}{V_2}\right)^{\gamma} = p_1 (r_c)^{\gamma}$$

So what we have the specific work output would be

$$w_{1-2} = \frac{p_2 v_2 - p_1 v_1}{1-\gamma}$$

So we can replace that with

$$w_{1-2} = \frac{R(T_2 - T_1)}{1-\gamma}$$

which is

$$w_{1-2} = u_2 - u_1$$

this is change in internal energy or

$$w_{1-2} = u_2 - u_1 = C_v (T_2 - T_1)$$

Now the process 2 to 3, this is constant volume heat addition process or the combustion. So here what will happen we will have the

$$T_3 = T_{max}$$

$$p_3 = p_{max}$$

$$v_3 = v_2 = v_{TDC}$$

$$w_{2-3} = 0$$

Now specific heat is added that

$$\dot{q}_{in} = q_{2-3} = C_v (T_3 - T_2) = u_3 - u_2$$

And

$$\dot{Q}_{in} = Q_{2-3} = \dot{m}_f Q_{HV} \eta_c = \dot{m}_m C_v (T_3 - T_2) = (\dot{m}_f + \dot{m}_a) C_v (T_3 - T_2)$$

So what we can write that

$$Q_{HV} \eta_c = (1 + F)\, C_v (T_3 - T_2)$$

So here Q_{HV} is the heating value of the fuel and F is the air fuel ratio.

So which is

$$F = \frac{\dot{m}_a}{\dot{m}_f}$$

So now after this combustion what will happen the gas mixture will leave having the maximum pressure and the temperature so this will be towards the end of the compression stroke.

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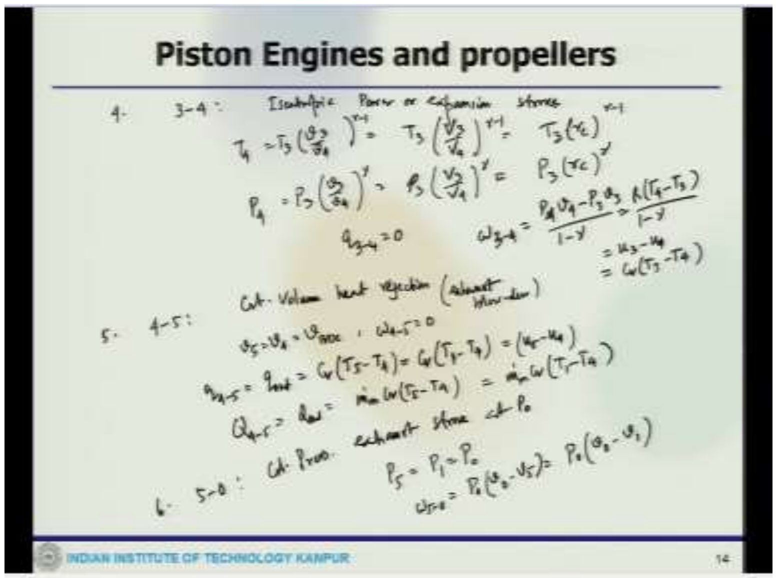

Now the fourth stage, this is process 3 to 4 which is again an isentropic power or expansion stroke, okay. Now it follows the compression stroke during the gas mixture expands and work is done and all the valves are closed, so what we get

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{\gamma-1} = T_4\left(\frac{V_3}{V_4}\right)^{\gamma-1} = T_3(r_c)^{\gamma-1}$$

$$p_4 = p_3\left(\frac{v_3}{v_4}\right)^{\gamma} = p_3\left(\frac{V_3}{V_4}\right)^{\gamma} = p_3(r_c)^{\gamma}$$

$$q_{3-4} = 0$$

So the specific work

$$w_{3-4} = \frac{p_4 v_4 - p_3 v_3}{1-\gamma}$$

$$w_{3-4} = \frac{R(T_4 - T_3)}{1-\gamma} = u_4 - u_3 = C_v(T_4 - T_3)$$

Now we have process 4 to 5, this is again constant volume heat rejection process or sort of exhaust blowdown. Now the exhaust valve is open and inter valve is closed, so we get

$$V_5 = V_4 = V_{BDC}$$

$$w_{4-5} = 0$$

Here specific heat rejection is Q out so

$$\dot{q}_{out} = q_{4-5} = C_v(T_5 - T_4) = C_v(T_1 - T_4) = u_5 - u_4$$

$$\dot{Q}_{out} = Q_{4-5} = \dot{m}_m C_v(T_5 - T_4) = \dot{m}_m C_v(T_1 - T_4)$$

Now we have the last process which is 5 to 0 which is again constant pressure exhaust stroke at p_5 And this piston executes an exhaust stroke in which the burned gases are fudged from the cylinder through the open exhaust valve. So here we have $p_5 = p_1 = p_0$ and specific work is

$$w_{5-0} = p_0(v_0 - v_5) == p_0(v_0 - v_1)$$

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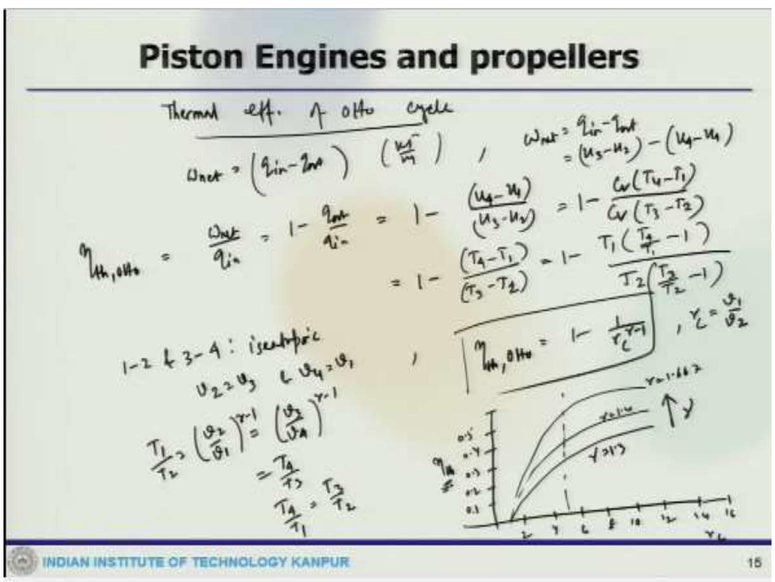

So we can find out the thermal efficiency of the Otto cycle, so thermal efficiency of Otto cycle. So since the Otto cycle is executed in a closed system we can disregard the changes in the kinetic and potential energies so the energy balance could be written like

$$w_{net} = (q_{in} - q_{out})\frac{kJ}{kg}$$

$$w_{net} = (u_3 - u_2) - (u_4 - u_1)$$

So the thermal efficiency of Otto cycle is defined

$$\eta_{th} = \frac{w_{net}}{q_{in}}\left(1 - \frac{q_{out}}{q_{in}}\right) = \left(1 - \frac{u_4 - u_1}{u_3 - u_2}\right) = \left(1 - \frac{C_v(T_4 - T_1)}{C_v(T_3 - T_2)}\right)$$

So what we get

$$= \left(1 - \frac{T_4 - T_1}{T_3 - T_2}\right) = 1 - \frac{T_1(\frac{T_4}{T_1} - 1)}{T_2(\frac{T_3}{T_2} - 1)}$$

Now since the process 1 to 2 and 3 to 4 are isentropic and $v_2 = v_3$ and $v_4 = v_1$ so what we can write

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \frac{T_4}{T_3}$$

so we can rearrange that like

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}$$

And now if we put this back here again what we get

$$\eta_{th,Otto} = 1 - \frac{1}{r_c^{\gamma-1}}$$

Where

$$r_c = \frac{v_1}{v_2} = \frac{v_{max}}{v_{min}}$$

So, so thermal efficiency is dependent on the compression ratio and obviously the heat ratio, so if you plot that for different heat ratio like this is let us say 2, 4, 6, 8, 10, 12, 14, 16 this is r_c and this is η_{th}, this is 0.1, 0.2, 3, 4, 5 so like that so it goes like that. So it is just different values of gamma if you increase that this one start with 1.3 something like that. So that is the typical curve that one can see.

So from here one can see that the, the thermal efficiency curve is steep at low compression ratio but flats out when out starting with a higher compression ratio beyond eight or something like that. So the increase in thermal efficiency is quite with the compression ratio is not a pronounced at high compression ratio that means when you go beyond certain compression ratio it not necessarily that if efficiency will increase further but at the lower r_c as we increase it, it increases.

Now for a particular given compression ratio this is let us say gamma 1.4 and gamma 1.667. So the mono atomic gas like argon or helium they will have the higher thermal efficiency compared to the heat ratio of 1.3 in the same. Now that typically the working fluids in actual engine contents larger molecules such as carbon dioxide and the specific heat ratio also decreases with temperature which is one of the reason that actual cycle will always have lower than the theoretical ideal auto cycle.

Second for a given compression ratio the thermal efficiency of a actual SI engine is less than that ideal Otto cycle due to reversible, that is obvious because what we have got here is the ideal one but theoretical one but actually there would be reverse abilities. And typically the SI engine efficiency would be about 25% to 30%.

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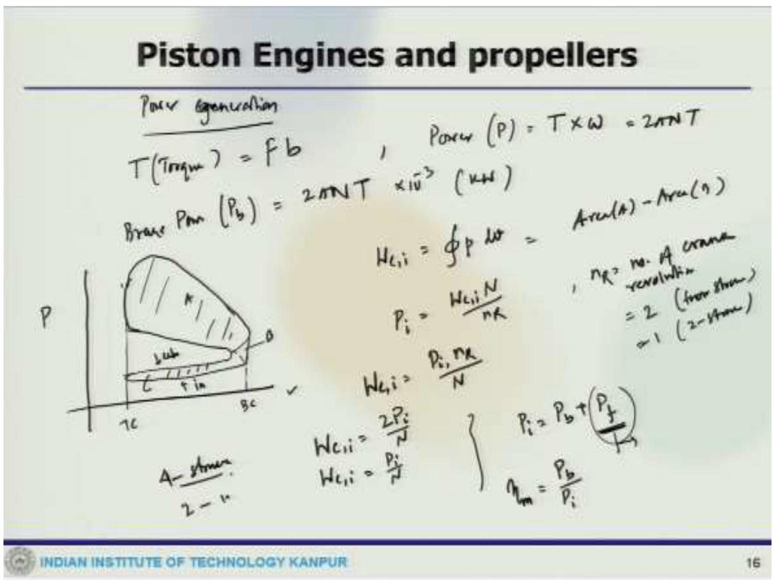

Now we can find out now power generation and fuel consumption. So the torque generated in the piston engine is normally measured with a dynamometer the engine is clamped on a test bed and so the torque which is; this is the torque exerted by the engine is

$$\tau = Fb$$

So the power which is delivered by the engine and absorbed by the dynamometer is let us say this is the power P is

$$P = T \times \omega = 2\pi NT$$

so the value of the engine power is called the brake power which is

$$P_b = 2\pi NT * 10^{-3}\ kW$$

So the indicated power is correlated and you can see in area diagram of a PV area diagram let us say, this is what happens at the intake stroke then it goes back here, goes like that and comes like that. So this is bottom dead center, top dead center, this is exhaust, this is intake. So what happens, so this is let us say this is area A, this is B and this is C. So you can see how the power is the indicated work per cycle per cylinder

$$W_{ci} = \oint pdV$$

And the net indicated work per cycle of the cylinder which is area A minus area B. Then the power per cylinder is related to the indicated power so per cylinder would be indicated per cylinder; indicated power

$$P = \frac{W_{ci}N}{n_R}$$

where in n_R is the number of crank revolution four-stroke engine $n_R = 2$ for two-stroke engine, so this is 2 for 4 stroke, 1 for 2 two-stroke engine, okay. So this power is the indicated power and then what we get

$$W_{ci} = \frac{P_i n_R}{N}$$

Now for 4-stroke engine this is

$$W_{ci} = \frac{2P_i}{N}$$

and for 4-stroke

$$W_{ci} = \frac{P_i}{N}$$

Now the brake power can be related with the indicated power, so indicated power is the brake power plus P_f and P_f is the power consumed in overcoming the friction of the bearing so driving, accessories, induction exhaustion stroke. So this is the power which has been used to some of these things to operate, okay. So; and then Eta mechanical efficiency would be ratio of brake power by indicated power. Typically, this is around 90% for modern automotive engines where the revolution is around 1800 to 2400 rpm or 75% for the maximum speed limit.

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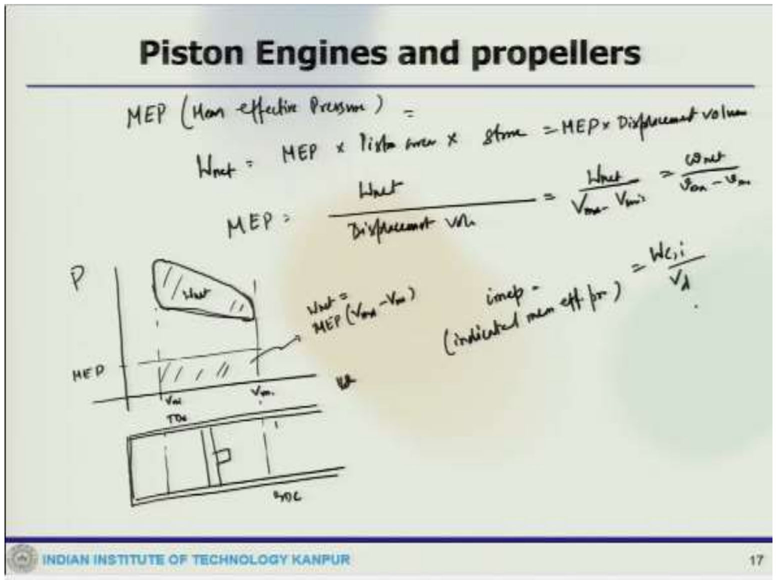

Now there would be another parameter which to describe this engines are the MEP which is Mean Effective Pressure. So the mean effective pressure is the fictitious pressure that if it is acted on the piston during the inter power stroke it produced the same amount of network that produce during the actual cycle. So which means W_{net} would be MEP into piston area into stroke, so that is MEP into displacement volume.

So MEP would be

$$MEP = \frac{W_{net}}{Displacement\ volume} = \frac{W_{net}}{V_{max} - V_{min}} = \frac{w_{net}}{v_{max} - v_{min}}$$

So one can see in a PV curve like this where let us say these are the two ends so the cycle lies there. So here it goes, comes back, so that is W_{net} and this is MEP and this if we look at the; so this is TDC that means V_{min}, this is V_{max} so this is MEP into $V_{max} - V_{min}$ so that is also W_{net}, so this area and this is where the cylinder lies and that is the bottom dead center so this is BDC.

So various mean effective pressure can be defined using in terms of like if it is indicated work then IMEP it is indicated mean effective pressure which is

$$IMEP = \frac{W_{ci}}{V_d}$$

So we will kind of using this mean effective pressure, you can define the other parameters and we can look at those details in the next class.