Fundamentals of Automotive Systems
Prof. C.S. Shankar Ram
Department of Engineering Design
Indian Institute of Technology-Madras

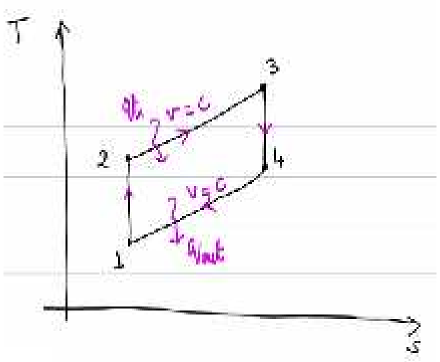
Lecture-09
Otto Cycle and Diesel Cycle
Part 01

Okay greetings, welcome to today's class, so we were looking at the otto cycle yesterday. So just a quick recap we were looking at what are called as air standard cycles which are typically used to do a first cut analysis of IC engine performance and we saw what was an air standard cycle, what were the assumptions typically made and we started off with the otto cycle right and just to quickly recap what we discussed looking at the PV diagram of this otto cycle.

So we map the various processes of intake compression power stroke and the exhaust stroke which are quickly found in a 4 stroke IC engine and we observed that it was mapped to a simpler version which where the so called pumping losses were not considered. So as far as the otto cycle is concerned we consider an equivalent piston and cylinder assembly in which the working fluid is just air and we start from the compression process ok.

<u>Processes in the Otto Cycle</u>

1) 1 → 2 : Isentropic Compression
2) 2 → 3 : Constant volume heat addition
3) 3 → 4 : Isentropic expansion
4) 4 → 1 : Constant volume heat rejection



We do not consider the intake and the exhaust processe compression process it should be 1 to 2 then the combustion process is replaced by a heat addition process that takes place at constant volume. Then there is an expansion process from 3 to 4 which is once again assumed to be isentropic and 4 to 1 is a constant volume heat rejection process and the motivation for this approximation comes from the shape of the PV diagram which is typically observed when we do measurements from an gasoline or a petrol engine ok.

So that is the motivation here, so just to list all the strokes all the what to say processes in an Otto cycle or I should say in the otto cycle the process from 1 to 2 is isentropic compression ok. The process from 2 to 3 is constant volume heat addition, the process from 3 to 4 is isentropic expansion, the process from 4 to 1 is constant volume heat rejection. So these are the 4 processes right that are involved in this air standard otto cycle.

So some people will call this as the air standard otto cycle some could referred to as just otto cycle and so on right ok. So now if we were to draw the TS diagram for the same cycle ok we will shortly see that sometimes the TS diagram is also pretty useful in analyzing these processes T stands for temperature, S stands for entropy ok. So if we were to map the same 4 processes let us say we start with state 1, 1 to 2 will be isentropic compressions.

So in the TS plot it is going to go vertically upwards right, so that is going to be isentropic compression and 2 to 3 is constant volume heat addition. So it is going to go something like this 3 to 4 is isentropic expansion, so that is going to go curve something like this and then fourth one is constant volume heat rejection ok. So if I were to mark all the processes it is important to mark important characteristics of each process and also the direction of the entire cycle right.

So this will be V is equal to constant ok, so this is the process where heat is added and this is the process where heat is released ok. So these are the 4 processes of the same air standard otto cycle expressed in the TS plane ok. So now if I were to obtain an expression for the thermal efficiency of the air standard otto cycle you can immediately see that the thermal efficiency for the air standard otto cycle is going to be the net work done divided by the net heat which is input right.

So efficiency is like output by input this case the output is the network output of the otto cycle. The input is the heat input which we given right, so how do we get expressions for these right.

Thermal Efficiency of the air standard Otto Cycle:

$$\eta_{th,Otto} = \frac{\omega_{net}}{q_{in}}$$

Recall that the first law of thermodynamics can be expressed as

$$\partial_q - \partial_w = d_e \ , e = u + ke + pe$$

When integrated over a cycle

$$\emptyset\partial_q - \emptyset\partial_w = \underbrace{\emptyset\partial_e}_{\substack{\downarrow \\ =0}} \quad \Rightarrow \quad q_{net} = w_{net} \longrightarrow \text{for a cycle}$$

$$\Rightarrow \quad w_{net} = q_{in} - q_{out}$$

$$\Rightarrow \quad \eta_{th,Otto} = \frac{w_{net}}{q_{in}} = \frac{q_{in}-q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

So recall that the first law of thermodynamics can be expressed as in differential form right, so it can be expressed as delta q minus delta w equals de where the net energy e is a sum of the internal energy plus the kinetic energy plus the potential energy right. So this is a standard form for the first law of thermodynamics that people will use ok when integrated over a cycle what is going to happen, it going to get delta q minus delta w equal to integral over the cycle de right.

So kindly recall from thermodynamics that heat transfer and work interactions are all path dependent quantities right, whereas the net energy is a path independent quantity right. So if I integrate over a cycle what is going to happen to this integral over a cycle of de, this is going to become 0 right because we end up at the same initial state right. So essentially since it is a path independent quantity it only depends on the final state and the initial state.

And since the 2 states happen to be the same, the net change is going to be 0, so the net heat transfer is going to be equal to the network output for a cycle ok, this expression is true when you have a cycle right. So the net heat transfer over a cycle is going to be equal to the net work output from that cycle, so what can we say about this otto cycle the network output of the Otto cycle should be equal to the net heat input given to the otto cycle.

The net heat input is going to be the heat which is given in minus the heat which is taken out or rejected right that is going to be Q_{in} minus Q_{out}. So going back this would give me eta thermal for the otto cycle will be equal to W net by q in that is going to be equal to Q_{in} minus Q_{out} divided by Q_{in} which I can rewrite as 1 minus Q_{out} by Q_{in} ok very standard expression. So now what about the expressions for Q_{out} and Q_{in} alright. So that is the next analysis that we need to do, so if we recall the heat addition takes place at constant volume right.

Heat addition, 2 ⟶ 3 $\underbrace{\int_2^3 \partial_q}_{q_{in}} - \underbrace{\int_2^3 \partial_w}_{=0} = \underbrace{\int_2^3 de}_{u_3 - u_2}$ (neglecting charges in ke & pe)

$$\boxed{q_{in} = u_3 - u_2}$$

Heat rejection, 4 ⟶ 1 $\int_4^1 \partial_q - \int_4^1 \partial_w = \int_4^1 d_e \quad \Rightarrow \quad q_{in} = u_1 - u_4$

$$\Rightarrow \quad |q_{out}| = u_4 - u_1$$

$$\eta_{th,Otto} = 1 - \frac{|q_{out}|}{q_{in}} = 1 - \frac{(u_4 - u_1)}{(u_3 - u_2)} \underset{\substack{\uparrow \\ \text{Constant specific heats}}}{=} 1 - \frac{\cancel{cv}(T_4 - T_1)}{\cancel{cv}(T_3 - T_2)}$$

So the heat addition process is the process from 2 to 3 right that is the one which takes place at constant volume right. So if we integrate the first law of thermodynamics over the process 2 to 3 what are we going to get, so this is going to be Q_{in} , this is going to be equal to 0 because the heat addition process takes place at constant volume ok. Then this I can write it as u_3 minus u_2 neglecting changes in kinetic energy and potential energy which is a reasonable assumption here right.

So considering the system and the process that it undergoes I can neglect the changes in kinetic and potential energy. So this implies that my heat input q in is going to be equal to u_3 minus u_2 right, so that is 1, similarly I can consider the heat rejection process that is from 4 to 1. So doing the same analysis from 4 to 1 ok dq 4 to 1 delta w, 4 to 1 de we are going get Q_{out} to be equal to u_1 minus u_4. Of course here you know like the if I have to be very careful I should have written this has the absolute value of q out ok going back right.

So because Q_{out} is the heat rejected from the otto cycle right, so any the sign convention in thermodynamics is that like if heat is taken from the system it is sign is negative ok and if heat is given to a system the sign of that quantity is going to be positive ok. So that is the sign convention that we utilize right, so I will use the Q_{out} instead of that I will use absolute magnitude of Q_{out} ok here even here ok.

So you can immediately see that this Q_{out} is going to be negative because u_1 is going to be less than u_4 , so this implies the absolute value of Q_{out} it is going to be equal to u_4 minus u_1 ok. So I am just rewriting, so that we are consistent ok, so now we are all set to look at the thermal efficiency expression once again. So we can immediately see that the thermal efficiency of the air standard Otto cycle is 1 minus magnitude of Q_{out} by Q_{in}. This is going to be 1 minus u_4 minus u_1 divided by u_3 minus u_2 and assuming constant specific heats.

We know from thermodynamics that delta u is going to be C v times delta T right, so we make the assumption of constant specific heats. So this is going to be 1 minus C v T_4 minus T_1 divided by C v T_3 minus T_2, so C v and C v cancel out ok, so we are not yet done right we need to simplify it further. Now what we have done we have essentially reduce the expression for the thermal efficiency of the Otto cycle in terms of temperatures at the critical states right the 4 corner states if I can call them that right or the nodes are 1 and 2, 1 2 3 and 4 right.

So we have reduce the expression in terms of temperatures now let us go further right. Let us use the other 2 processes right, so till now we have used processes 2 to 3 and 4 to 1 what about the other 2 processes right. So let us look at the isentropic compression process, isentropic compression process is the process from 1 to 2, so the process relationship is going to be typically the isentropic process is basically governed by PV power gamma equals constant that is how we write down what is called as a process relationship right for an isentropic process.

So using the ideal gas equation of state along with that we can always rewrite that as TV power gamma minus 1 equals constant, so I can write T_1 V_1 power gamma minus 1 equal to T_2 V_2 power gamma minus 1 ok. So this is what is called as a process relationship ok, so this governs the isentropic process. So this will give me T_2 equal to T_1 V_1 by V_2 to the power gamma minus 1, so by the way what is gamma is nothing but the ratio of specific heats C_p by C_v right.

So typically it is value is taken as 1.4 for air under standard conditions right, so that is the meaning of gamma. So now if we look at this T_2 is T_1 V_1, T_1 times V_1 by V_2 whole power gamma minus 1 but what is V_1 by V_2 , if we go up V_1 is the volume at bottom dead centers center, V_2 is the volume at top dead center. So what is the ratio called as compression ratio right, so that is the definition of compression ratio.

So immediately we can see that T_2 is going to be equal to T_1 r to the power gamma minus 1 where r is nothing but V_1 by V_2 ok, so this is the compression ratio R ok. So similarly let us consider the isentropic expansion process which is from 3 to 4, so what happens here, so the process relationship becomes this. So this will give me T_4 or I can say T_3 equals T_4 V_4 by V_3 to the power gamma minus 1.

So once again what is V_4 by V_3, V_4 is here volume at BDC V_3 is also volume at TDC right because the heat addition and rejection process both take place at constant volume. So what is going to be V_4 by V_3 once again R the compression ratio right, so this implies the T_3 is going to be equal to T_4 to the power gamma minus 1 ok we are almost done now. So substituting these we immediately get the thermal efficiency of the air standard Otto cycle to be 1 minus T_4 minus T_1 divided by for T_3 I am going to substitute T_4 r to the power gamma minus 1.

For T_2 let us substitute T_1 r to the power gamma minus 1, so if you simplify this what is it that we will get we can immediately see that r to the power gamma minus 1 is common in the denominator if you take it out you get T_4 minus T_1 and that factor cancels between the numerator and the denominator. So the thermal efficiency of the air standard otto cycle reduces to 1 minus 1 divided by r to the power gamma minus1, so you see that it reduces to a very simple expression ok.

So the thermal efficiency of the Otto cycle depends only on the air standard Otto cycle right depends only on the compression ratio r.

$$\eta_{th,Otto} = 1 - \frac{|q_{out}|}{q_{in}} = 1 - \frac{(u_4-u_1)}{(u_3-u_2)} \underset{\substack{\uparrow \\ \text{Constant specific heats}}}{=} 1 - \frac{\cancel{cv}(T_4-T_1)}{\cancel{cv}(T_3-T_2)}$$

Isentropic compression, $1 \longrightarrow 2$: $T_1 V_1^{(\gamma-1)} = T_2 V_2^{(\gamma-1)} \quad \Rightarrow T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{(\gamma-1)}$

$$\gamma = \frac{c_P}{c_V}$$

Isentropic expansion, $3 \longrightarrow 4$: $T_3 V_3^{(\gamma-1)} = T_4 V_4^{(\gamma-1)} \quad \Rightarrow T_3 = T_4 \left(\frac{V_4}{V_3}\right)^{(\gamma-1)} = T_4 r^{(\gamma-1)}$

$$\Rightarrow \eta_{th,Otto} = 1 - \frac{(T_4 - T_1)}{T_4 r^{(\gamma-1)} - T_1 r^{(\gamma-1)}} \Rightarrow \boxed{\eta_{th,Otto} = 1 - \frac{1}{r^{(\gamma-1)}}}$$

As r ↑, $\eta_{th,Otto}$ ↑ However, the phenomenon of knocking in SI engines limits the value of r.

So we can immediately observe that as the compression ratio increases the value of the thermal efficiency also increases right. Because you can immediately see that as r increases r power gamma minus 1 will increase it is reciprocal will decrease and we are subtracting a smaller number from 1 right. So the thermal efficiency will increase right but however we will later study what is called as the phenomenon of knocking in SI engines and this limits the value of r ok.

So we cannot keep on increasing the value of compression ratio ok there is something called knocking in SI engines which restricts the value of r ok we will be look at that later ok when we come to the analysis of the combustion process in SI engines ok. So to quickly summarize in the air standard Otto cycle we looked at the 4 processes the main feature is that like the heat addition process is assumed to take place at constant volume in the Otto cycle.

We use simple expressions that we learnt in thermodynamics right to derive an expression for the thermal efficiency ok, so that is what we have done ok.