Engineering Thermodynamics

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Module 07
Lecture No 44

An Overview of Reciprocating Engine Otto cycle

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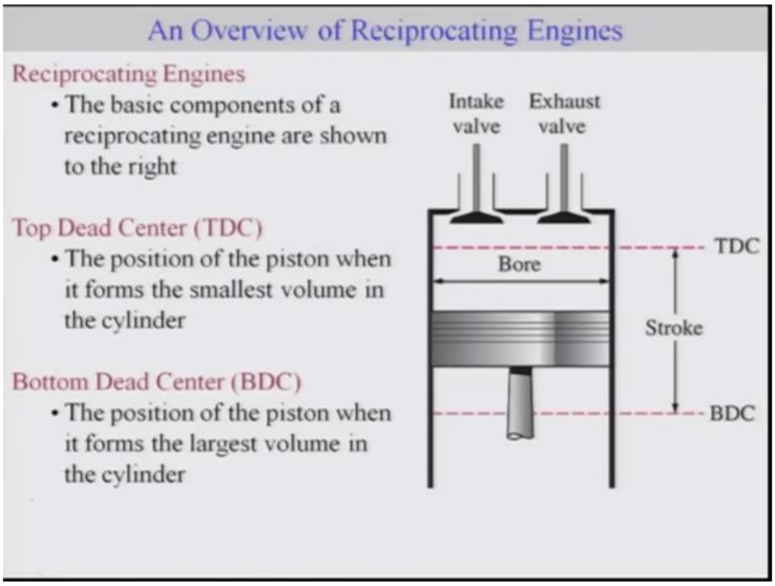

An Overview of Reciprocating Engines

Reciprocating Engines

- The basic components of a reciprocating engine are shown to the right

Top Dead Center (TDC)

- The position of the piston when it forms the smallest volume in the cylinder

Bottom Dead Center (BDC)

- The position of the piston when it forms the largest volume in the cylinder

Okay, welcome back so in the last lecture we described the air standard assumption which would be useful for our analysis for the gas power cycle. So here, let me first review the reciprocating engines so this is an illustration of reciprocating engine which is shown here okay. So the inlet valve is this where of course your gas or the fuel will be injected okay and the exhaust valve would be where the combustion gas would be removed okay. So this is your top dead center, the position where the piston forms the smallest volume in the cylinder and the bottom dead center is the position of the piston where it forms the largest volume in the cylinder.

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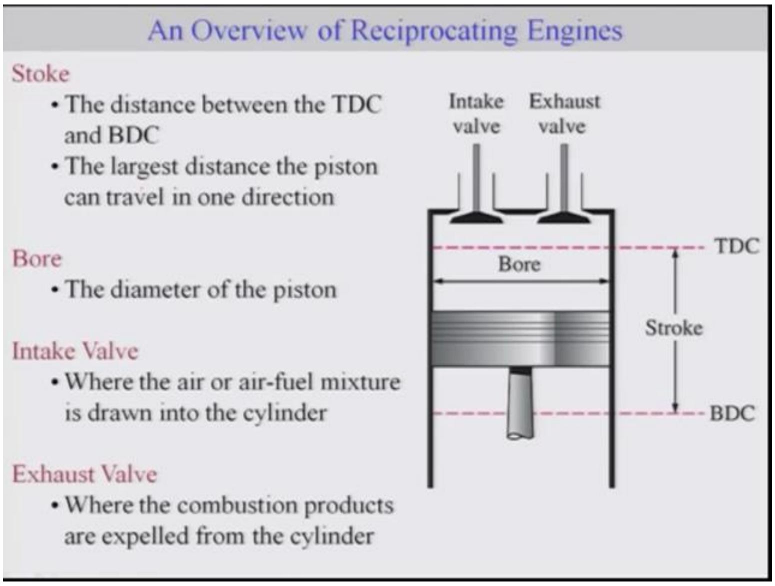

An Overview of Reciprocating Engines

Stoke

- The distance between the TDC and BDC
- The largest distance the piston can travel in one direction

Bore

- The diameter of the piston

Intake Valve

- Where the air or air-fuel mixture is drawn into the cylinder

Exhaust Valve

- Where the combustion products are expelled from the cylinder

So this means this piston keeps moving from the BDC to TDC and the length of this TDC and BDC would be or the difference between TDC and BDC is basically nothing but the one stroke. So this is the stroke is nothing but the largest distance of the piston which can travel in one direction okay. The diameter is called bore so as I already mentioned, the inlet valve and exhaust valve, now at the, if you take this piston to the TDC, there is certain volume which is also left.

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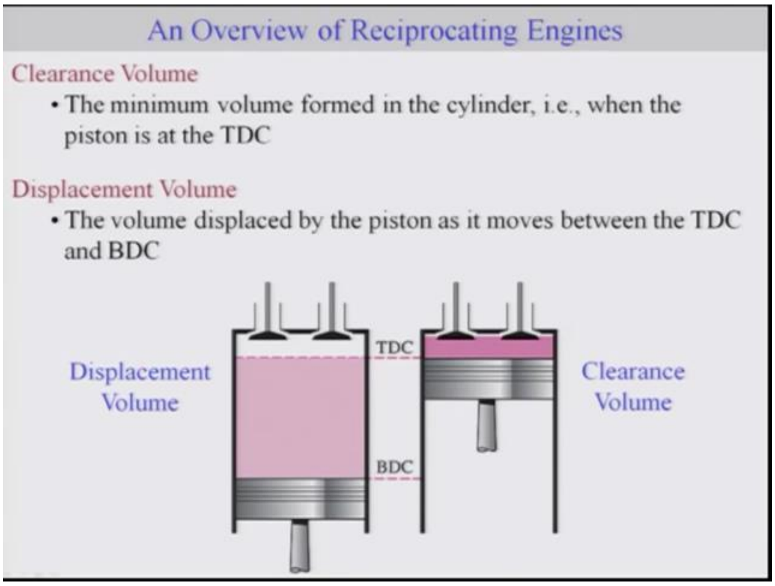

An Overview of Reciprocating Engines

Clearance Volume

- The minimum volume formed in the cylinder, i.e., when the piston is at the TDC

Displacement Volume

- The volume displaced by the piston as it moves between the TDC and BDC

Okay and this volume which is left is called nothing but the clearance volume okay and the volume which you can displace is from BDC to TDC is nothing but the displacement volume.

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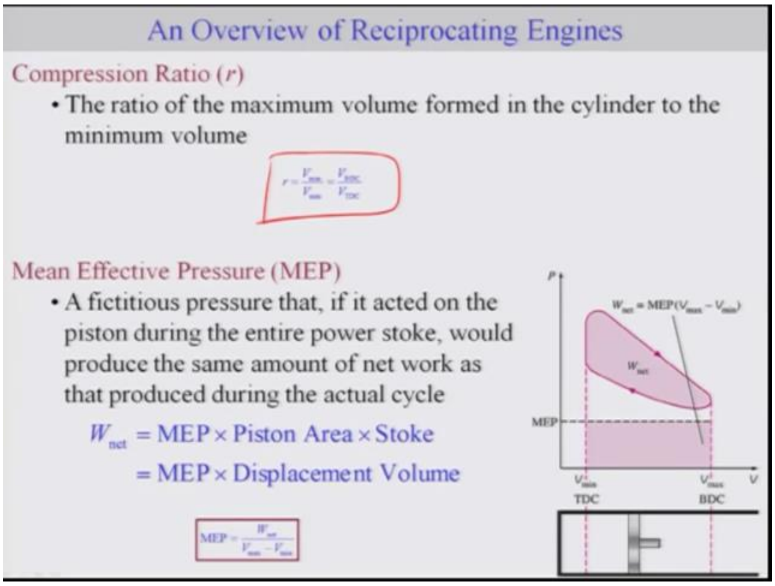

An Overview of Reciprocating Engines

Compression Ratio (r)

- The ratio of the maximum volume formed in the cylinder to the minimum volume

$$r = \frac{V_{max}}{V_{min}} = \frac{V_{BDC}}{V_{TDC}}$$

Mean Effective Pressure (MEP)

- A fictitious pressure that, if it acted on the piston during the entire power stoke, would produce the same amount of net work as that produced during the actual cycle

$$W_{net} = \text{MEP} \times \text{Piston Area} \times \text{Stoke}$$
$$= \text{MEP} \times \text{Displacement Volume}$$

$$\text{MEP} = \frac{W_{net}}{V_{max} - V_{min}}$$

We will be making use of compression ratio in our analysis which is nothing but the ratio of the maximum volume to the minimum volume okay and maximum volume of course corresponds to the BDC so volume corresponding to BDC is the is the volume formed in the cylinder okay that will be the maximum volume and the volume, corresponding to the TDC of the cylinder that means the empty volume could be the minimum volume because this is the top dead center okay, so this the ratio will be considered as compression ratio. We will be also making use of something called mean effective pressure which is nothing buy fictitious pressure that effected on the piston during that entire power stroke would produce the same amount of network as that produced during the actual cycle.

You can see the illustration here, so if this is the complete cycle okay, this is the complete cycle here, and the corresponding work is W net. Now this net can be also, can be written as some fictitious pressure which is this multiplied by the difference in the volume so essentially this itself would be your effective W net, so that is what we are referring to effective pressure in the system, so which is nothing but if you look into the formulation, MAP multiplied by the displacement volume and hence MAP is nothing but W net divided by the difference in the volume, Vmax - Vmin.

Okay, so as I have already mentioned you have internal combustion and external combustion, so this is going to be internal combustion based analysis where you can consider 2 forms of reciprocating engines; one is the spark ignition engine, where the combustion of air fuel mixture is initiated by a spark, this is basically engines in most cars, the gasoline engine and the other one is the compression based ignition engine where the air fuel mixture is self ignited as a result of compressing that mixture with self ignition temperature, this would be the case for diesel engine, okay.

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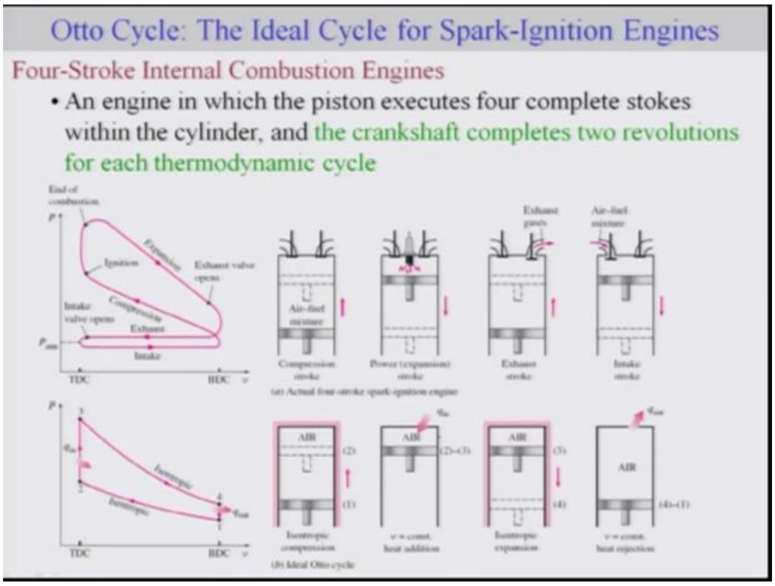

Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

Four-Stroke Internal Combustion Engines

- An engine in which the piston executes four complete stokes within the cylinder, and the crankshaft completes two revolutions for each thermodynamic cycle

So we will be first considering the spark ignition engines okay so this would be your 4 stroke internal combustion engine particularly spark ignition engine, so let me first go through the basic the actual process and then we will try to represent this actual process by a simplified cycles which will be called our Otto cycle okay. So in this one particularly an internal combustion engine consists of 4 strokes. So this is an example of 4 stroke internal combustion engine and essentially this complete cycle consists of 4 times of this one single stroke, so you can clearly see 4 so the direction shows that this is the 1 stroke, 2 stroke, 3 and 4. As well as it the crank shaft completes 2 revolutions for each thermodynamics cycle because you can clearly see if it here, it will be your 1 revolution and this will be another revolution okay.

So let me start from initially what happens so let me start with this particular first image so here, you have this inlet valve okay so this is your inlet valve and this is your exhaust valve right. So here, if we can consider that, this is the point you start cycle, okay, initial point of your cycle, where the inlet valves open and hence you allow your air fuel mixture to come in, expansion. So this is your inlet valve which opens and this gas intake is considered here and upon here, the compression stroke takes you to the point where sufficiently compress that you can start your ignition, so this is where the second state okay.

So ignition happens, this ignition initiates the combustion, the combustion ends here okay and after the combustion, this expansion happens so the combustion ends here and this expansion is shown by this stroke, so this becomes the second part of the stroke. Um then the exhaust valve is opened. Once your exhaust valve is opened, this would be your exhaust stroke so extensionally the volume gets reduced and then your air fuel mixture is again placed here okay.

So you pass the air fuel mixture which will expand the volume which will be intake stroke okay, so this is your intake valve open, so this becomes your intake stroke which is actually this so though we are starting with the compression stroke okay, we can also start from this analysis as a intake stroke. So let me again go through this explanation again, so here the first step corresponding to this image is nothing but your compression stroke which is this okay, so this is your compression stroke okay followed by your expansion stroke followed by your exhaust stroke followed by your intake stroke.

Now this becomes a complete cycle so you have compression stroke, expansion stroke, exhaust stroke and then intake stroke okay. It is very clear that this is not in a closed system, not a closed thermodynamic cycle, this is the open because your air fuel mixtures is renewed again, but what we are going to do for this analysis of such 4 stroke internal combustion engine that we will consider it to be a closed thermodynamic cycle and this can be considered by an ideal otto cycle where this compression stroke can be considered as isentropic compression.

This whole combustion will be considered as a constant volume considered to be very fast reaction and hence the energy, whatever the combustion occurs can be considered as a energy from the external medium that is your going to be Q in okay and the first part which compression itself, which happens in the compression stroke is considered to be adiabatic so that would be your isentropic compression okay so this is your adiabatic reversible compression and this is isentropic followed by heat addition.

Here, this compression is considered as a heat addition, so we are making use of air standard assumption and then followed by your isentropic expansion and then followed by your heat rejection okay. So in other words, what we have done is, though these particular images are not exactly in the same stroke okay but so what we have done is that overall cycle which involves this step as in actual 4 stroke spark ignition engine can be represented in idealized cycle based on air standard assumption and this would be your ideal Otto cycle okay so this becomes your otto cycle analysis and this is your PV diagram for that.

So let me go through simply in bore subtle points of this otto cycle. So otto cycles we will be considering the 4 stroke engine and this cycle can be assumed as an ideal otto cycle. Here we are going to use of air standard assumption, so essentially ideal otto cycle consists of 4 internal reversible processes as we already described earlier.

So this is the first would be your isentropic compression followed by constant volume heat addition, so the combustion is going to be considered as constant volume heat addition, then isentropic expansion followed by constant volume heat rejection. The exhaust gas which is taken out of the system would be considered as constant volume heat rejection. So here the corresponding PV diagram again, so this we have already looked at. The corresponding TS diagram would be this okay so 1 to 2, isentropic compression. This would be your constant volume heat addition, isentropic expansion, constant volume heat rejection okay.

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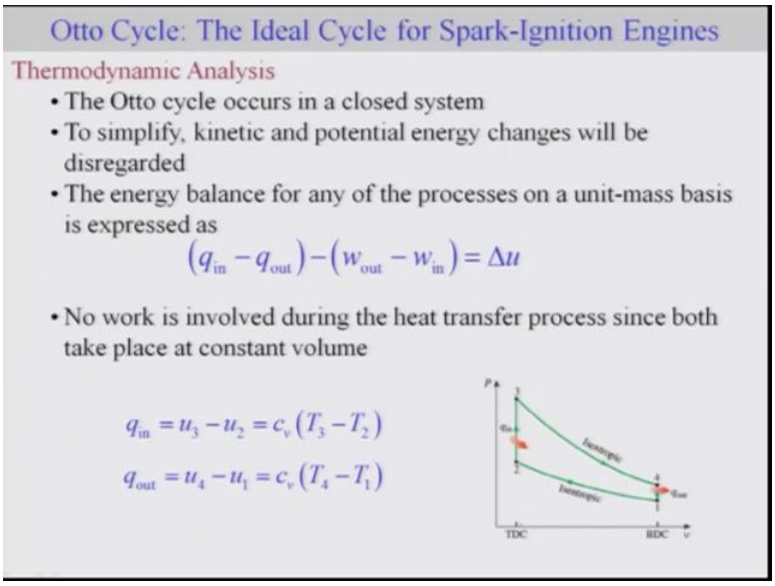

Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

Thermodynamic Analysis

- The Otto cycle occurs in a closed system
- To simplify, kinetic and potential energy changes will be disregarded
- The energy balance for any of the processes on a unit-mass basis is expressed as

$$(q_{in} - q_{out}) - (w_{out} - w_{in}) = \Delta u$$

- No work is involved during the heat transfer process since both take place at constant volume

$$q_{in} = u_3 - u_2 = c_v (T_3 - T_2)$$

$$q_{out} = u_4 - u_1 = c_v (T_4 - T_1)$$

Now we can make use of a thermodynamic analysis by considering that kinetic energy, potential energy changes will be 0 and thus your energy balance for any process based on a unid mass can be simply considered here that this will be your Q in - Q out, net Q in - Q out is = simply your change in internal energy of the system, it is considered to a closed system. So as we know that no work is involved during the heat transfer process since both are operating at a constant volume okay so this is at constant volume. So we know that Q in for the case of a constant volume considering this is air is simply delta U and simply Q out is also delta U and since delta U can be written in terms of heat capacity and change in temperature, we can write expression Q in terms of CV terms, CV and change in temperature.

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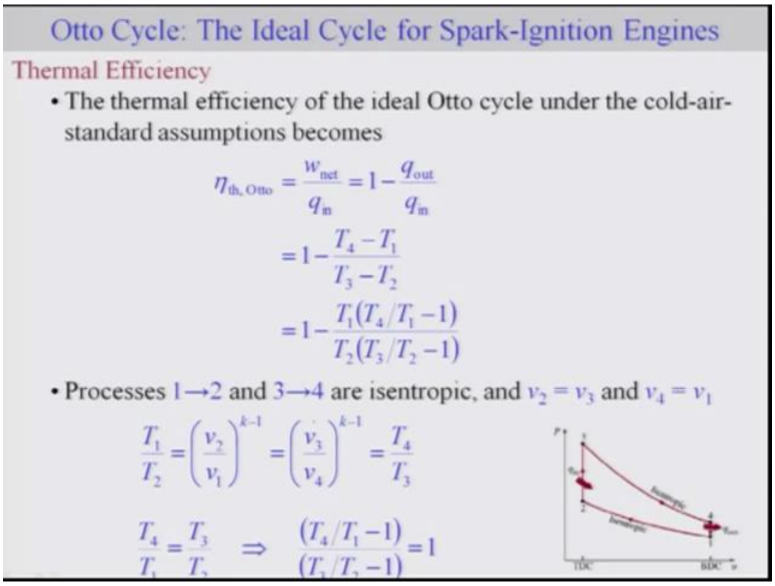

Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

Thermal Efficiency

- The thermal efficiency of the ideal Otto cycle under the cold-air-standard assumptions becomes

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

$$= 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

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

- Processes 1→2 and 3→4 are isentropic, and $v_2 = v_3$ and $v_4 = v_1$

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

$$\frac{T_4}{T_1} = \frac{T_3}{T_2} \Rightarrow \frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)} = 1$$

Now, for the case of thermal efficiency, we can write simply eta in terms of Wnet divided by Q in and this can be further written in this form. Now, this is an ideal reversible cycle, we can replace Q out and Q in, in terms of CV and this is what you get and this can be written as the ratio of T1 and T2 and these terms will come as a separate one and one can show that considering that 1 and 2 and 3 and 4 are isentropic processes and there is constant volume and based on this ideal gas relation of the ratio of temperature to V2 by V1 to the power K, where K is nothing but your CP by CV. One can show that this term goes to 1, eta otto okay for thermal efficiency is nothing but 1 - T1 by T2, okay.

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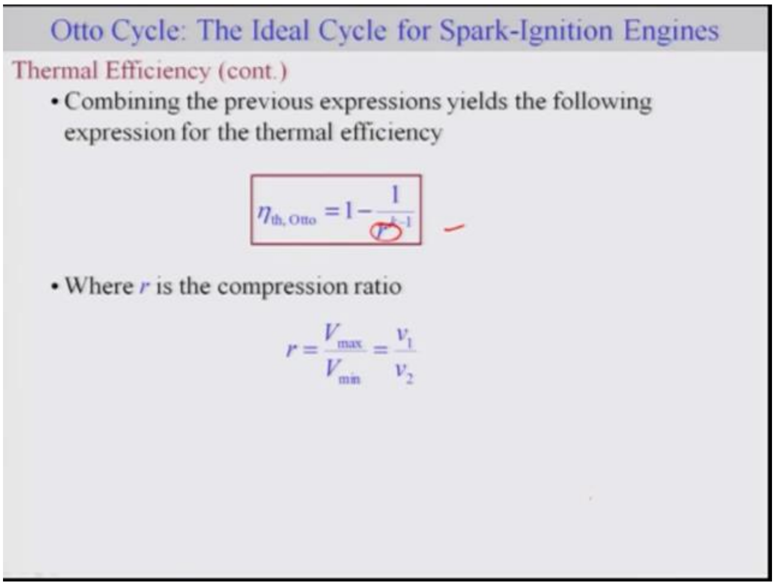

Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

Thermal Efficiency (cont.)

- Combining the previous expressions yields the following expression for the thermal efficiency

$$\boxed{\eta_{\text{th, Otto}} = 1 - \frac{1}{r^{k-1}}}$$

- Where r is the compression ratio

$$r = \frac{V_{\max}}{V_{\min}} = \frac{v_1}{v_2}$$

Compression ratio is nothing but V1 by V2 thus this can be also written as 1 - 1 by R, K - 1, okay that is what is written here. Now, based on this expression, it is very clear that if one can increase the efficiency by decreasing R or increasing K so you can have more R in order to have higher efficiency.

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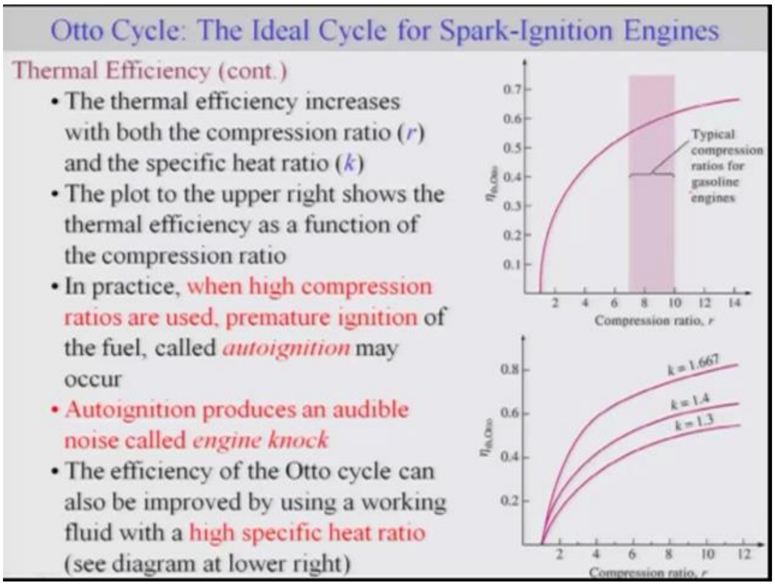

Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

Thermal Efficiency (cont.)

- The thermal efficiency increases with both the compression ratio (r) and the specific heat ratio (k)
- The plot to the upper right shows the thermal efficiency as a function of the compression ratio
- In practice, when high compression ratios are used, premature ignition of the fuel, called *autoignition* may occur
- Autoignition produces an audible noise called *engine knock*
- The efficiency of the Otto cycle can also be improved by using a working fluid with a high specific heat ratio (see diagram at lower right)

This is a typical range for the gasoline engine somewhere from 7 to 10 and as I said, you can increase the efficiency by increasing the heat capacity which essentially means that you can use working fluid with a higher specific hear ratio in order to have higher efficiency of otto cycle okay. So you can make use of this analysis of ideal otto cycle based on air standard assumption and based on this particular cycle definition and this analysis, one can do certain examples and this is an example which we can try okay.

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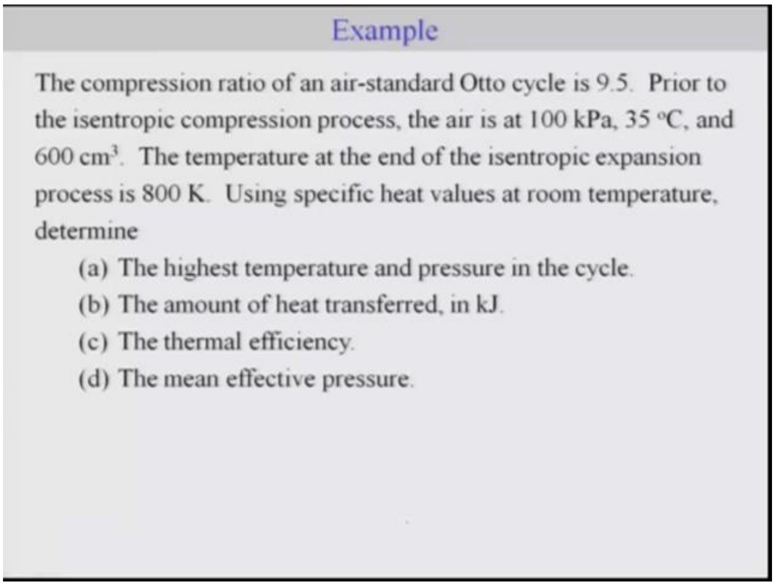

Example

The compression ratio of an air-standard Otto cycle is 9.5. Prior to the isentropic compression process, the air is at 100 kPa, 35 °C, and 600 cm^3. The temperature at the end of the isentropic expansion process is 800 K. Using specific heat values at room temperature, determine

(a) The highest temperature and pressure in the cycle.
(b) The amount of heat transferred, in kJ.
(c) The thermal efficiency.
(d) The mean effective pressure.

And the idea of this particular example is to attempt by describing the process on a PV diagram and making use of different energy analysis which we have done and represented. So enjoy by doing this example and I will see you in the next lecture, where we are going to describe the diesel engine concepts okay, so I will see you in the next lecture.