ESO 201A: Thermodynamics

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Gas Power Cycle: part2

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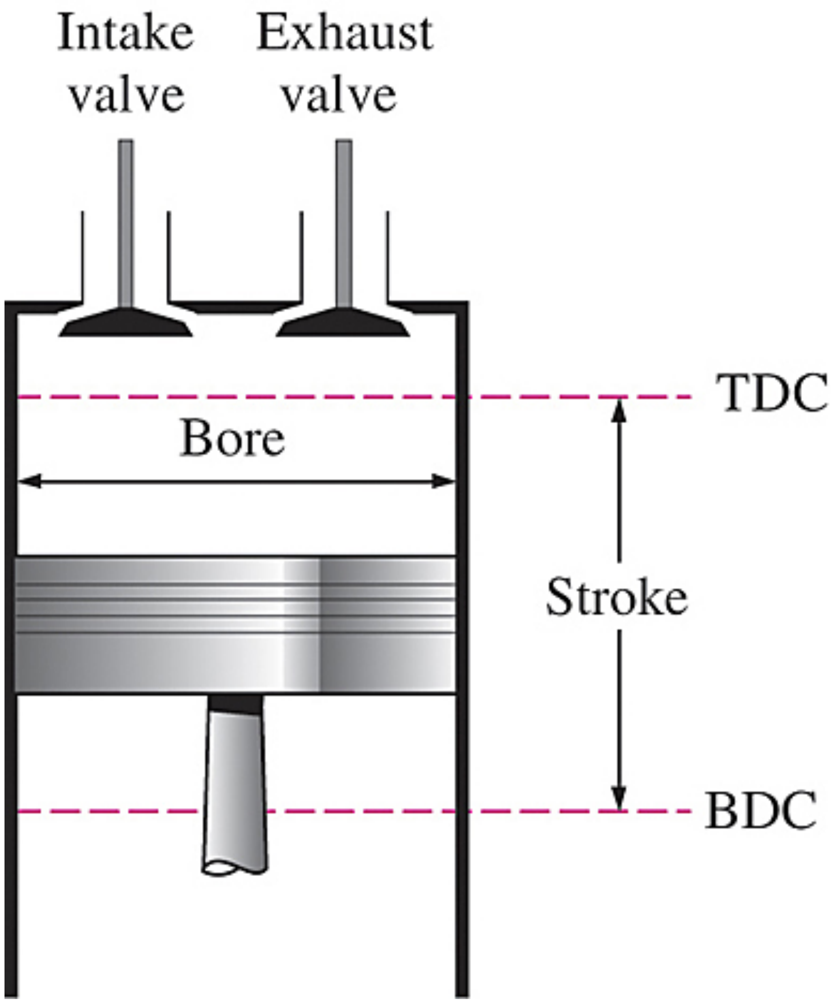
Learning Objectives

- Evaluate the performance of gas power cycles for which the working fluid remains a gas throughout the entire cycle.
- Develop simplifying assumptions applicable to gas power cycles.
- Review the operation of reciprocating engines.
- Analyze both closed and open gas power cycles.
- Solve problems based on the Otto, Diesel, and Brayton cycles.

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

An Overview of Reciprocating Engines

Stoke

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

Bore

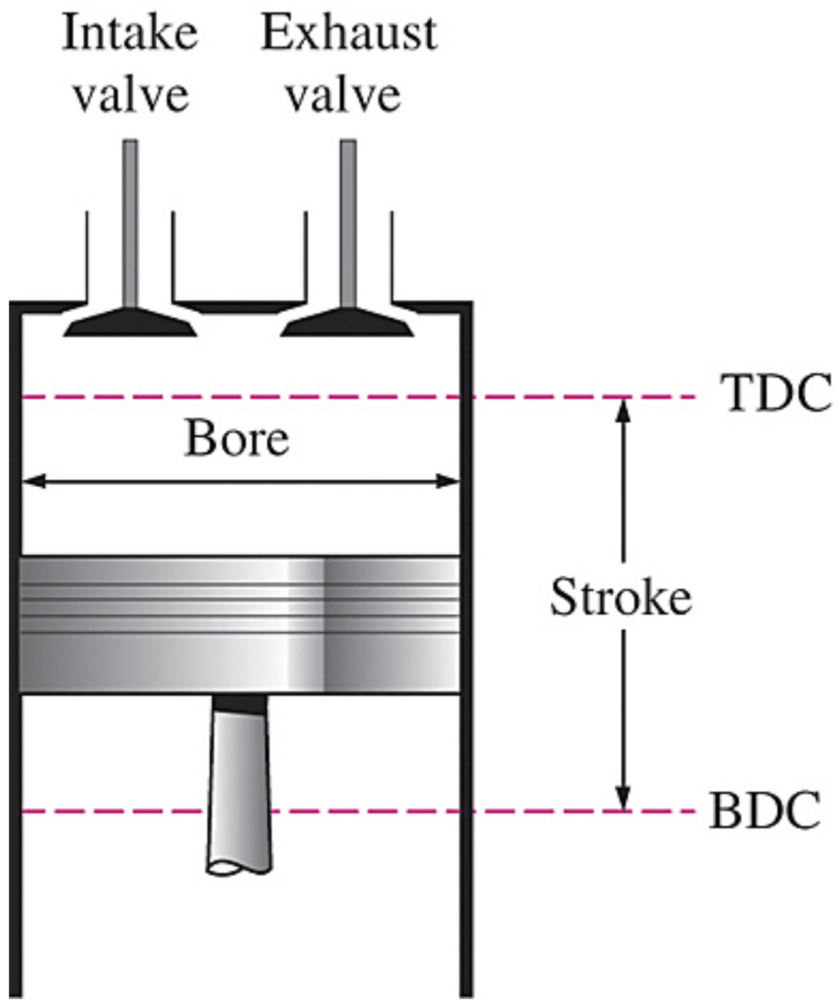
- The diameter of the piston

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



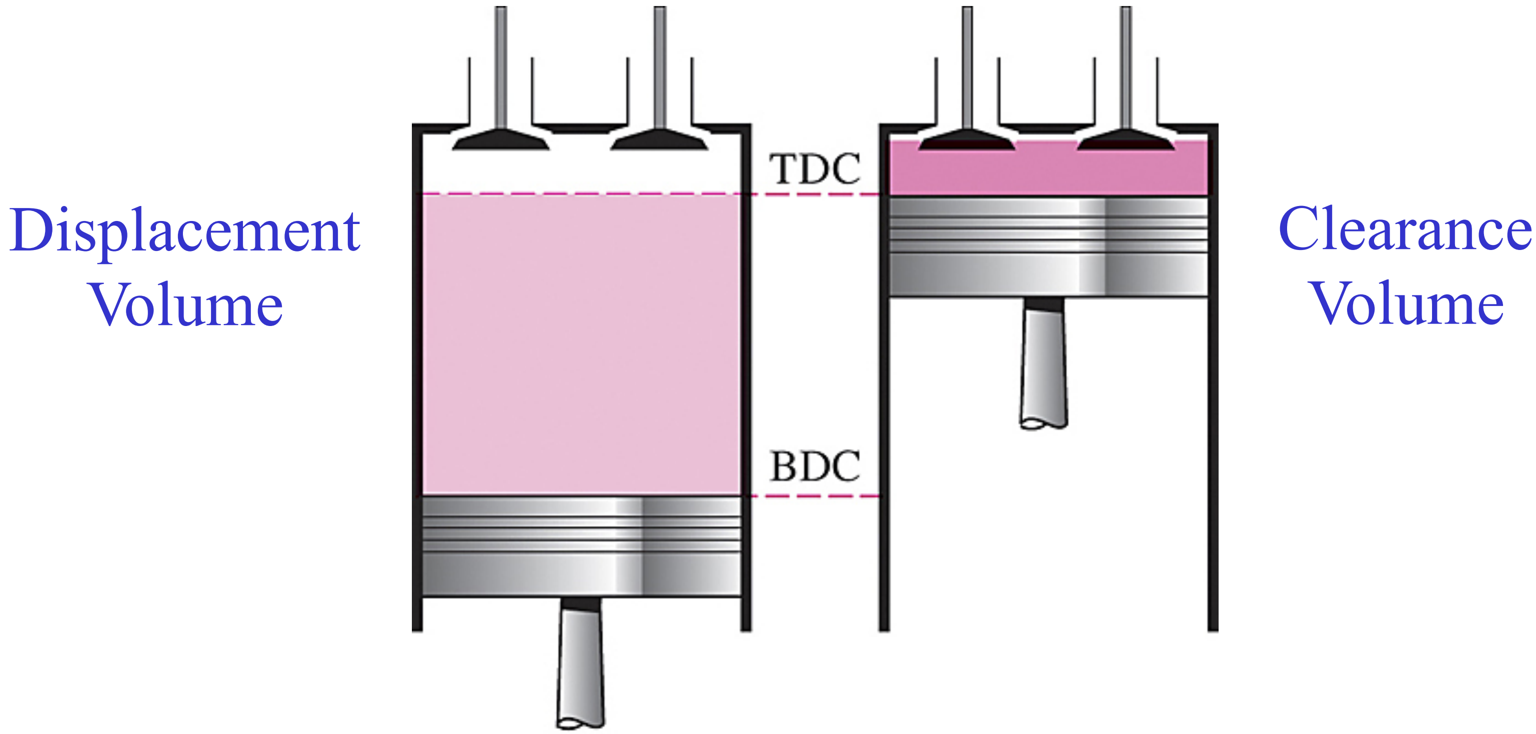
An Overview of Reciprocating Engines

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



An Overview of Reciprocating Engines

Compression Ratio (r)

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

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

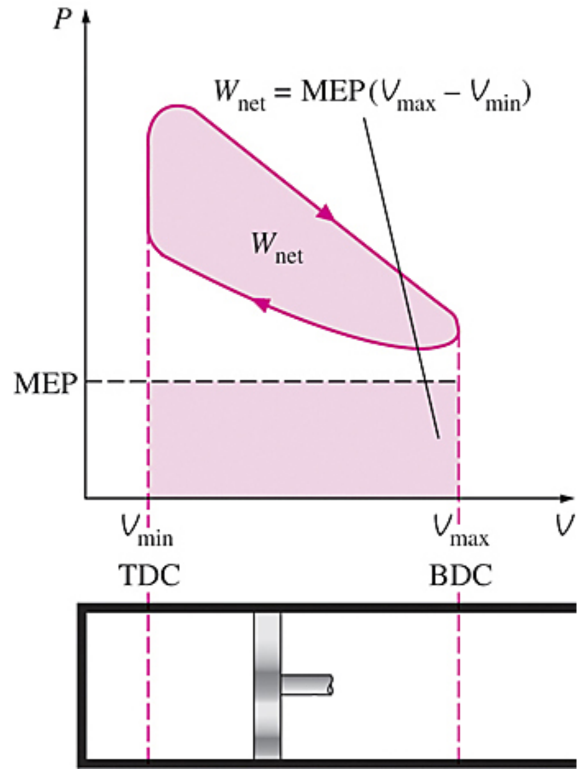
Mean Effective Pressure (MEP)

- 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

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

$$= \text{MEP} \times \text{Displacement Volume}$$

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



An Overview of Reciprocating Engines

Spark-Ignition Engines

- The combustion of the air-fuel mixture is initiated by a spark plug
- E.g., engines in most cars

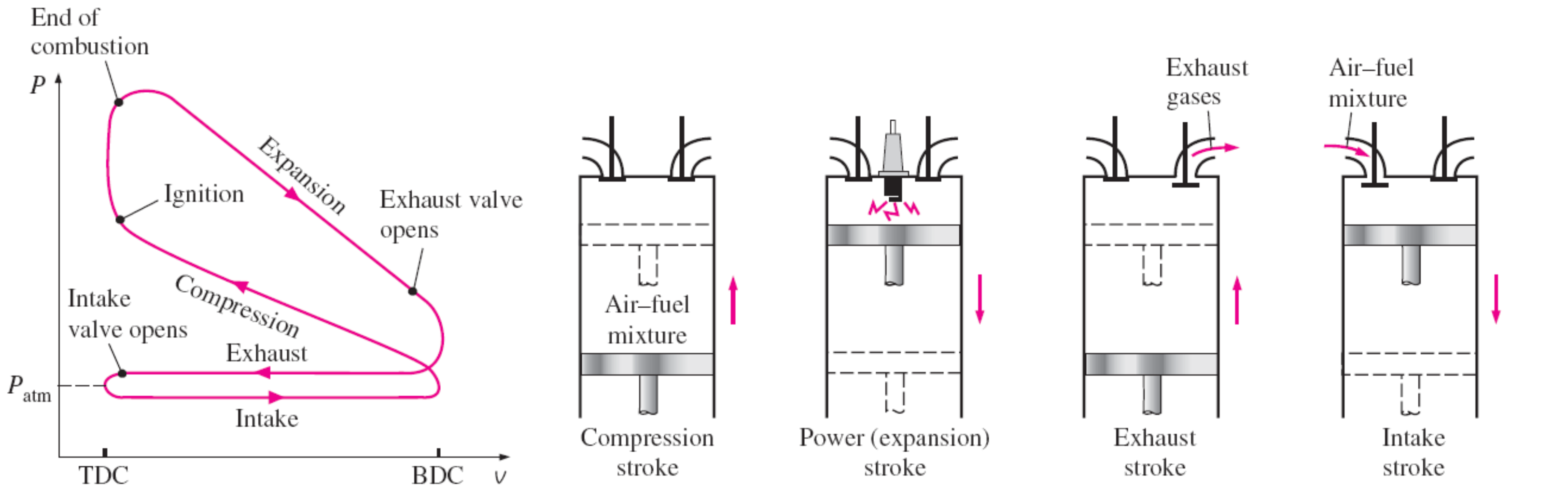
Compression-Ignition Engines (CI)

- The air-fuel mixture is self-ignited as a result of compressing the mixture above its self ignition temperature
- E.g., Diesel engines

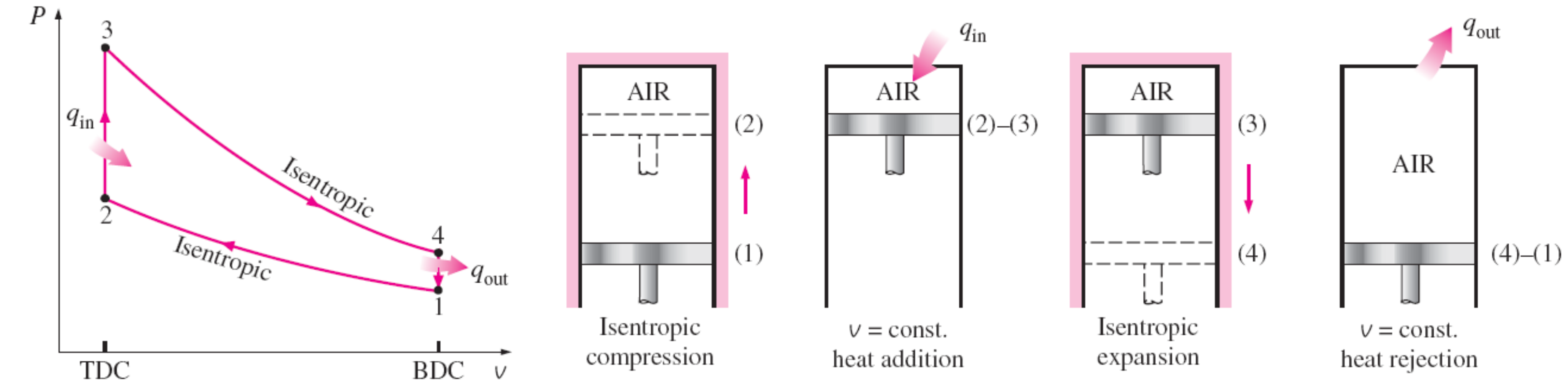
Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

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



(a) Actual four-stroke spark-ignition engine



(b) Ideal Otto cycle

Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

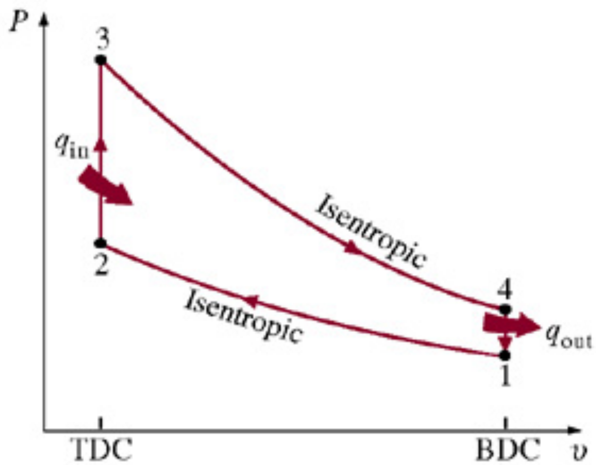
Simplification and Analysis

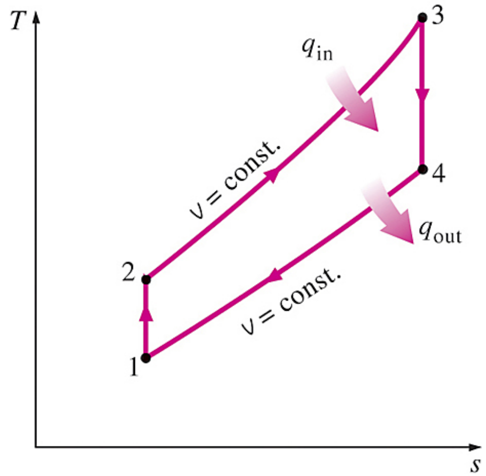
- The analysis of the four-stoke engine can be simplified significantly if the air-standard assumptions are utilized
- The resulting cycle is the ideal *Otto Cycle*, which consists of four internally reversible processes

1→2	Isentropic compression
2→3	Constant-volume heat addition
3→4	Isentropic expansion
4→1	Constant-volume heat rejection

Nikolaus Otto

- Here are the *P*-*v* and *T*-*s* diagrams for the Otto cycle





Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

Thermodynamic Analysis

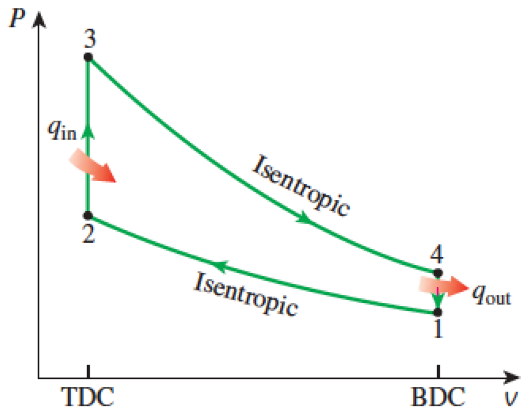
- The Otto cycle occurs in a closed system
- To simplify, kinetic and potential energy changes will be disregarded
- The energy balance for any of the processes on a unit-mass basis is expressed as

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

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

$$q_{\text{in}} = u_3 - u_2 = c_v\left(T_3 - T_2\right)$$

$$q_{\text{out}} = u_4 - u_1 = c_v\left(T_4 - T_1\right)$$



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

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

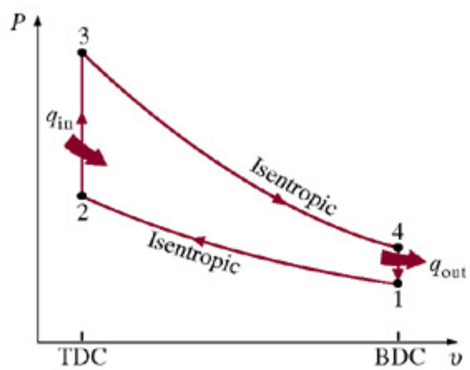
$$= 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

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

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

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

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



Otto Cycle: The Ideal Cycle for Spark-Ignition Engines

Thermal Efficiency (cont.)

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

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

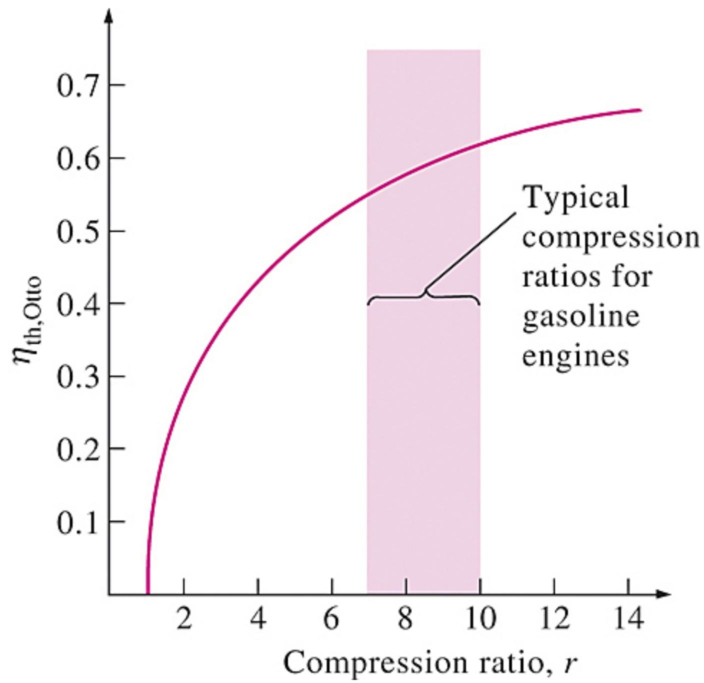
- Where r is the compression ratio

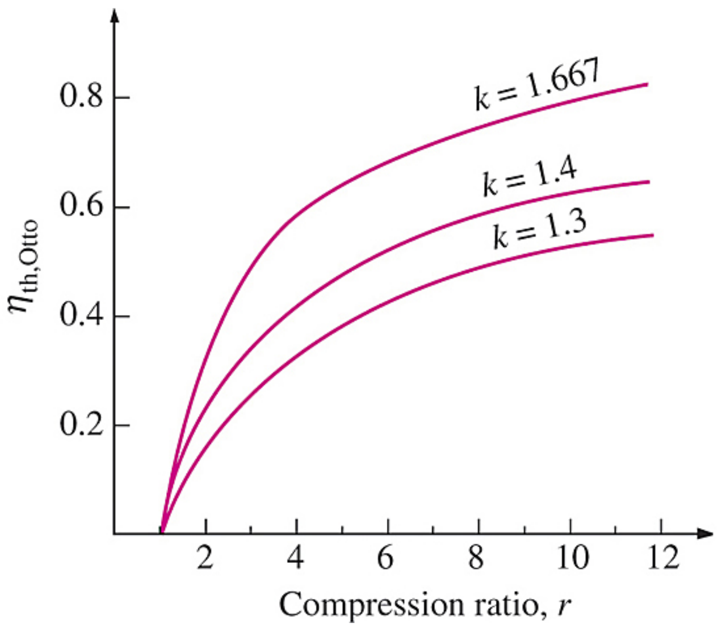
$$r = \frac{V_{\max}}{V_{\min}} = \frac{v_1}{v_2}$$

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)





Example

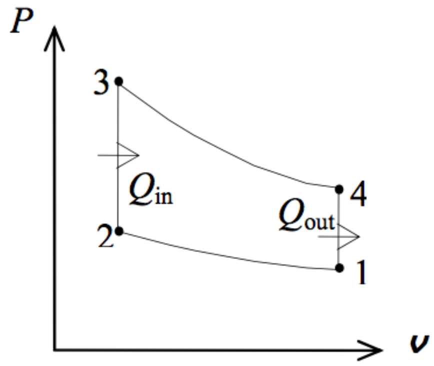
The compression ratio of an air-standard Otto cycle is 9.5. Prior to the isentropic compression process, the air is at 100 kPa, 35 ^{o}C, and 600 cm^3. The temperature at the end of the isentropic expansion process is 800 K. Using specific heat values at room temperature, determine

(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.

Example

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

(*a*) Process 1-2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (308\text{ K})(9.5)^{0.4} = 757.9\text{ K}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{v_1}{v_2}\frac{T_2}{T_1}P_1 = (9.5)\left(\frac{757.9\text{ K}}{308\text{ K}}\right)(100\text{ kPa}) = 2338\text{ kPa}$$

Process 3-4: isentropic expansion.

$$T_3 = T_4\left(\frac{v_4}{v_3}\right)^{k-1} = (800\text{ K})(9.5)^{0.4} = \mathbf{1969\ K}$$

Process 2-3: v = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2}P_2 = \left(\frac{1969\text{ K}}{757.9\text{ K}}\right)(2338\text{ kPa}) = \mathbf{6072\ kPa}$$

Example

(*b*) $$m = \frac{P_1 \boldsymbol{v}_1}{RT_1} = \frac{(100\text{ kPa})(0.0006\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(308\text{ K})} = 6.788\times10^{-4}\text{ kg}$$

$$Q_{\text{in}} = m(u_3 - u_2) = mc_{\boldsymbol{v}}(T_3 - T_2) = (6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(1969 - 757.9)\text{K} = \mathbf{0.590\ kJ}$$

(c) Process 4-1: $\boldsymbol{v}$= constant heat rejection.

$$Q_{\text{out}} = m(u_4 - u_1) = mc_{\boldsymbol{v}}(T_4 - T_1) = -(6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(800 - 308)\text{K} = 0.240\text{ kJ}$$

$$W_{\text{net}} = Q_{\text{in}} - Q_{\text{out}} = 0.590 - 0.240 = 0.350\text{ kJ}$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{\text{in}}} = \frac{0.350\text{ kJ}}{0.590\text{ kJ}} = \mathbf{59.4\%}$$

(*d*) $$\boldsymbol{v}_{\min} = \boldsymbol{v}_2 = \frac{\boldsymbol{v}_{\max}}{r}$$

$$\text{MEP} = \frac{W_{\text{net,out}}}{\boldsymbol{v}_1 - \boldsymbol{v}_2} = \frac{W_{\text{net,out}}}{\boldsymbol{v}_1(1 - 1/r)} = \frac{0.350\text{ kJ}}{(0.0006\text{ m}^3)(1 - 1/9.5)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{652\ kPa}$$

Next lecture

- Evaluate the performance of gas power cycles for which the working fluid remains a gas throughout the entire cycle.
- Develop simplifying assumptions applicable to gas power cycles.
- Review the operation of reciprocating engines.
- Analyze both closed and open gas power cycles.
- Solve problems based on the Otto, Diesel, and Brayton cycles.