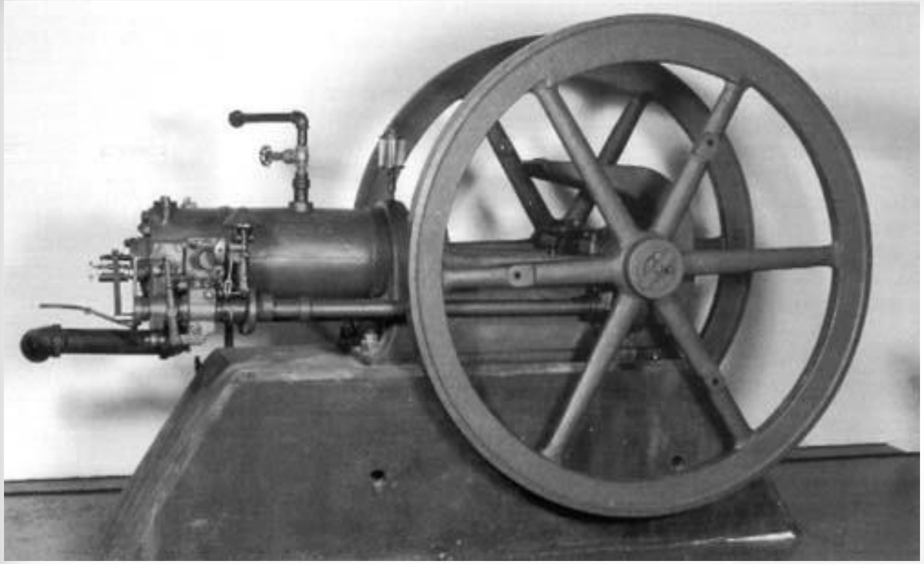
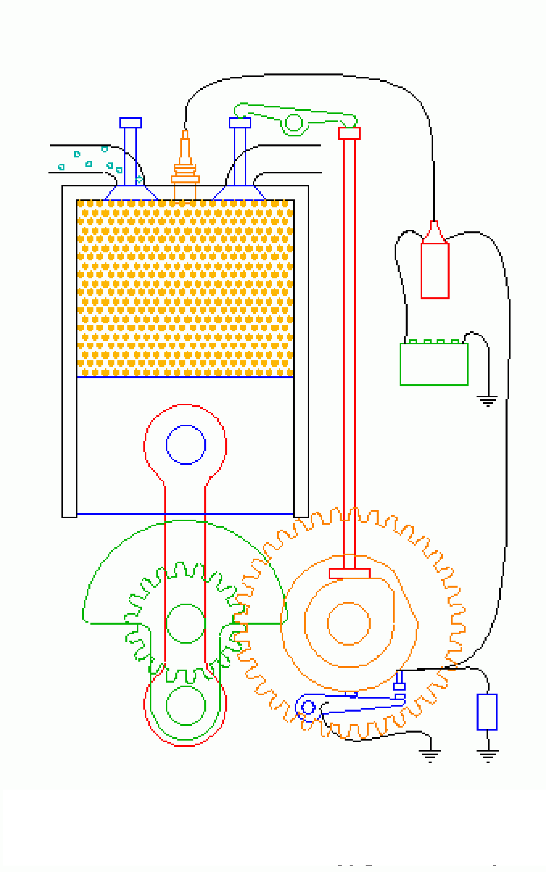
TERMODINAMIKA dan PEMBAKARAN

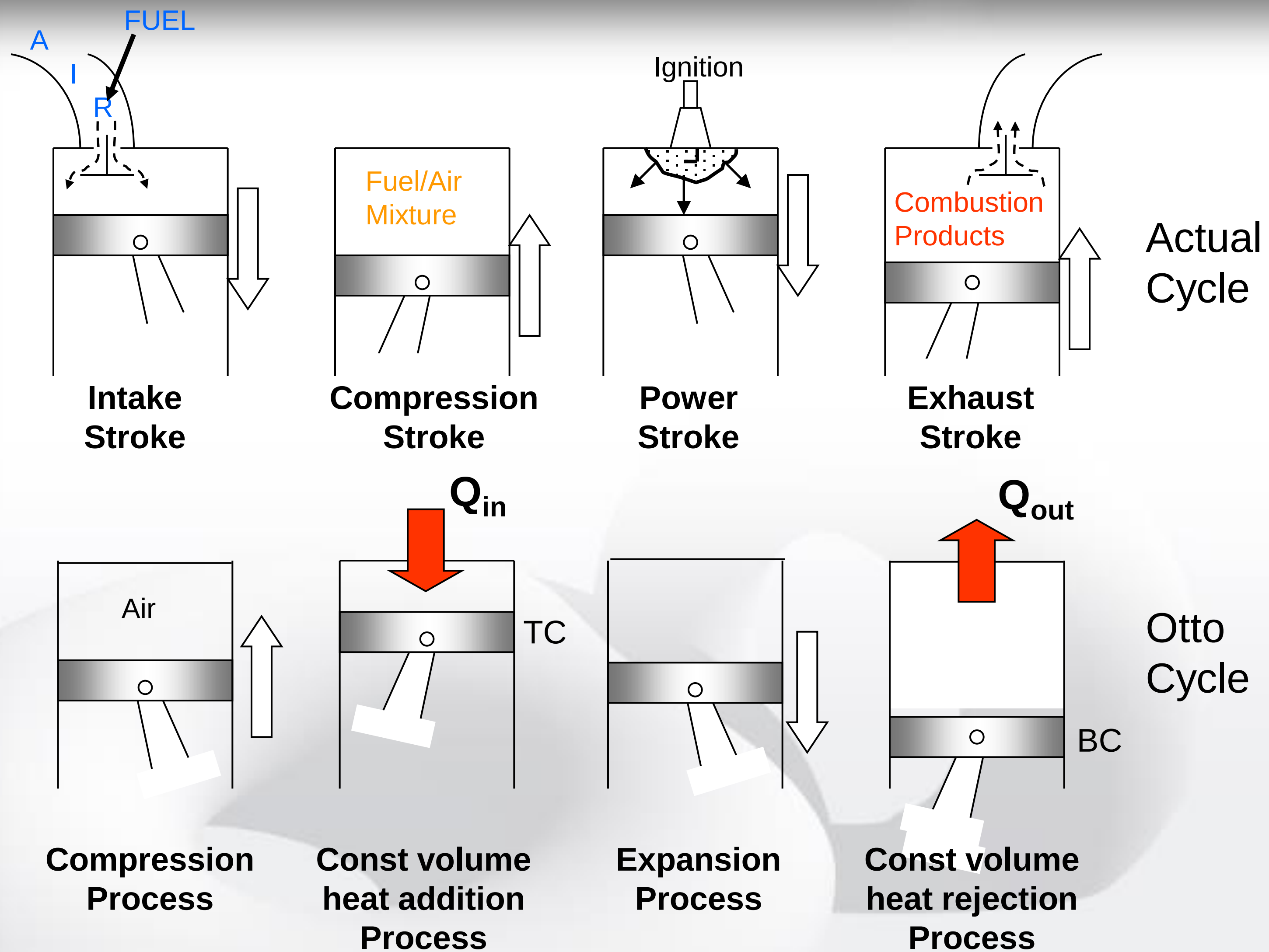
Satworo Adiwidodo, S.T., M.T

SIKLUS OTTO

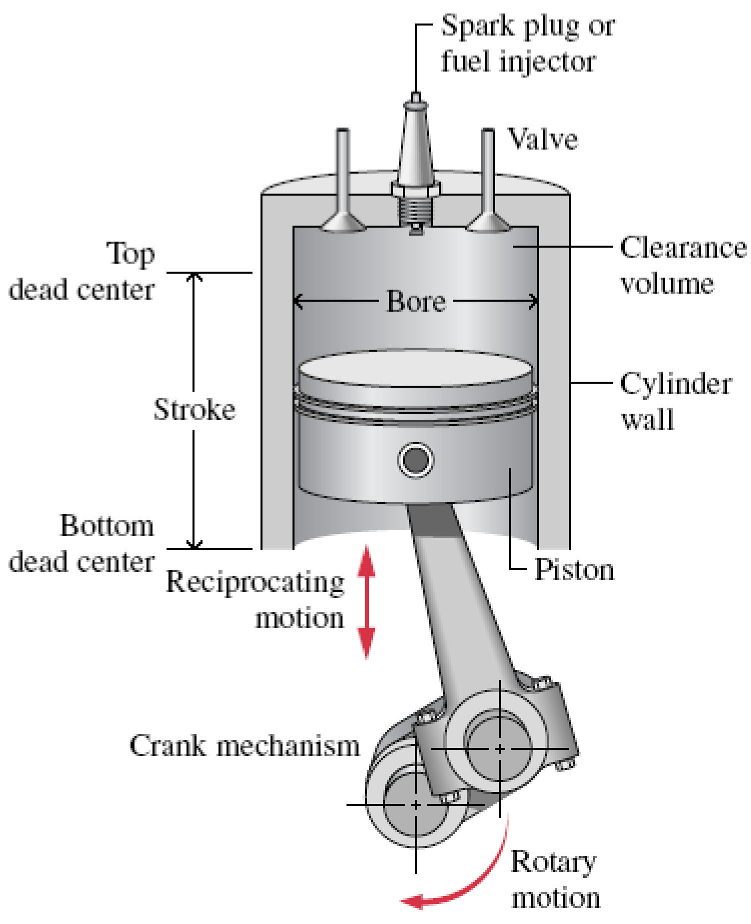


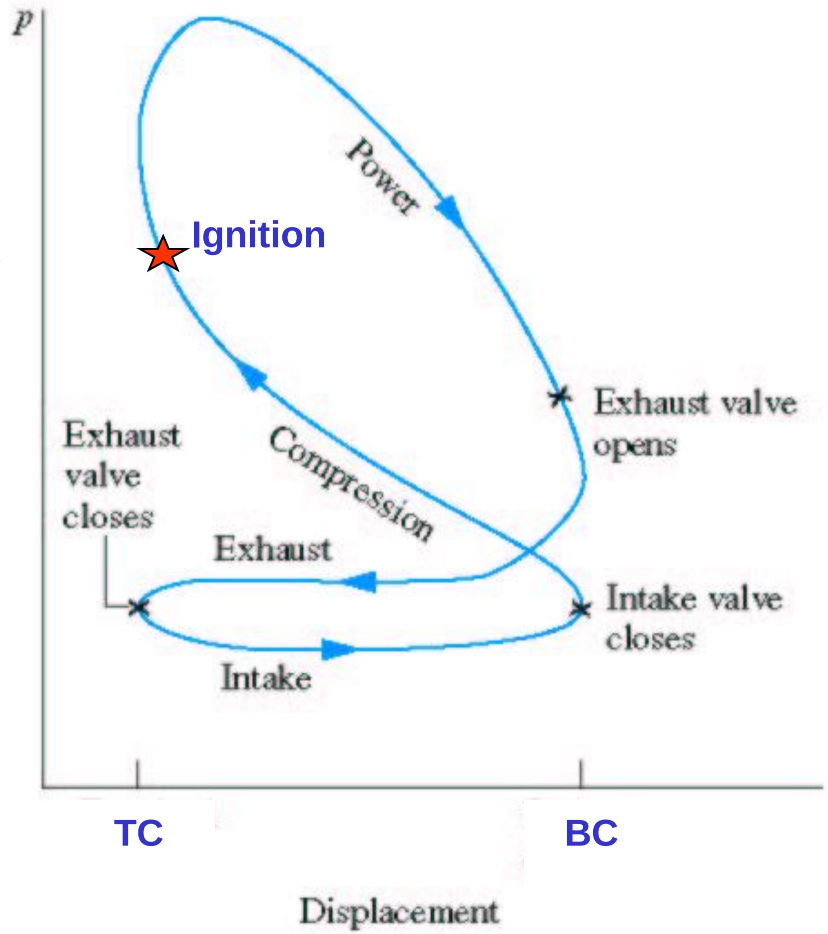


SI Engine Cycle vs Thermodynamic Otto Cycle

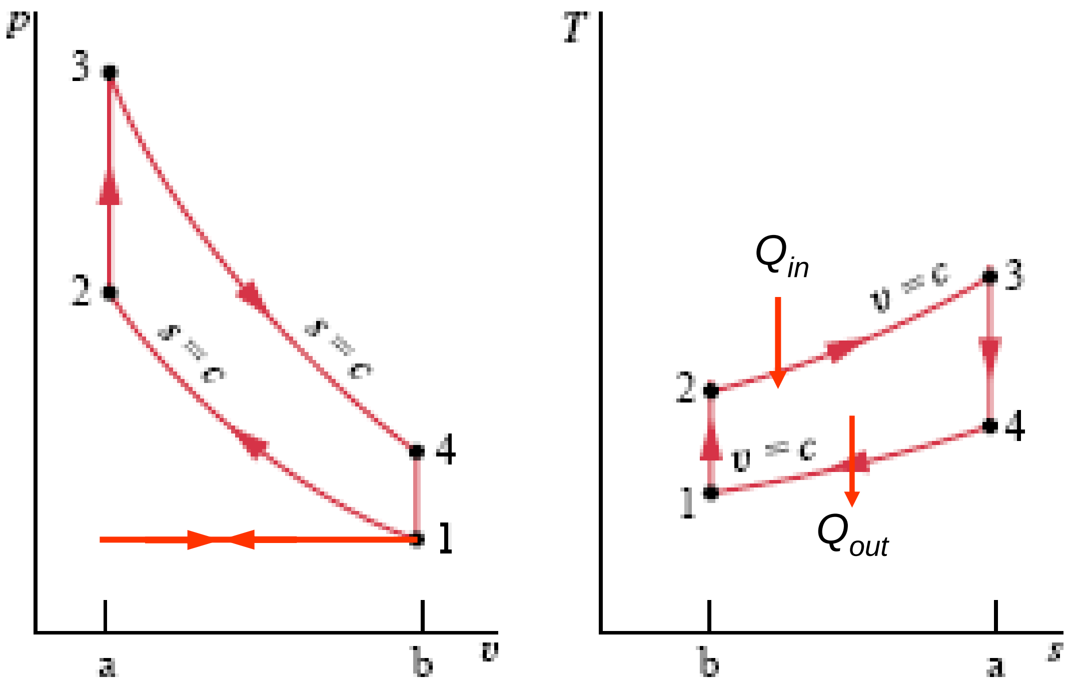


Actual SI Engine cycle





SIKLUS OTTO



$$r_v = \frac{v_1}{v_2} = \frac{v_4}{v_3}$$

Process 0 → 1 intake
Process 1 → 2 Isentropic compression
Process 2 → 3 Constant volume heat addition (isovolumetric)
Process 3 → 4 Isentropic expansion
Process 4 → 1 Constant volume heat rejection (isovolumetric)
Process 1 → 0 Exhaust

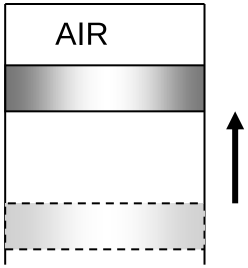
Analysis of Otto Cycle

1→2 <u>Isentropic Compression, entropy (s) constant</u>

air standar analysis →from tabel

$$(u_2 - u_1) = \frac{\cancel{Q}}{m} - \frac{W_{in}}{m}$$

$$\frac{W_{in}}{m} = -(u_2 - u_1)$$



$$\frac{v_2}{v_1} = \frac{v_{r2}}{v_{r1}} \quad \text{Jika s1= s2}$$

cold air standar analysis →constant *k*

$$\frac{W_{in}}{m} = -(u_2 - u_1) = -c_v(T_2 - T_1)$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} = r_v^{\,k-1}$$

$$\frac{P_2}{P_1} = \frac{T_2}{T_1} \cdot \frac{v_1}{v_2} = r_v^{\,k}$$

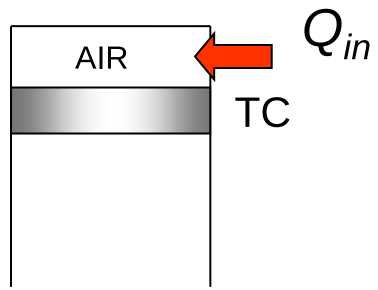
Analysis of Otto Cycle

2→3 Constant Volume Heat Addition

air standar analysis →from tabel

$$(u_3 - u_2) = (+\frac{Q_{in}}{m}) - \frac{\cancel{W}}{m}$$

$$\frac{Q_{in}}{m} = (u_3 - u_2)$$



$$\frac{P_3}{P_2} = \frac{T_3}{T_2}$$

cold air standar analysis →constant *k*

$$\frac{Q_{in}}{m} = c_v (T_3 - T_2)$$

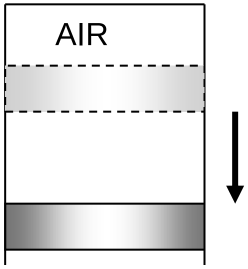
Analysis of Otto Cycle

3 → 4 Isentropic Expansion

air standar analysis →from tabel

$$(u_4 - u_3) = \frac{\not{Q}}{m} - \frac{W_{out}}{m}$$

$$\frac{W_{out}}{m} = (u_3 - u_4)$$



$$\frac{v_4}{v_3} = \frac{v_{r4}}{v_{r3}}$$ Jika s3= s4

cold air standar analysis →constant *k*

$$\frac{W_{out}}{m} = c_v (T_3 - T_4)$$

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{k-1} = \frac{1}{r^{k-1}}$$

$$\frac{P_4}{P_3} = \frac{T_4}{T_3} \cdot \frac{v_3}{v_4} = \frac{1}{r^k}$$

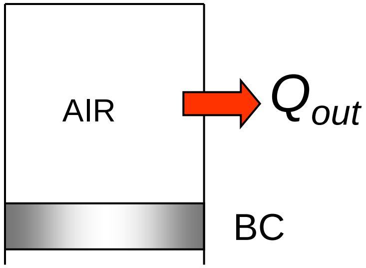
Analysis of Otto Cycle

4 → 1 Constant Volume Heat Removal

air standar analysis →from tabel

$$(u_1 - u_4) = \frac{Q_{out}}{m} - \frac{\cancel{W}}{m}$$

$$\boxed{\frac{Q_{out}}{m} = (u_1 - u_4)}$$



$$\boxed{\frac{P_4}{T_4} = \frac{P_1}{T_1}}$$

cold air standar analysis →constant *k*

$$\boxed{\frac{Q_{out}}{m} = c_v (T_1 - T_4)}$$

Analysis of Otto Cycle

Net cycle work:

$$W_{cycle} = W_{out} + (-W_{in}) = m(u_3 - u_4) - m(u_2 - u_1)$$

Cycle indicated thermal efficiency:

Air standar analysis:

$$\eta_{th} = \frac{W_{cycle}}{Q_{in}} = \frac{(u_3 - u_4) - (u_2 - u_1)}{(u_3 - u_2)} = \frac{(u_3 - u_2) - (u_4 - u_1)}{u_3 - u_2} = 1 - \frac{u_4 - u_1}{u_3 - u_2}$$

Cold Air standar analysis:

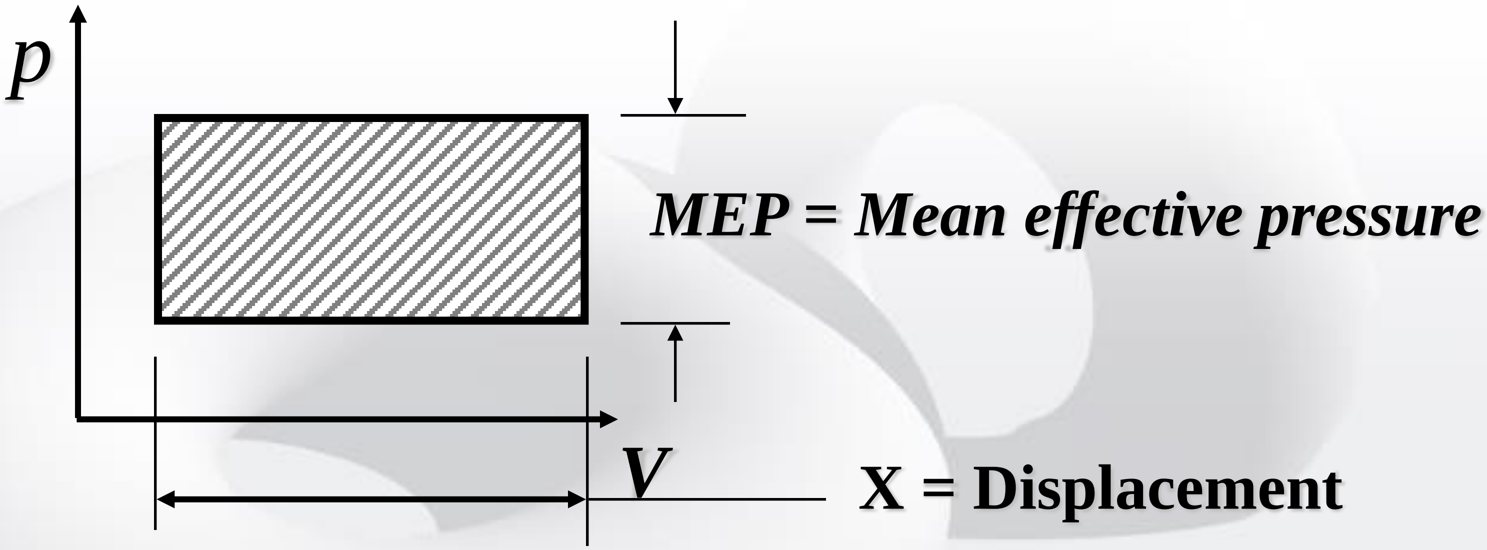
$$\eta_{th} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)} = 1 - \frac{T_1}{T_2} = \boxed{1 - \frac{1}{r^{k-1}}}$$

Indicated mean effective pressure

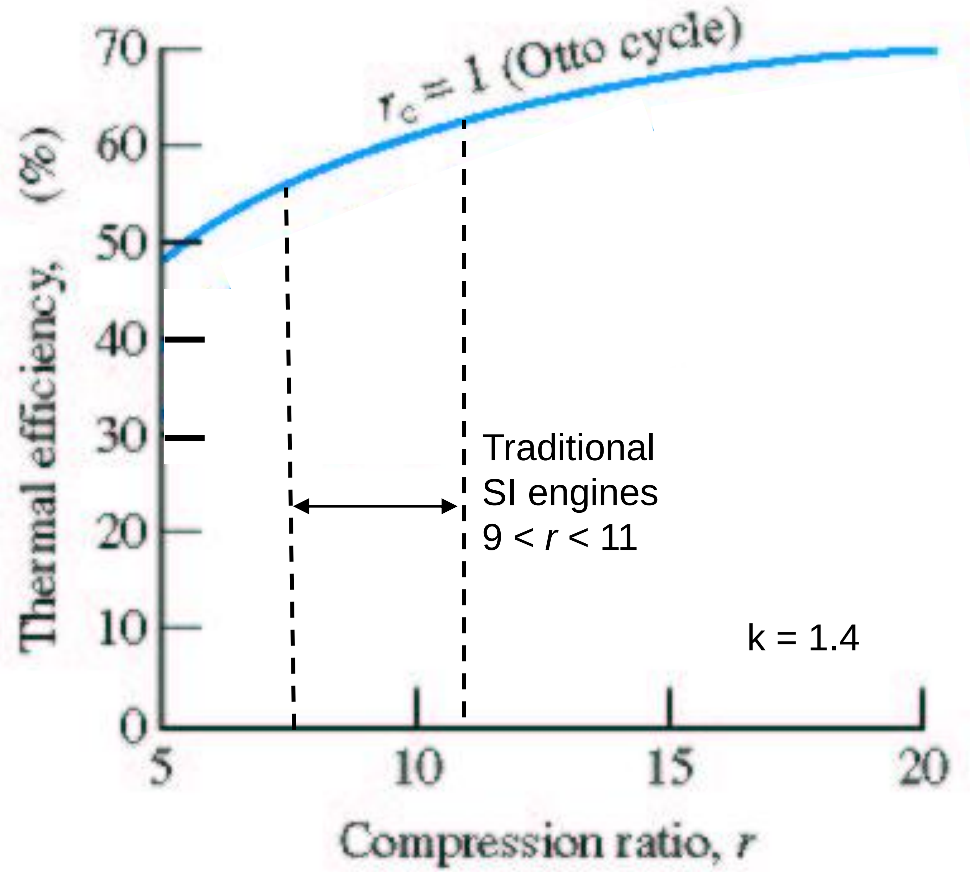
Indicated mean effective pressure is:

$$imep = \frac{W_{cycle}}{V_1 - V_2} \rightarrow \frac{imep}{P_1} = \frac{Q_{in}}{P_1 V_1}\left(\frac{r}{r-1}\right)\eta_{th} = \boxed{\frac{1}{k-1}\left(\frac{Q_{in}/m}{u_1}\right)\left(\frac{r}{r-1}\right)\eta_{th}}$$

Work per cycle is represented in terms of a <u>mean effective pressure</u> and the displacement.



Efek Kompresi rasio terhadap effisiensi thermal



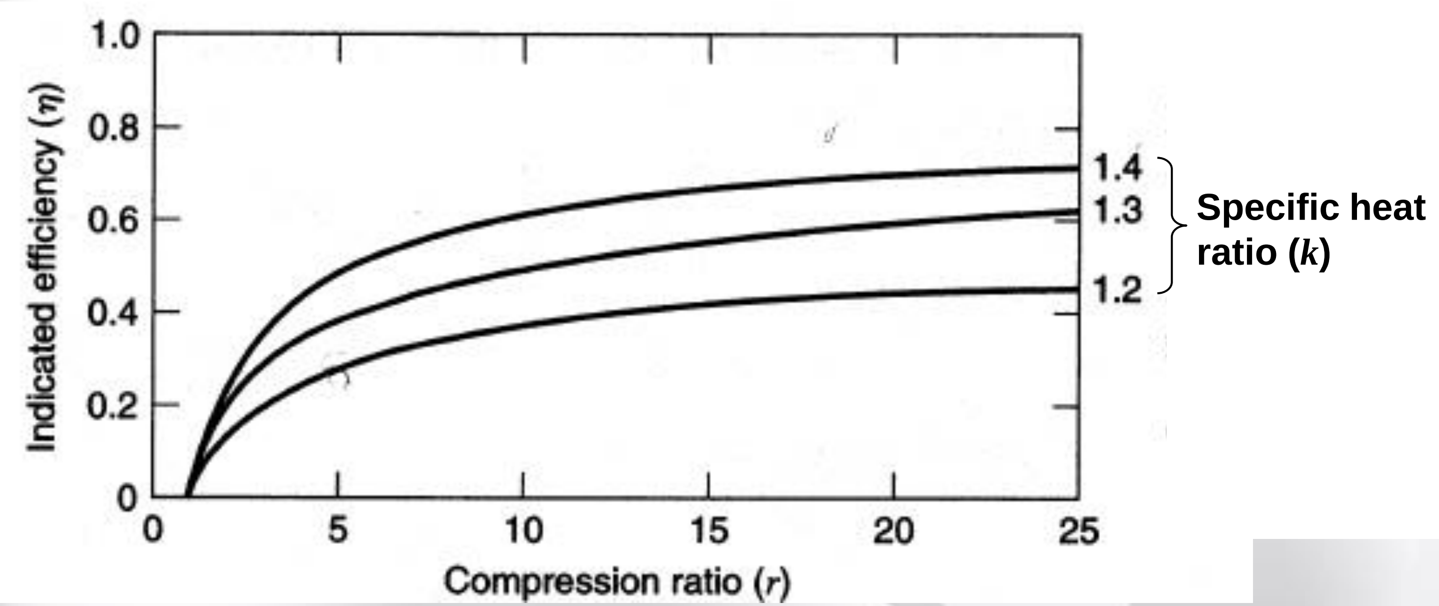
$$\eta_{th \atop const\ c_V} = 1 - \frac{1}{r^{k-1}}$$

- Spark ignition engine compression ratio limited by T_3 (autoignition) and P_3 (material strength), both $\sim r^k$

- For r = 8 the efficiency is 56%

Efek Specific Heat Ratio terhadap Efisiensi Thermal

$$\eta_{th_{const\ c_V}} = 1 - \frac{1}{r^{k-1}}$$



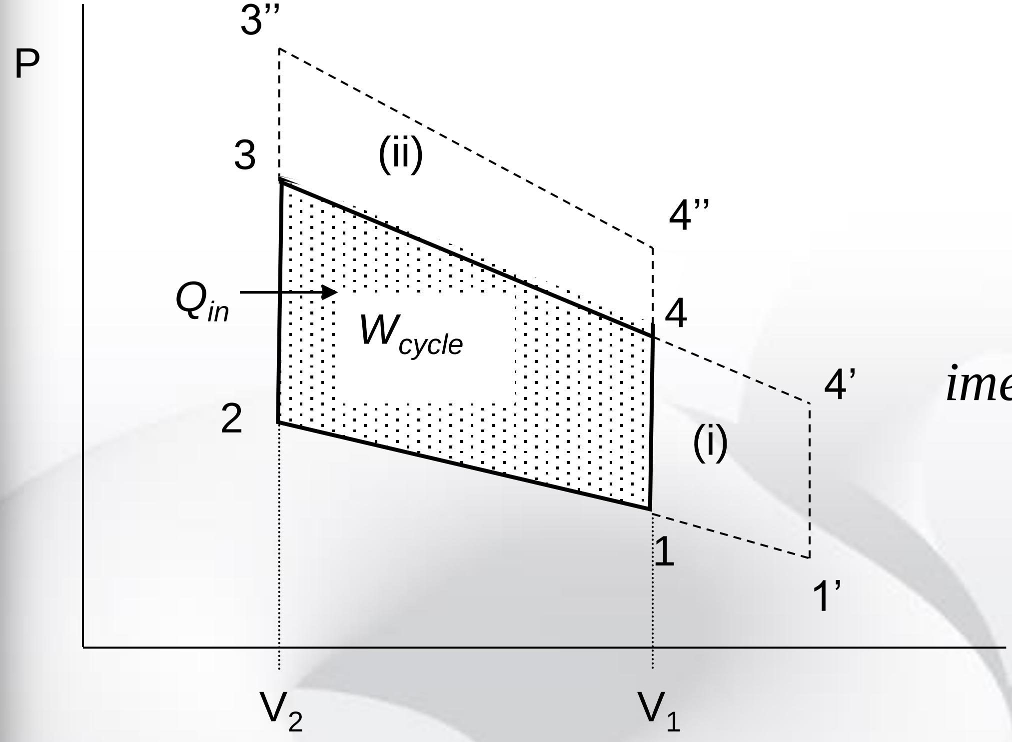
Cylinder temperatures vary between 300K and 2000K so $1.2 < k < 1.4$
$k = 1.3$ most representative

Faktor yang berpengaruh terhadap kerja per siklus

The net cycle work of an engine can be increased by either:

i) Increasing the *r* (1'→2)

ii) Increase Q_{in} (2→3")



$$imep = \frac{W_{cycle}}{V_1 - V_2} = \frac{Q_{in}}{V_1}\left(\frac{r}{r-1}\right)\eta_{th}$$

Example 9.1 Analyzing the Otto Cycle

The temperature at the beginning of the compression process of an air-standard Otto cycle with a compression ratio of 8 is 540°R, the pressure is 1 atm, and the cylinder volume is 0.02 ft^3. The maximum temperature during the cycle is 3600°R. Determine (a) the temperature and pressure at the end of each process of the cycle, (b) the thermal efficiency, and (c) the mean effective pressure, in atm.

Solution

Known: An air-standard Otto cycle with a given value of compression ratio is executed with specified conditions at the beginning of the compression stroke and a specified maximum temperature during the cycle.

Find: Determine the temperature and pressure at the end of each process, the thermal efficiency, and mean effective pressure, in atm.

Schematic and Given Data:

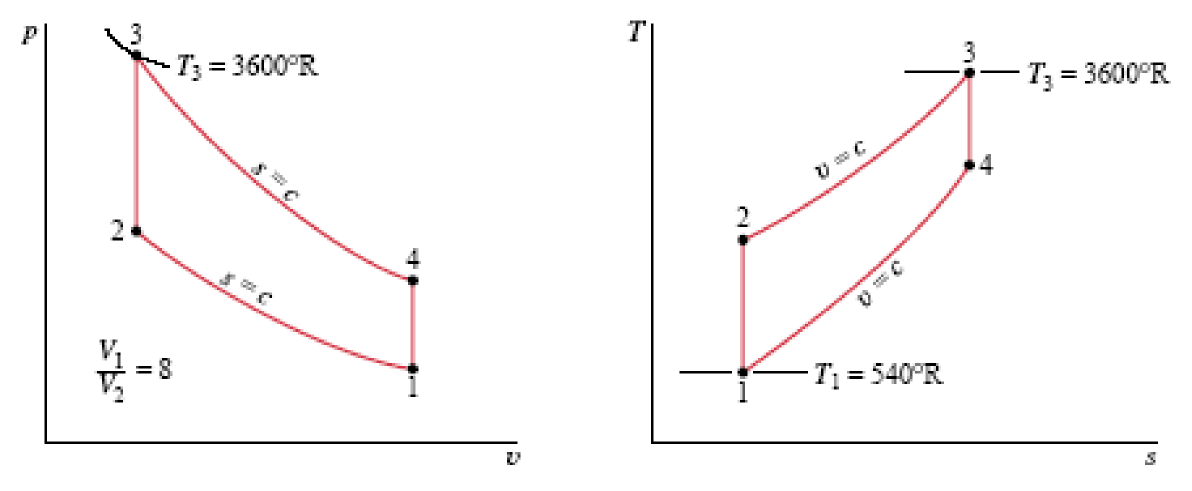


Figure E9.1

Assumptions:

1. The air in the piston–cylinder assembly is the closed system.
2. The compression and expansion processes are adiabatic.
3. All processes are internally reversible.
4. The air is modeled as an ideal gas.
5. Kinetic and potential energy effects are negligible.

Sambungan …

Analysis: (a) The analysis begins by determining the temperature, pressure, and specific internal energy at each principal state of the cycle. At $T_1 = 540°R$, Table T-9E gives $u_1 = 92.04$ Btu/lb and $v_{r1} = 144.32$.

For the isentropic compression Process 1–2

$$v_{r2} = \frac{V_2}{V_1} v_{r1} = \frac{v_{r1}}{r} = \frac{144.32}{8} = 18.04$$

Interpolating with v_{r2} in Table T-9E, we get $T_2 = 1212°R$ and $u_2 = 211.3$ Btu/lb. With the ideal gas equation of state

$$p_2 = p_1 \frac{T_2}{T_1} \frac{V_1}{V_2} = (1 \text{ atm})\left(\frac{1212°R}{540°R}\right)8 = 17.96 \text{ atm} \triangleleft$$

The pressure at state 2 can be evaluated alternatively by using the isentropic relationship, $p_2 = p_1(p_{r2}/p_{r1})$.

Since Process 2–3 occurs at constant volume, the ideal gas equation of state gives

$$p_3 = p_2 \frac{T_3}{T_2} = (17.96 \text{ atm})\left(\frac{3600°R}{1212°R}\right) = 53.3 \text{ atm} \triangleleft$$

At $T_3 = 3600°R$, Table T-9E gives $u_3 = 721.44$ Btu/lb and $v_{r3} = 0.6449$.

For the isentropic expansion Process 3–4

$$v_{r4} = v_{r3} \frac{V_4}{V_3} = v_{r3} \frac{V_1}{V_2} = 0.6449(8) = 5.16$$

Interpolating in Table T-9E with v_{r4} gives $T_4 = 1878°R$, $u_4 = 342.2$ Btu/lb. The pressure at state 4 can be found using the isentropic relationship $p_4 = p_3(p_{r4}/p_{r3})$ or the ideal gas equation of state applied at states 1 and 4. With $V_4 = V_1$, the ideal gas equation of state gives

$$p_4 = p_1 \frac{T_4}{T_1} = (1 \text{ atm})\left(\frac{1878°R}{540°R}\right) = 3.48 \text{ atm} \triangleleft$$

Tabel T-9E=A-22E (Book)

Sambungan …

(b) The thermal efficiency is

$$\eta = 1 - \frac{Q_{41}/m}{Q_{23}/m} = 1 - \frac{u_4 - u_1}{u_3 - u_2}$$

$$= 1 - \frac{342.2 - 92.04}{721.44 - 211.3} = 0.51(51\%) \triangleleft$$

(c) To evaluate the mean effective pressure requires the net work per cycle. That is

$$W_{cycle} = m[(u_3 - u_4) - (u_2 - u_1)]$$

where m is the mass of the air, evaluated from the ideal gas equation of state as follows:

$$m = \frac{p_1 V_1}{(\overline{R}/M)T_1}$$

$$= \frac{(14.696 \text{ lbf/in.}^2)|144 \text{ in.}^2/\text{ft}^2|(0.02 \text{ ft}^3)}{\left(\frac{1545}{28.97} \frac{\text{ft} \cdot \text{lbf}}{\text{lb} \cdot {}^\circ\text{R}}\right)(540^\circ\text{R})}$$

$$= 1.47 \times 10^{-3} \text{ lb}$$

Inserting values into the expression for W_{cycle}

$$W_{cycle} = (1.47 \times 10^{-3} \text{ lb})[(721.44 - 342.2) - (211.3 - 92.04)] \text{ Btu/lb}$$

$$= 0.382 \text{ Btu}$$

Sambungan …

The displacement volume is $V_1 - V_2$, so the mean effective pressure is given by

$$\text{mep} = \frac{W_{\text{cycle}}}{V_1 - V_2} = \frac{W_{\text{cycle}}}{V_1(1 - V_2/V_1)}$$

$$= \frac{0.382\ \text{Btu}}{(0.02\ \text{ft}^3)(1 - 1/8)} \left|\frac{778\ \text{ft}\cdot\text{lbf}}{1\ \text{Btu}}\right| \left|\frac{1\ \text{ft}^2}{144\ \text{in.}^2}\right|$$

$$= 118\ \text{lbf/in.}^2 = 8.03\ \text{atm} \triangleleft$$

❶ This solution utilizes Table T-9E for air, which accounts explicitly for the variation of the specific heats with temperature. A solution also can be developed on a cold air-standard basis in which constant specific heats are assumed. This solution is left as an exercise, but for comparison the results are presented in the following table for the case $k = 1.4$, representing atmospheric air:

Parameter	Air-Standard Analysis	Cold Air-Standard Analysis, $k = 1.4$
T_2	1212°R	1241°R
T_3	3600°R	3600°R
T_4	1878°R	1567°R
η	0.51 (51%)	0.565 (56.5%)
mep	8.03 atm	7.05 atm

Latihan

Otto Cycle

9.1 An air-standard Otto cycle has a compression ratio of 8.5. At the beginning of compression, $p1$= 100 kPa and $T1$ = 300 K. The heat addition per unit mass of air is 1400 kJ/kg. Determine

(a) the net work, in kJ per kg of air.

(b) the thermal efficiency of the cycle.

(c) the mean effective pressure, in kPa.

(d) the maximum temperature in the cycle, in K.

9.2 Solve Problem 9.1 on a **cold air-standard basis with specific heats evaluated at 300 K.**

Latihan

9.3 At the beginning of the compression process of an air standard Otto cycle, p_1 1 bar, T_1 290 ^{O}K, V_1 400 cm^3. The maximum temperature in the cycle is 2200 ^{O}K and the compression ratio is 8. Determine

(a) the heat addition, in kJ.

(b) the net work, in kJ.

(c) the thermal efficiency.

(d) the mean effective pressure, in bar.

9.4 Solve Problem 9.3 on a cold air-standard basis with specific heats evaluated at 300 ^{O}K.