Internal Combustion Engines – ME422

Ideal Standard Cycles

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Ideal Air Standard Cycles

- Introduction
- Comparison between thermodynamic and mechanical cycles
- Performance parameters
  imep, bmep, mechanical efficiency, indicated eff., volumetric eff.
- Ideal cycles and thermal efficiencies
  Otto cycle, Diesel cycle, Dual cycle
- Comparison of cycles
- Deviations from actual engine cycles

Assumptions

Air standard cycles,

serve as introduction to the more detailed and accurate models of IC engines

provide insight into some of the important parameters that effect engine performance

Assumptions;

- Neglect heat transfer to and from cylinder walls,
- Replace combustion process by a heat addition process that occurs at constant volume (in Otto cycle) or at constant pressure (in Diesel cycle),
- Do not consider gas exchange process,
- Assume cylinder charge as a perfect gas (c_p and c_v are assumed constant) which is pure air.

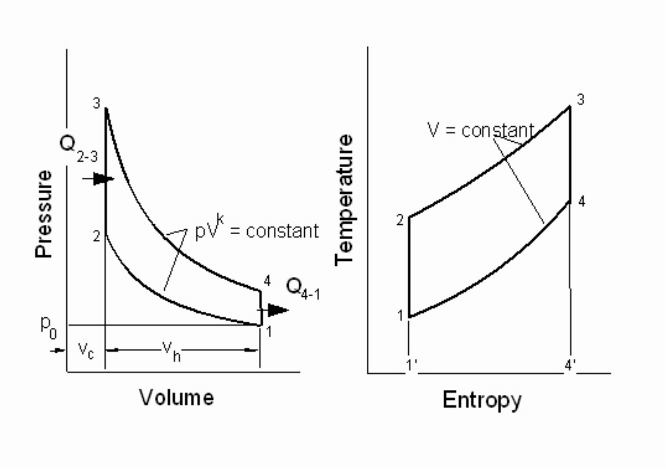
Otto Cycle

The Otto cycle is used as a basis of comparison for SI engines

The cycle consists of four processes,

1 – 2	isentropic compression from V_1 to V_2
2 – 3	addition of heat Q_{23} at constant volume
3 – 4	isentropic expansion to the original volume
4 – 1	rejection of heat Q_{41} at constant volume

Otto Cycle



Otto Cycle

Work done during the cycle, 1-2-3-4 is,

$$W_{cycle} = \oint p\,dV = \oint T\,ds$$

Constant volume heat input to the cycle per unit mass of working fluid

$$Q_{23} = \int_{T_2}^{T_3} c_v\,dT = c_v\left(T_3 - T_2\right)$$

Constant volume heat extraction from the cycle per unit mass

$$Q_{41} = -\int_{T_4}^{T_1} c_v\,dT = -c_v\left(T_1 - T_4\right) = c_v\left(T_4 - T_1\right)$$

Otto Cycle

1st law of thermodynamics
$$dE = dQ - dW$$
$$dE = 0$$

Thermal efficiency

$$\eta_{\text{t-otto}} = \frac{W}{Q_{23}} = \frac{\text{work done}}{\text{heat input}}$$

$$\eta_{\text{t-otto}} = \frac{Q_{23} - Q_{41}}{Q_{23}} = 1 - \frac{Q_{41}}{Q_{23}}$$

$$\eta_{\text{t-otto}} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

Otto Cycle

Initial pressure p_1 and temperature T_1

using $p_1 V_1^k = p_2 V_2^k$ for an adiabatic compression

and $pV = mRT$ from ideal gas law

$$p_2 = p_1 \left(\frac{V_1}{V_2} \right)^k \qquad T_2 = T_1 \left(\frac{V_1}{V_2} \right)^{k-1} \qquad k = \frac{c_p}{c_v}$$

compression ratio $\varepsilon = \dfrac{V_1}{V_2}$ (sıkıştırma oranı)

$$T_2 = T_1 \, \varepsilon^{k-1}$$

Otto Cycle

from 2 → 3 , constant volume heat addition

$$p_2 V_2 = mRT_2 \qquad p_3 V_3 = mRT_3 \qquad V_2 = V_3$$

$$T_3 = T_2 \frac{p_3}{p_2}$$

defining $\beta = \dfrac{p_3}{p_2}$ "pressure ratio" (basınç artış oranı)

$$T_3 = T_1 \ \beta \ \varepsilon^{k-1}$$

Otto Cycle

from 3 → 4 , adiabatic expansion,

$$p_4 V_4^k = p_3 V_3^k$$

$$p_4 V_4 V_4^{k-1} = p_3 V_3 V_3^{k-1}$$

From ideal gas law $p_4 V_4 = mRT_4 \qquad p_3 V_3 = mRT_3$

$$\frac{V_4}{V_3} = \frac{V_1}{V_2} = \varepsilon$$

$$T_4 V_4^{k-1} = T_3 V_3^{k-1} \qquad T_4 = \frac{T_3}{\varepsilon^{k-1}} \qquad T_4 = T_1 \ \beta$$

Thermal Efficiency

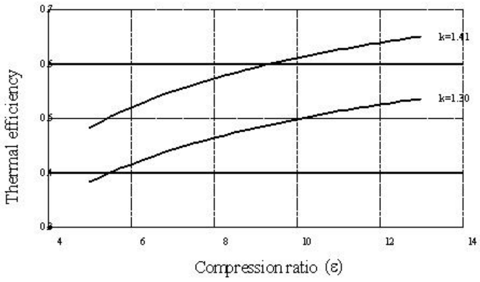
Thermal efficiency of Otto cycle is given by,

$$\eta_{\text{t-otto}} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

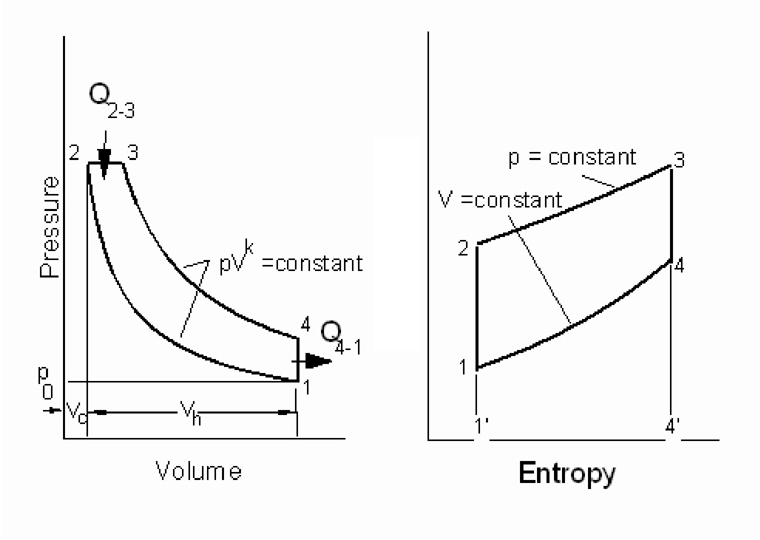
placing the temperatures T_2, T_3 and T_4 in terms of T_1

$$\eta_{t-otto} = 1 - \frac{1}{\varepsilon^{k-1}}$$

Thermal Efficiency



Diesel Cycle



Diesel Cycle

Work done during the cycle, 1-2-3-4 is,

$$W_{cycle} = \oint p\,dV = \oint T\,ds$$

Constant pressure heat input to the cycle per unit mass of working fluid

$$Q_{23} = \int_{T_2}^{T_3} c_p\,dT = c_p\left(T_3 - T_2\right)$$

Constant volume heat extraction from the cycle per unit mass

$$Q_{41} = -\int_{T_4}^{T_1} c_v\,dT = -c_v\left(T_1 - T_4\right) = c_v\left(T_4 - T_1\right)$$

Diesel Cycle

1st law of thermodynamics

$$dE = dQ - dW$$

$$dE = 0$$

Thermal efficiency

$$\eta_{\text{t-diesel}} = \frac{W}{Q_{23}} = \frac{\text{work done}}{\text{heat input}}$$

$$\eta_{\text{t-diesel}} = \frac{Q_{23} - Q_{41}}{Q_{23}} = 1 - \frac{Q_{41}}{Q_{23}}$$

$$\eta_{\text{t-diesel}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)}$$

Diesel Cycle

$$T_2 = T_1 \ \varepsilon^{k-1}$$

$$T_3 = T_2 \frac{V_3}{V_2} = T_1 \ \ \alpha \ \ \varepsilon^{k-1}$$

$$T_4 = \frac{T_3 \alpha^{k-1}}{\varepsilon^{k-1}} = T_1 \ \ \alpha^{\text{k}}$$

Diesel Cycle

Defining "cut-off ratio" or "load ratio" (hacim artış oranı)

$$\alpha = \frac{V_3}{V_2}$$

Thermal Efficiency

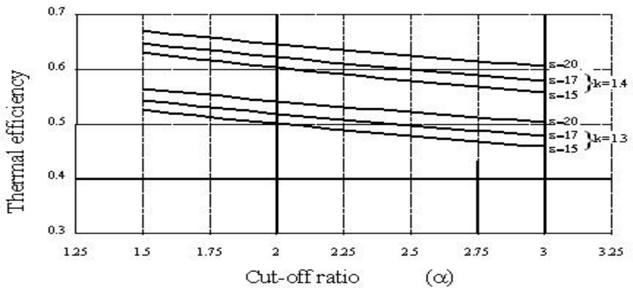
Thermal efficiency of Diesel cycle is given by,

$$\eta_{\text{t-diesel}} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

placing the temperatures T_2, T_3 and T_4 in terms of T_1

$$\eta_{t-diesel} = 1 - \frac{1}{\varepsilon^{k-1}} \frac{\alpha^{k} - 1}{k\,(\alpha - 1)}$$

Thermal Efficiency



As the value of α increases (heat addition is extended towards expansion) the efficiency is reduced due to additional heat required to compansate the expansion

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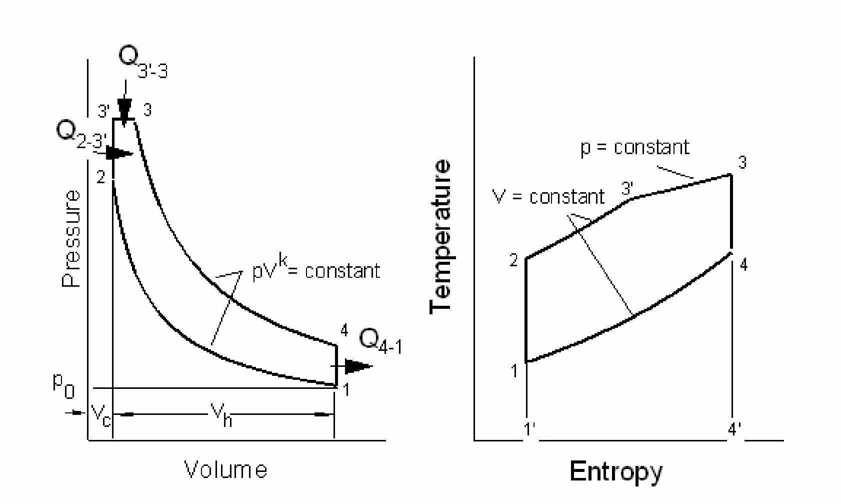
Dual Cycle



Dual Cycle

Work done during the cycle, 1-2-3’-3-4 is,

$$W_{cycle} = \oint p\,dV = \oint T\,ds$$

Constant volume heat input followed by constant pressure heat input to the cycle per unit mass of working fluid

$$Q_{23} = c_v\left(T_{3'} - T_2\right) + c_p\left(T_3 - T_{3'}\right)$$

Constant volume heat extraction from the cycle per unit mass

$$Q_{41} = -\int_{T_4}^{T_1} c_v\,dT = -c_v\left(T_1 - T_4\right) = c_v\left(T_4 - T_1\right)$$

Dual Cycle

Thermal efficiency

$$\eta_{\text{t-dual}} = 1 - \frac{c_v(T_4 - T)_1}{c_v(T_{3'} - T_2) + c_p(T_3 - T_{3'})}$$

Dual Cycle

$$T_2 = T_1 \ \varepsilon^{k-1}$$

$$T_{3'} = T_1 \ \beta \ \varepsilon^{k-1}$$

$$T_3 = T_1 \ \beta \ \alpha \ \varepsilon^{k-1}$$

$$T_4 = T_1 \ \alpha^{\mathrm{k}} \beta$$

Thermal Efficiency

Thermal efficiency of Dual cycle is given by,

$$\eta_{t-dual} = 1 - \frac{1}{\varepsilon^{k-1}} \frac{\beta\alpha^{\mathrm{k}} - 1}{\beta - 1 + k\,\beta(\alpha - 1)}$$

Putting $\alpha = 1$ Otto cycle thermal efficiency

$\beta = 1$ Diesel cycle thermal efficiency

is obtained

Thermal Efficiency

Otto cycle

$$\eta_{th-Otto} = 1 - \frac{1}{\varepsilon^{k-1}}$$

Diesel cycle

$$\eta_{th-Diesel} = 1 - \frac{1}{\varepsilon^{k-1}} \frac{\alpha^k - 1}{k(\alpha - 1)}$$

Dual cycle

$$\eta_{th-Dual} = 1 - \frac{1}{\varepsilon^{k-1}} \frac{\beta\,\alpha^k - 1}{\beta - 1 + k\beta\,(\alpha - 1)}$$

Comparison of Ideal Cycles

For $\alpha > 1$ and $k > 1$

$\frac{\alpha^k - 1}{k(\alpha - 1)}$ term is greater than 1

therefore $\eta_{t\text{-otto}} > \eta_{t\text{-diesel}}$ for a constant value of compression ratio

Also $\eta_{t\text{-otto}} > \eta_{t\text{-dual}} > \eta_{t\text{-diesel}}$

efficiency of Dual cycle lies between Otto and Diesel cycles according to the value of β

Comparison of Ideal Cycles

In real engines,

SI engines have a compression ratio between 10:1 to 12:1

this value is limited due to engine knock

CI engines have compression ratio higher than 14:1 to provide temperature and pressure required for self ignition of the fuel

compression ratio of 16:1 to 18:1 is sufficient for efficiency, but used for improving ignition quality

high compression ratio increases thermal and mechanical stresses