Internal Combustion Engines – MAK 493E

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

Ideal Air Standard Cycles

Refferences :

Heywood, J.B., Internal Combustion Engine Fundamentals, McGraw Hill Book Comp, New York, 1988.
Pages 161 – 183

Soruşbay, C., Ergeneman, M., Arslan, E., Safgönül, B., İçten Yanmalı Motorlar, Birsen Yayınevi, İstanbul, 2002 (3. Baskı)
Pages 3 – 23 and 38 - 41

Stone, R., Introduction to IC Engines, Macmillan, London, 1994.
Pages 33 - 34

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.

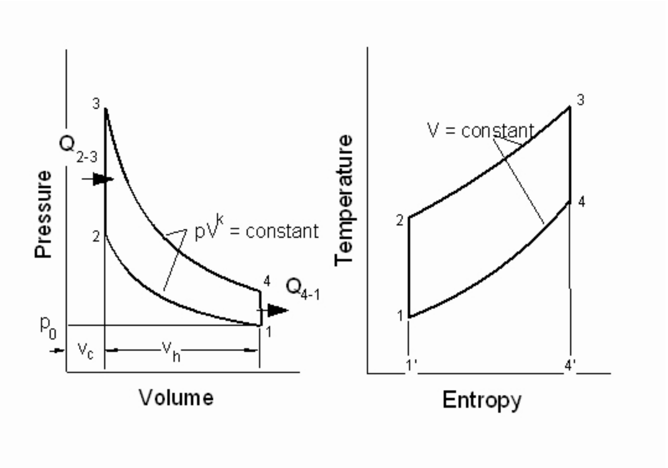
Otto Cycle

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

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

Constant volume heat extraction from the cycle per unit mass

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

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 $\rightarrow$ 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 $\rightarrow$ 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 $\quad p_4 V_4 = mRT_4 \qquad p_3 V_3 = mRT_3$

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

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

Thermal Efficiency

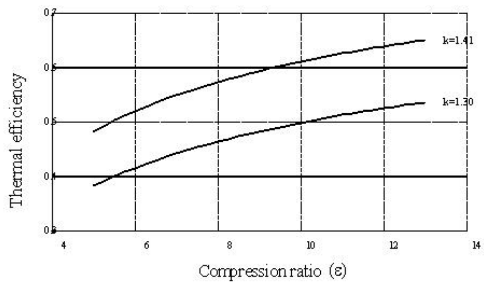
Thermal efficiency of Otto cycle is given by,

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

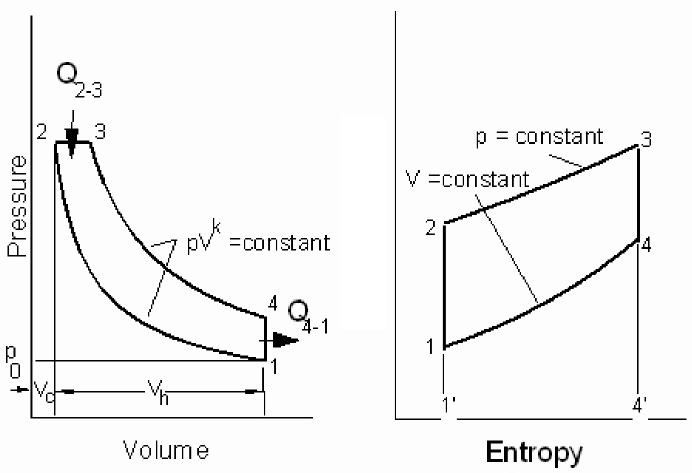
placing the temperatures T_2, T_3 and T_4 in terms of T_1

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

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

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

Constant volume heat extraction from the cycle per unit mass

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

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

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

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

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

Diesel Cycle

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

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

Thermal Efficiency

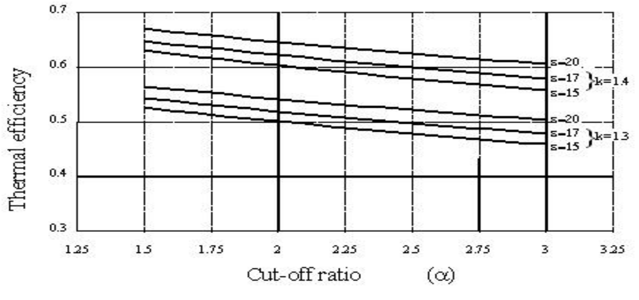
Thermal efficiency of Diesel cycle is given by,

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

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

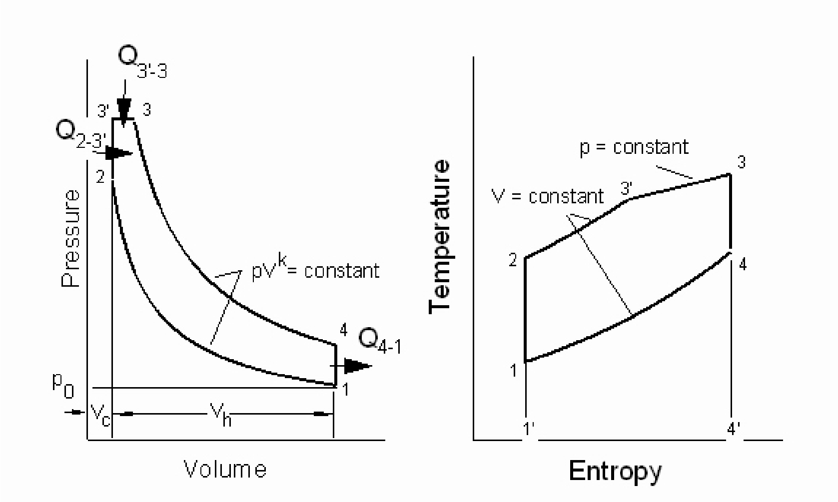
$$\eta_{t-diesel} = 1 - \frac{1}{\varepsilon^{k-1}} \frac{\alpha^k - 1}{k(\alpha - 1)}$$

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

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

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

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

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

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

Thermal Efficiency

Thermal efficiency of Dual cycle is given by,

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

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