APPLIED THERMODYNAMICS BME401

ATME College of Engineering

Introduction

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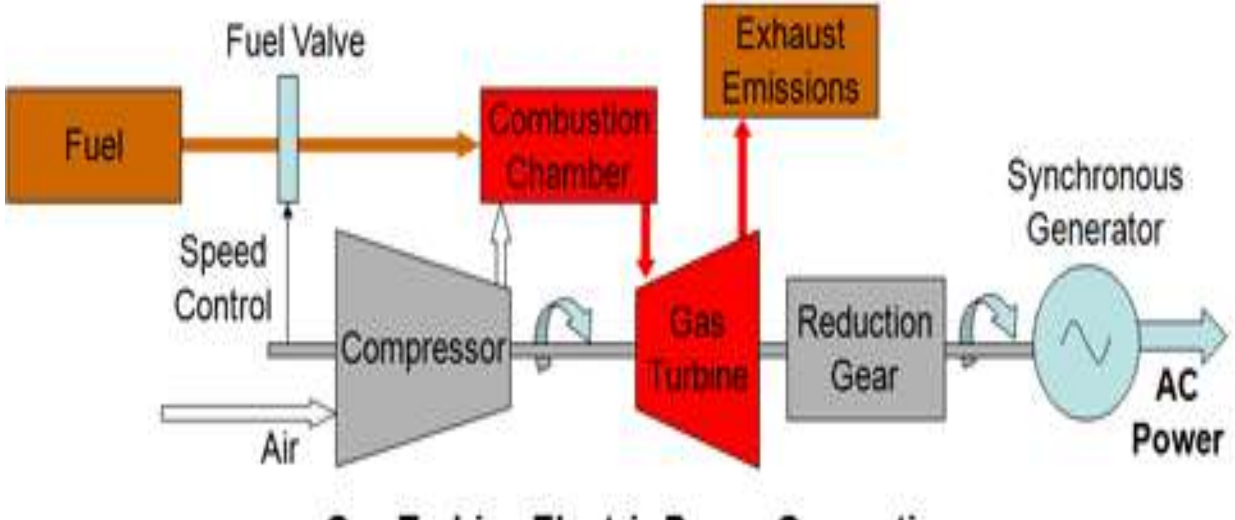
Syllabus

- **Module – 1: Air standard cycles, I.C. Engines**
- **Module – 2: Gas power Cycles**
- **Module – 3: Vapour Power Cycles**
- **Module – 4: Refrigeration Cycles, Psychometrics and Air-conditioning Systems**
- **Module – 5: Reciprocating Compressors, Steam nozzles**

Importance of studying the subject (Applications of Applied Thermodynamics)



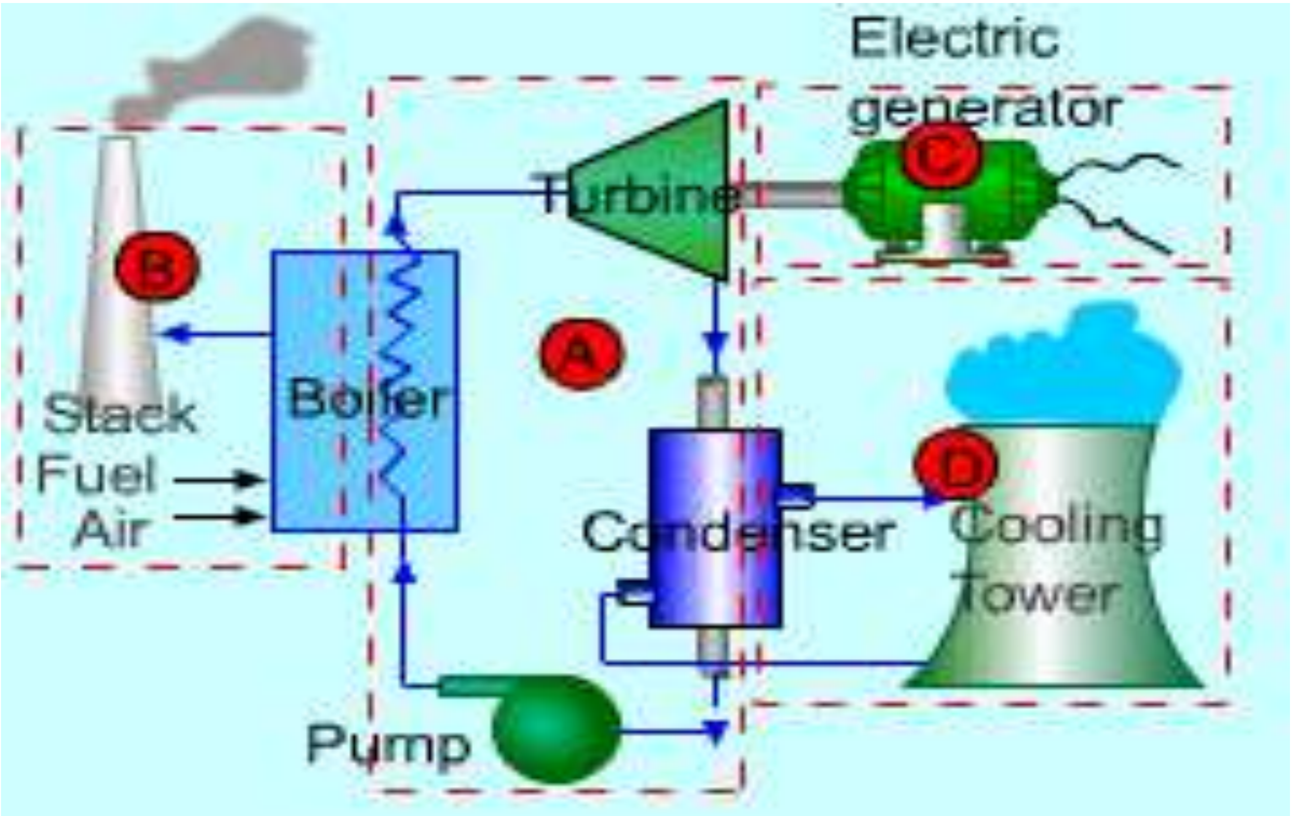
Gas Turbine Electric Power Generation

Gas turbine used in rocket

Importance of studying the subject (Applications of Applied Thermodynamics)

Coal: 204,724.5 MW (55.6%)
Large Hydro: 45,399.22 MW (12.3%)
Small Hydro: 4,671.56 MW (1.3%)
Wind Power: 37,505.18 MW (10.2%)
Solar Power: 33,730.56 MW (9.2%)
Biomass: 10,001.11 MW (2.7%)
Nuclear: 6,780 MW (1.8%)
Gas: 24,955.36 MW (6.8%)
Diesel: 509.71 MW (0.1%)

Vapour Power Cycle in Thermal power plant



Importance of studying the subject (Applications of Applied Thermodynamics)

Refrigeration Cycles, Psychometrics and Air-conditioning Systems

Importance of studying the subject (Applications of Applied Thermodynamics)

Reciprocating Compressors

References

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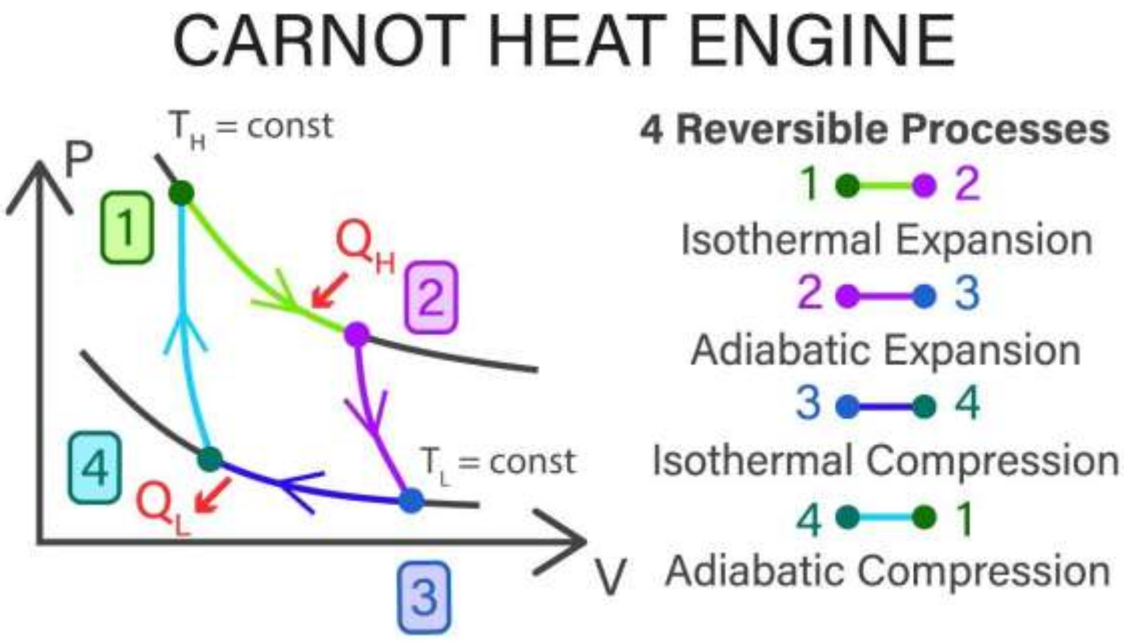
- Applications of Thermodynamics, V.Kadambi, T. R.Seetharam, K. B.Subramanya Kumar, Wiley Indian Private Ltd
- Thermodynamics, Yunus A, Cengel, Michael A Boles, Tata McGraw Hill, 7th Edition
- Thermodynamics for engineers, Kenneth A. Kroos and Merle C. Potter, Cengage Learning 2016
- Thermodynamics, Radhakrishnan, PHI 2nd revised Edition
- I.C Engines, Ganeshan.V, Tata McGraw Hill 4th Edi. 2012
- I.C.Engines, M.L.Mathur & Sharma, Dhanpat Rai& sons- India

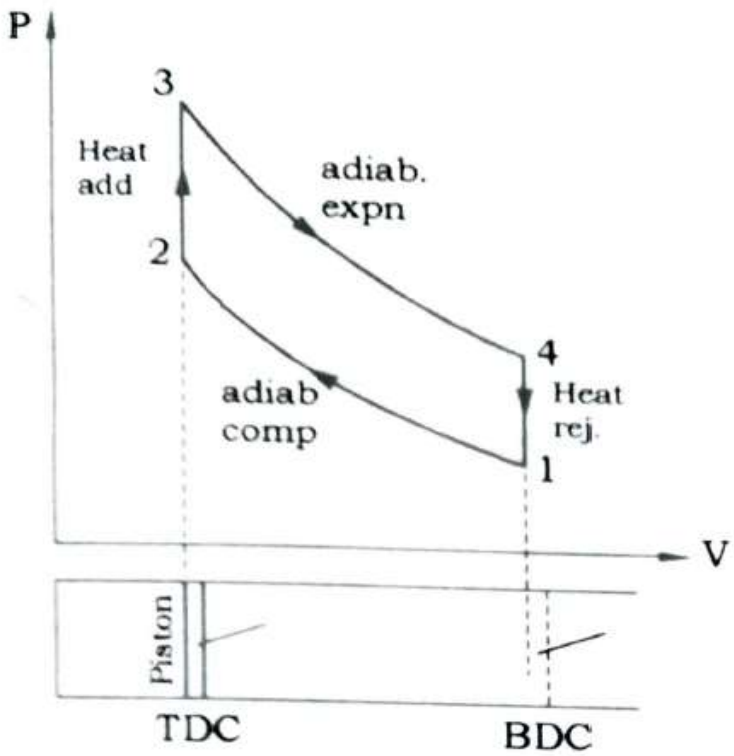
Module – 1: Air standard cycles

- **Air standard cycles:** Carnot, Otto, Diesel, Dual and Stirling cycles, p-v and T -S diagrams, description, efficiencies and mean effective pressures. Comparison of Otto and Diesel cycles.

- **I.C.Engines:** Classification of IC engines, Combustion of SI engine and CI engine, Detonation and factors affecting detonation, Performance analysis of I.C Engines, Heat balance, Morse test.

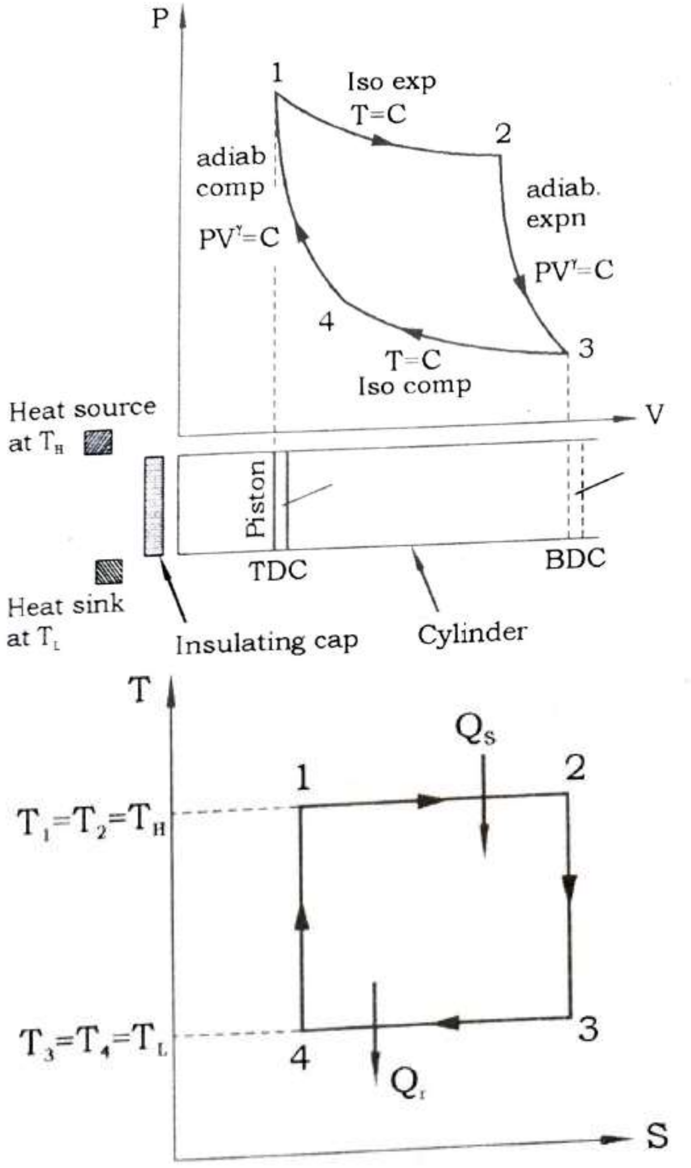
Air standard cycles





Carnot cycle

Expression for air standard efficiency in Carnot cycle



Process 1-2: Isothermal Expansion

∴ Heat absorbed or heat added or heat supplied $= Q_S = P_1V_1 \ln\left(\frac{V_2}{V_1}\right)$

under ideal conditions, we have $PV = mRT$ i.e., $P_1V_1 = mRT_1$

$$\therefore Q_S = mRT_1 \ln\left(\frac{V_2}{V_1}\right) \quad \text{-----(1)}$$

Process 2-3: Adiabatic Expansion

w.k.t. from adiabatic process, heat transfer $Q = 0$

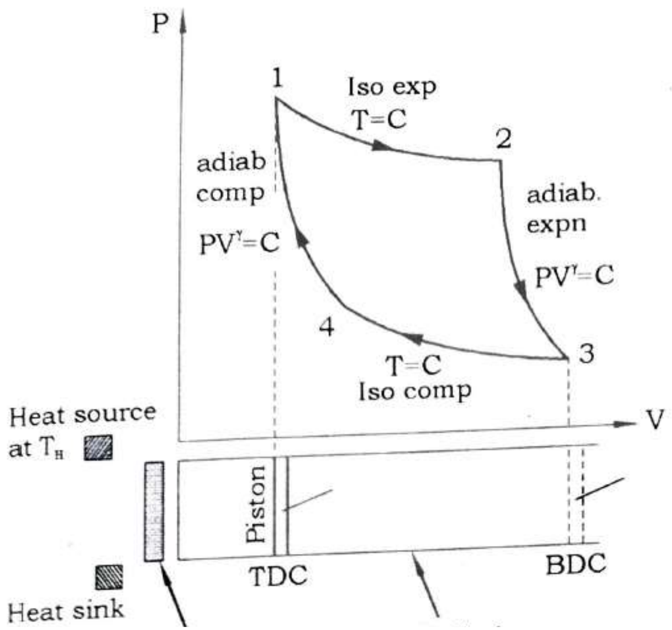
$$\frac{T_2}{T_3} = \left(\frac{V_3}{V_2}\right)^{\gamma-1} \quad \text{-----(2)}$$

Carnot cycle

Process3-4: Isothermal compression

$$\text{Heat rejected} = Q_r = P_3V_3 \ln\left(\frac{V_3}{V_4}\right)$$

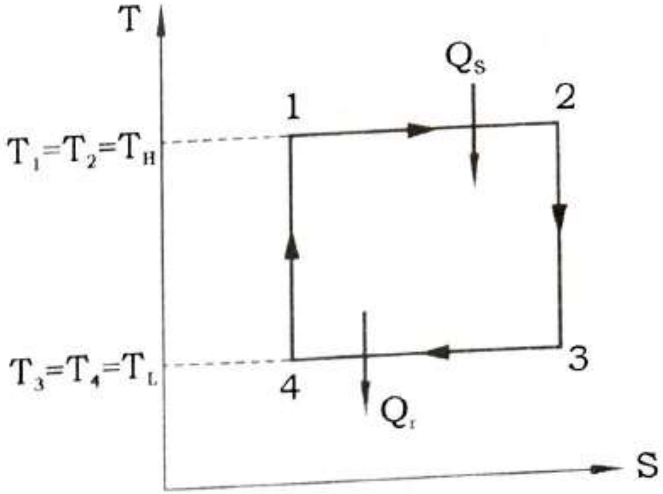
$$= mRT_3 \ln\left(\frac{V_3}{V_4}\right) \quad \text{-----(3)}$$



Process 4-1: Adiabatic compression

w.k.t. for adiabatic process, heat transfer Q = 0

$$\frac{T_4}{T_1} = \left(\frac{V_1}{V_4}\right)^{\gamma-1} \quad \text{-----(4)}$$



Carnot cycle

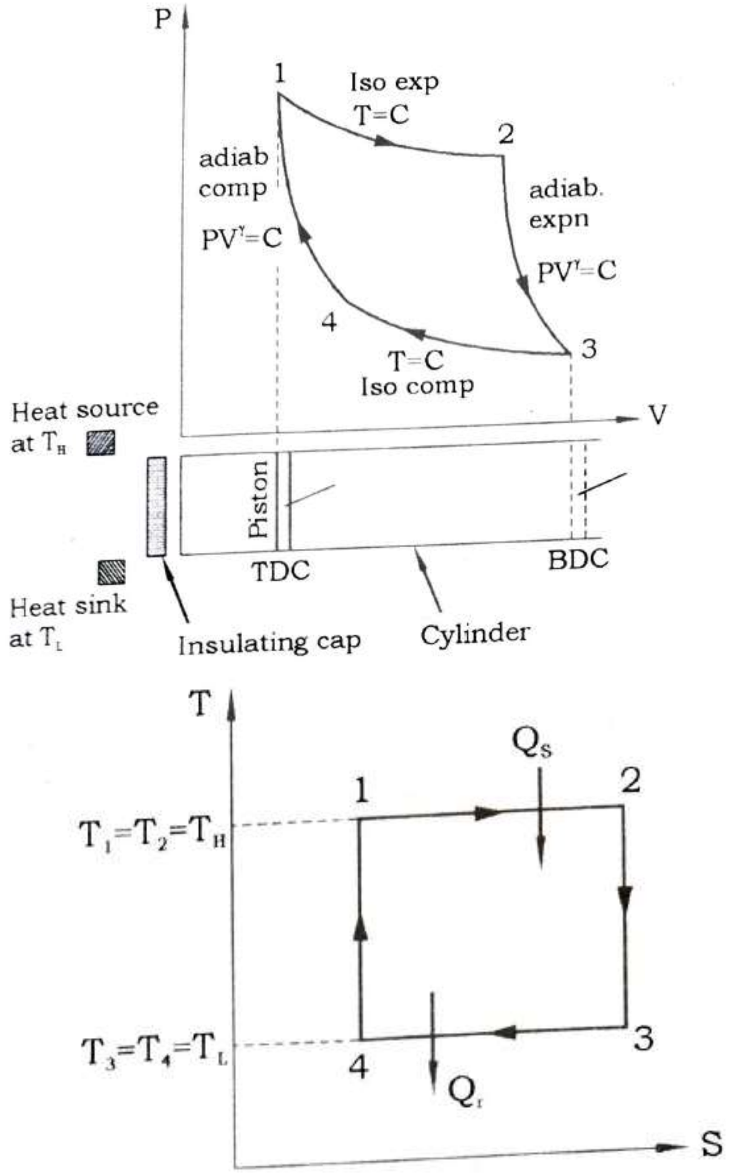
To find air standard efficiency:

w.k.t. efficiency $\eta_{air} = \dfrac{\text{Work done (WD)}}{\text{Heat supplied } (Q_H)}$

$$= \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$$

$$= \frac{Q_S - Q_r}{Q_S}$$

$$\eta_{air} = 1 - \frac{Q_r}{Q_s} = 1 - \frac{m.RT_3 \ln\left(\frac{V_3}{V_4}\right)}{m.RT_1 \ln\left(\frac{V_2}{V_1}\right)}$$



Carnot cycle

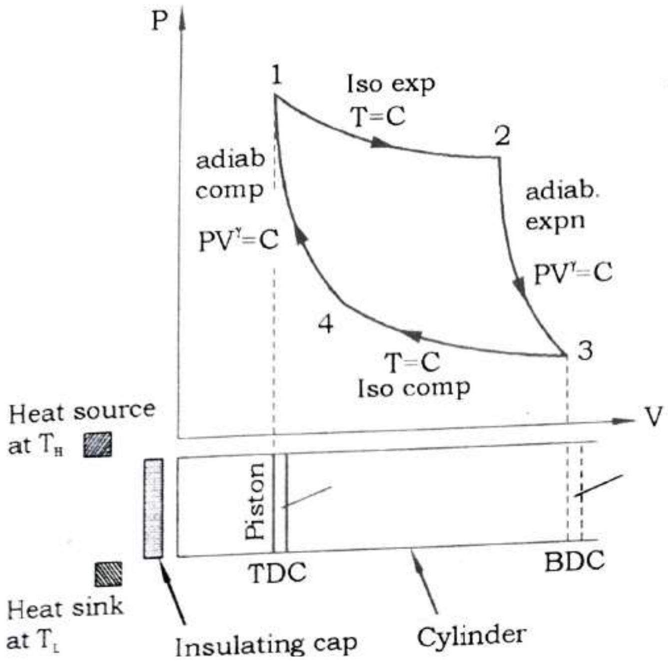
Consider equation (2) $\frac{T_2}{T_3} = \left(\frac{V_3}{V_2}\right)^{\gamma-1}$

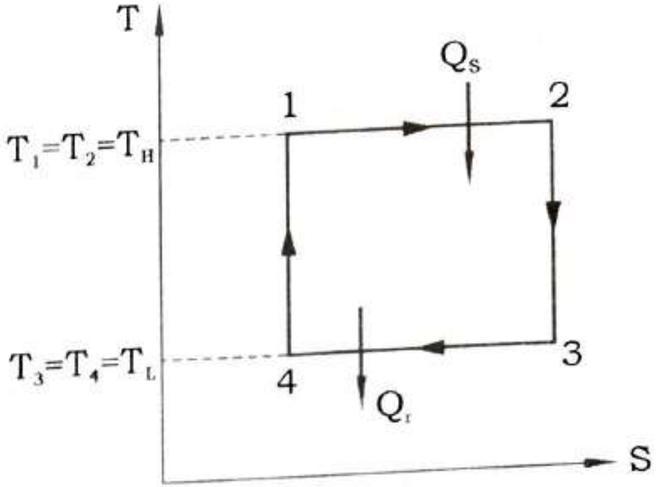
But, from t-s diagram, $T_2 = T_1$ and $T_3 = T_4$

$$\therefore \quad \frac{T_1}{T_4} = \left(\frac{V_3}{V_2}\right)^{\gamma-1}$$

we have $\left(\frac{V_1}{V_4}\right)^{\gamma-1} = \left(\frac{V_2}{V_3}\right)^{\gamma-1}$

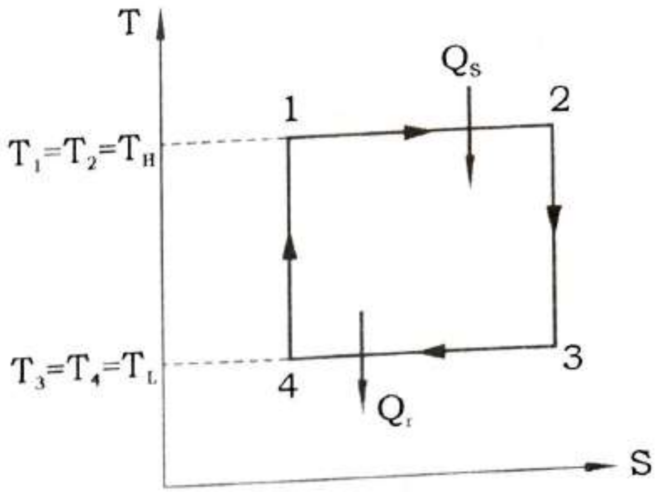
$$\frac{V_1}{V_4} = \frac{V_2}{V_3} \quad \text{or} \quad \frac{V_3}{V_4} = \frac{V_2}{V_1}$$





Carnot cycle

, we get $$\eta_{air} = 1 - \frac{m.RT_3 \ln\left(\frac{V_2}{V_1}\right)}{m.RT_1 \ln\left(\frac{V_2}{V_1}\right)} = 1 - \frac{T_3}{T_1}$$



$$\eta_{air} = 1 - \frac{T_L}{T_H} \quad \text{for Carnot cycle}$$

where $T_L = T_3 = T_4$ = Lowest temperature of the cycle, and
$T_H = T_1 = T_2$ = highest temperature of the cycle

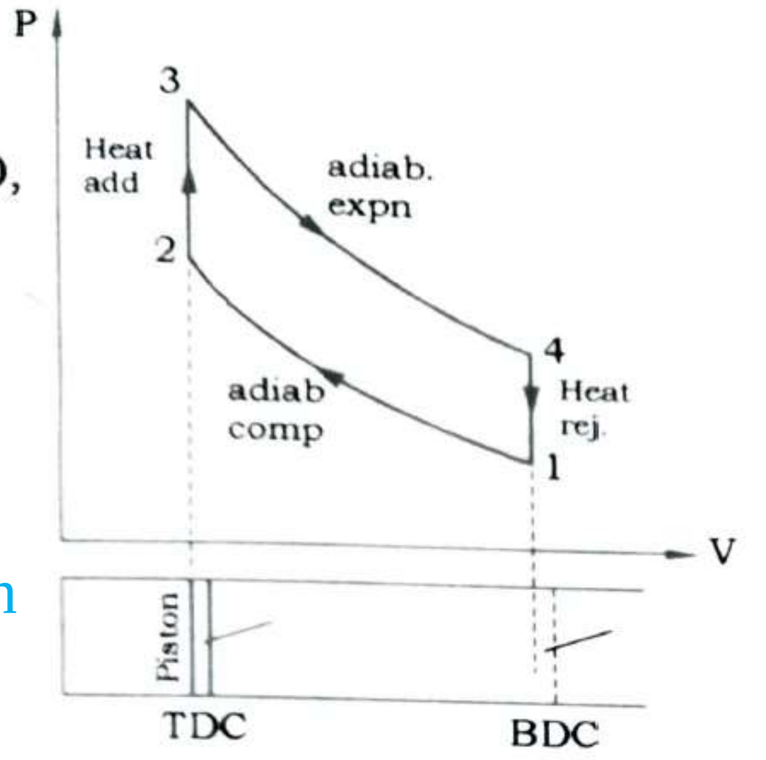
Otto cycle (constant volume cycle)

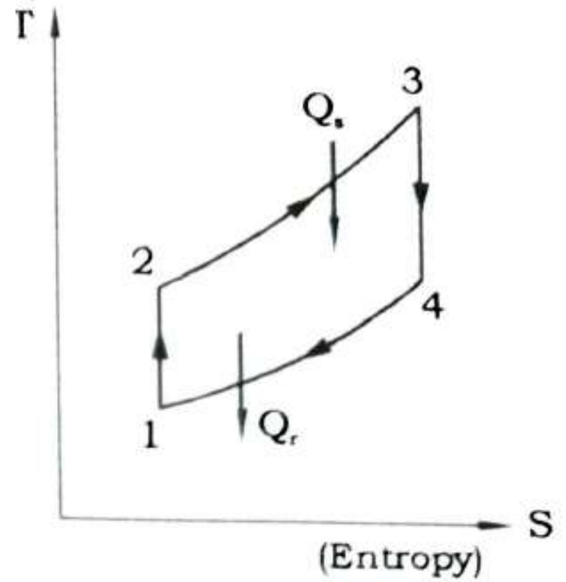
Expression for air standard efficiency in Otto cycle

Process 1-2: Adiabatic compression

w.k.t. for adiabatic process, heat transfer Q = 0,

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} \quad \text{-----(1)}$$





Process 2-3: constant volume heat addition

Heat supplied $Q_s = mC_v (T_3 - T_2)$ -----(2)

Otto cycle (constant volume cycle)

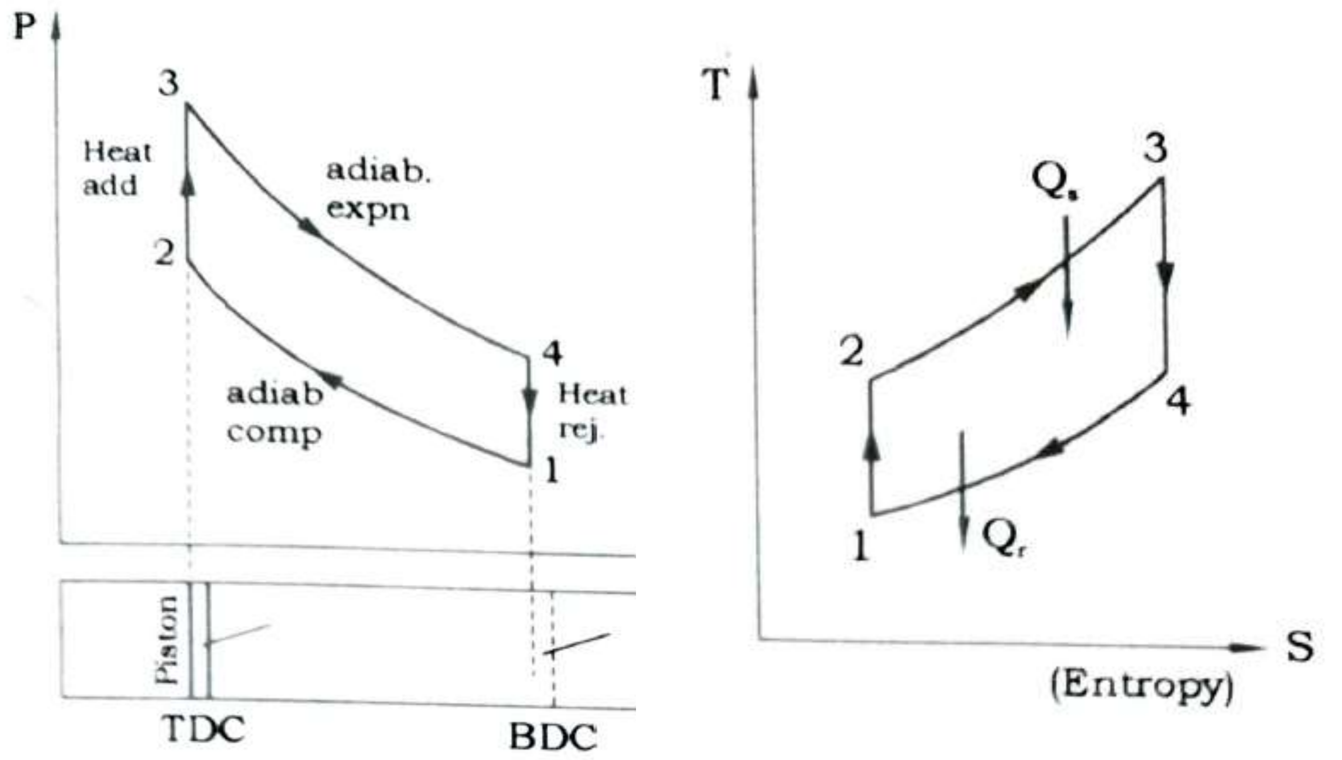
Process 3-4: Adiabatic Expansion

w.k.t. for adiabatic process, heat transfer Q = 0,

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} \quad \text{-----(3)}$$

Process 4-1: constant volume heat rejection

$$\text{Heat rejected } Q_r = mC_V (T_4 - T_1) \quad \text{-----(4)}$$



Otto cycle (constant volume cycle)

To find air standard efficiency:

$$\text{w.k.t. efficiency } \eta_{air} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$$

$$= \frac{Q_s - Q_r}{Q_s}$$

$$\text{i.e., } \eta_{air} = 1 - \frac{Q_r}{Q_s} = 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)}$$

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

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

From equation (1) we have $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$

But $V_2 = V_3$ and $V_1 = V_4$

$$\therefore \frac{T_1}{T_2} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} \quad \text{or} \quad \frac{T_2}{T_1} = \left(\frac{V_4}{V_3}\right)^{\gamma-1}$$

Otto cycle (constant volume cycle)

we have $\frac{T_3}{T_4} = \frac{T_2}{T_1}$

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

$$\eta_{air} = 1 - \frac{\left(\frac{T_3}{T_2} - 1\right)T_1}{\left(\frac{T_3}{T_2} - 1\right)T_2}$$

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

Defining compression ratio $R_C = \frac{V_1}{V_2}$,

we have from equation (1),

$$\frac{T_1}{T_2} = \left(\frac{1}{R_C}\right)^{\gamma-1} \quad \text{or} \quad \frac{T_1}{T_2} = \frac{1}{(R_C)^{\gamma-1}}$$

we get $\eta_{air} = 1 - \frac{1}{(R_C)^{\gamma-1}}$ for Otto cycle

Mean Effective Pressure (MEP) for Otto cycle

Mathematically, $MEP = P_m = \frac{\text{Work done / cycle}}{\text{Swept volume}}$

$$= \frac{Q_s - Q_r}{V_1 - V_2}$$

$$= \frac{mC_V(T_3 - T_2) - mC_V(T_4 - T_1)}{V_1 - V_2}$$

$$MEP = \frac{mC_V[(T_3 - T_2) - (T_4 - T_1)]}{V_1 - V_2} \quad \text{-----(1)}$$

Mean Effective Pressure (MEP) for Otto cycle

Express temperatures T_2 T_3 and T_4 in terms of T_1

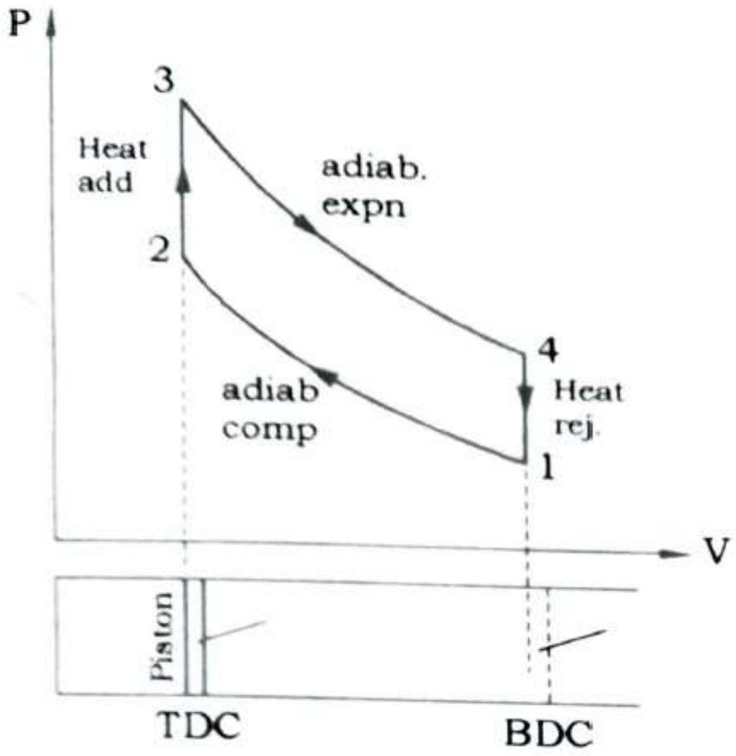
$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} \quad \text{or} \quad \frac{T_1}{T_2} = \left(\frac{1}{R_C}\right)^{\gamma-1} \quad \left(\because R_C = \frac{V_1}{V_2}\right)$$

$$\therefore \; T_2 = T_1.(R_C)^{\gamma-1} \quad \text{-----(2)}$$

For constant volume process 2-3,

we have $\frac{P}{T}$ = constant.

$$\frac{P_2}{T_2} = \frac{P_3}{T_3} \quad \text{or} \quad \frac{P_3}{P_2} = \frac{T_3}{T_2}$$



Mean Effective Pressure (MEP) for Otto cycle

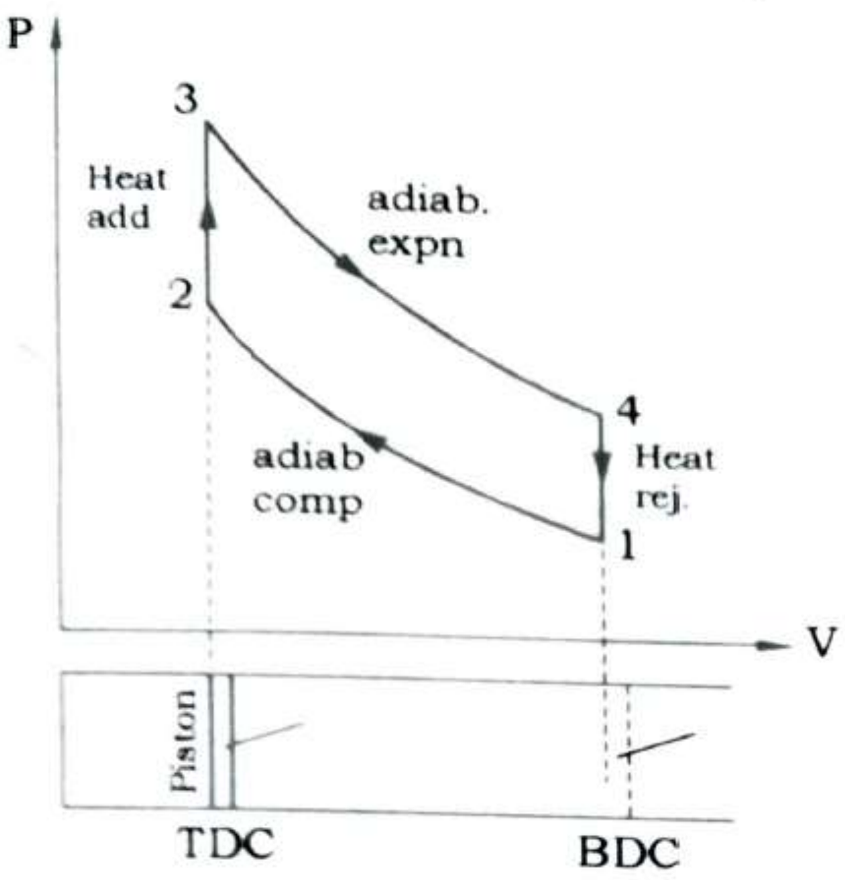
$$\therefore T_3 = T_2 \cdot \left(\frac{P_3}{P_2}\right) = T_2\ \alpha$$

where α = explosion ratio or pressure ratio = $\frac{P_3}{P_2}$

$T_3 = T_1 (R_C)^{\gamma-1} \cdot \alpha$ from equation (2) -----(3)

For adiabatic process 3-4, we have, $\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1}$

But $V_4 = V_1$ & $V_3 = V_2$



Mean Effective Pressure (MEP) for Otto cycle

$$\therefore \frac{T_3}{T_4} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \quad \text{or} \quad \frac{T_3}{T_4} = (R_C)^{\gamma-1}$$

$$T_4 = \frac{T_3}{(R_C)^{\gamma-1}} = \frac{T_1.(R_C)^{\gamma-1}.\alpha}{(R_C)^{\gamma-1}} \quad \text{from equation (3)}$$

$$\therefore T_4 = T_1\,\alpha \qquad \text{-----(4)}$$

Substituting equations (2), (3) and (4) in (1), we have

$$\text{MEP} = \frac{mC_V\left\{\left[T_1(R_C)^{\gamma-1}.\alpha - T_1(R_C)^{\gamma-1}\right]\right\}}{(V_1 - V_2)}$$

$$= \frac{mC_V.T_1\left[\left(\alpha.R_C^{\gamma-1} - R_C^{\gamma-1}\right) - (\alpha - 1)\right]}{(V_1 - V_2)} \qquad \text{-----(5)}$$

Under ideal conditions, at point (1),

we have $P_1V_1 = mRT_1$, $\quad V_1 = \frac{mRT_1}{P_1}$ -----(6)

compression ratio $R_C = \frac{V_1}{V_2}$

$$\therefore V_2 = \frac{V_1}{R_C} = \frac{mRT_1}{P_1.R_C} \quad \text{from equation (6)} \qquad \text{-----(7)}$$

Mean Effective Pressure (MEP) for Otto cycle

Substituting equations (6) and (7) in (5), we have

$$MEP = \frac{m.C_V T_1 \left[\left(\alpha R_C^{\gamma-1} - R_C^{\gamma-1}\right) - (\alpha - 1)\right]}{\frac{mRT_1}{P_1} - \frac{mRT_1}{P_1 R_C}} = \frac{m.C_V T_1 \left[R_C^{\gamma-1}(\alpha - 1) - (\alpha - 1)\right]}{\frac{mRT_1}{P_1}\left(1 - \frac{1}{R_C}\right)}$$

$$MEP = \frac{P_1 C_V (\alpha - 1) \left[R_C^{\gamma-1} - 1\right]}{R\left[\frac{R_C - 1}{R_C}\right]} \quad \text{-----(8)}$$

w.k.t. Gas constant $R = C_P - C_V$

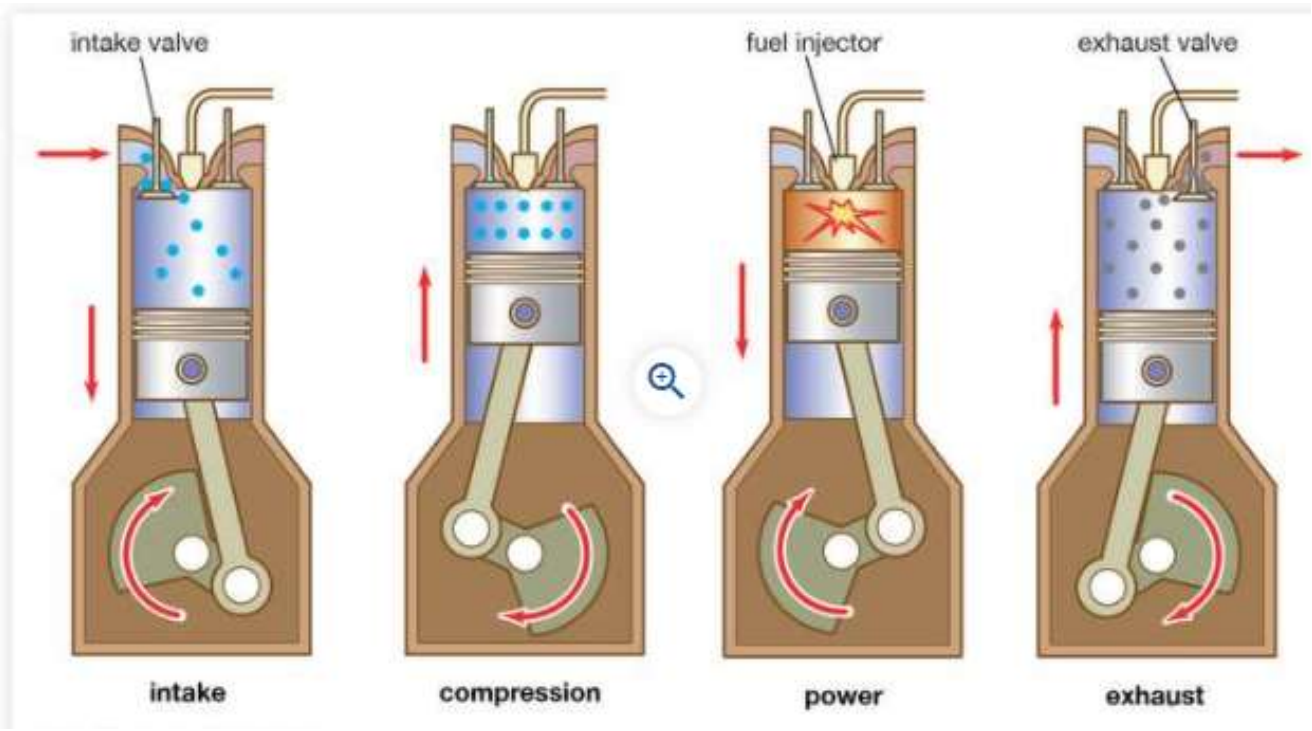
$$\frac{R}{C_V} = \frac{C_P}{C_V} - 1$$

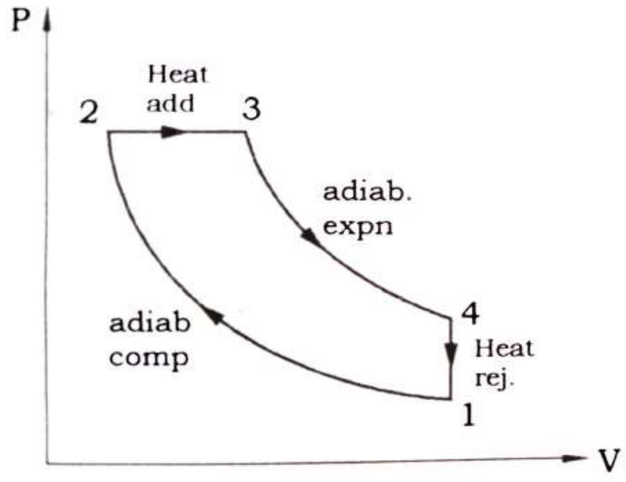
$$\frac{R}{C_V} = \gamma - 1 \qquad \therefore \frac{C_V}{R} = \frac{1}{\gamma - 1}$$

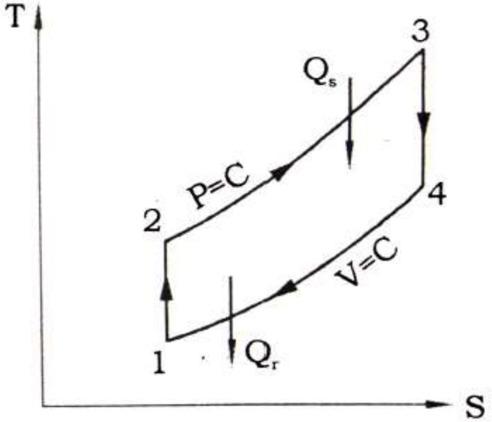
$$MEP = P_m = \frac{P_1.R_C(\alpha - 1)\ R_C^{\gamma-1} - 1}{(\gamma - 1)(R_C - 1)}$$

Diesel cycle (Constant Pressure cycle)

Expression for air standard efficiency in Diesel cycle



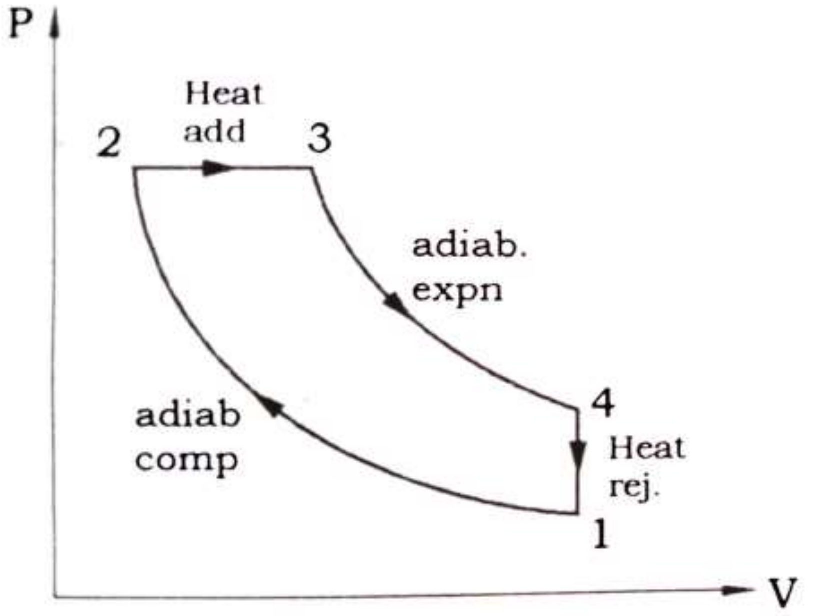




Diesel cycle (constant Pressure cycle)

Process 1-2: Adiabatic compression

heat transfer Q = 0, and $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$ -----(1)



Process 2-3: constant Pressure heat addition

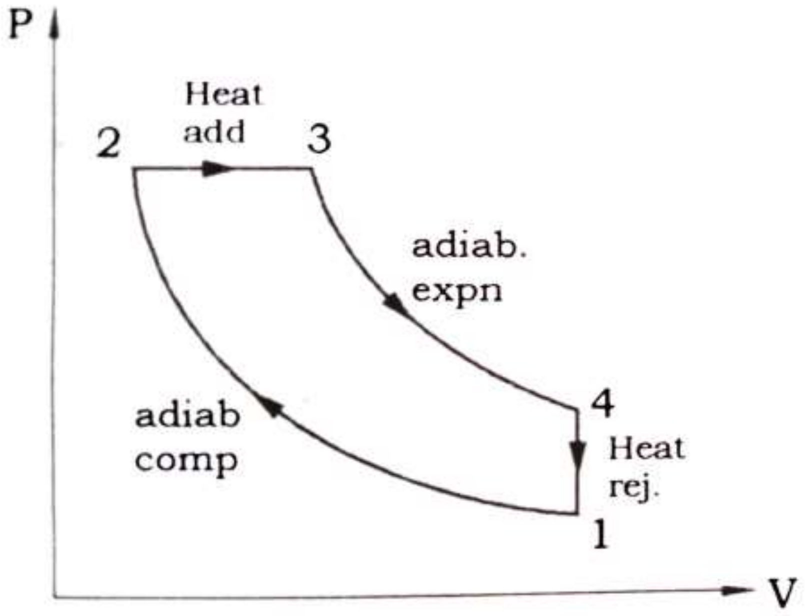
Heat supplied at constant pressure = $Q_s = mC_P(T_3 - T_2)$ -----(2)

Diesel cycle (constant Pressure cycle)

Process 3-4: Adiabatic Expansion

w.k.t. for adiabatic process, heat transfer Q = 0,

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} \quad \text{-----(3)}$$



Process 4-1: constant volume heat rejection

$$\text{Heat rejected } Q_r = mC_V (T_4 - T_1) \quad \text{-----(4)}$$

Diesel cycle (constant Pressure cycle)

w.k.t. $\eta_{air} = \dfrac{\text{Work done}}{\text{Heat supplied}}$

$$= \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s}$$

$$\eta_{air} = 1 - \frac{mC_V(T_4 - T_1)}{m.C_P(T_3 - T_2)}$$

$$\frac{C_P}{C_V} = \gamma$$

$$\therefore \eta_{air} = 1 - \frac{1(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

Express temperatures T_2 T_3 and T_4 in terms of T_1

From equation (1), $\dfrac{T_1}{T_2} = \left(\dfrac{1}{R_C}\right)^{\gamma-1}$

$\because R_C = \dfrac{V_1}{V_2}$ = compression ratio

$$T_2 = T_1 (R_C)^{\gamma-1}$$

For constant pressure process 2-3, $\dfrac{V}{T}$ = constant

$$\frac{V_2}{T_2} = \frac{V_3}{T_3} \quad \text{or} \quad \frac{T_3}{T_2} = \frac{V_3}{V_2}$$

Diesel cycle (constant Pressure cycle)

Defining cut-off ratio $\rho = \dfrac{V_3}{V_2}$,

$$T_3 = T_2\left(\frac{V_3}{V_2}\right) = T_2\,\rho$$

$$T_3 = T_1\,(R_C)^{\gamma-1}.\rho$$

From equation (3), $\dfrac{T_3}{T_4} = \left(\dfrac{V_1}{V_3}\right)^{\gamma-1}$

or $\dfrac{T_3}{T_4} = \left(\dfrac{V_1}{V_2}.\dfrac{V_2}{V_3}\right)^{\gamma-1}$

$$\frac{T_3}{T_4} = R_C^{\gamma-1}.\frac{1}{\rho^{\gamma-1}} \qquad T_4 = T_3.\frac{\rho^{\gamma-1}}{(R_C)^{\gamma-1}}$$

we have $T_4 = T_1.(R_C)^{\gamma-1}\rho\,\dfrac{\rho^{\gamma-1}}{(R_C)^{\gamma-1}}$

$$\therefore T_4 = T_1\,\rho^{\gamma}$$

$$\therefore \eta_{air} = 1 - \frac{1(T_4 - T_1)}{\gamma\,(T_3 - T_2)}$$

$$\eta_{air} = 1 - \frac{1}{\gamma}\,\frac{(T_1\,\rho^{\gamma} - T_1)}{(T_1\,R_C^{\gamma-1}\rho - T_1\,R_C^{\gamma-1})}$$

$$= 1 - \frac{1}{\gamma}\,\frac{T_1\,(\rho^{\gamma} - 1)}{T_1\,R_C^{\gamma-1}(\rho - 1)}$$

$$.\ \eta_{air} = 1 - \frac{1}{\gamma.(R_C)^{\gamma-1}}.\frac{(\rho^{\gamma} - 1)}{(\rho - 1)}$$

Mean Effective Pressure (MEP) for Diesel cycle

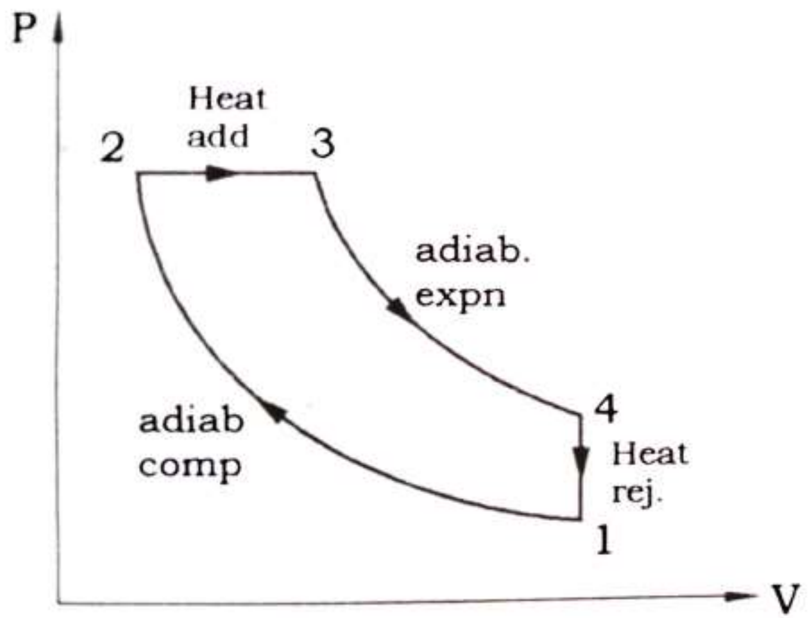
$$P_m = \frac{\text{Work done / cycle}}{\text{swept volume}}$$

$$= \frac{Q_s - Q_r}{V_1 - V_2}$$

$$= \frac{mC_p(T_3 - T_2) - mC_v(T_4 - T_1)}{V_1 - V_2}$$

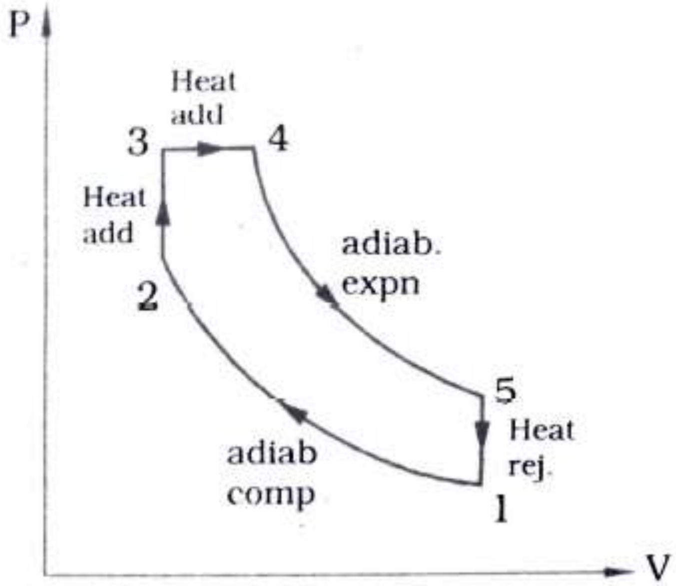
Express all temperature in terms of T_1

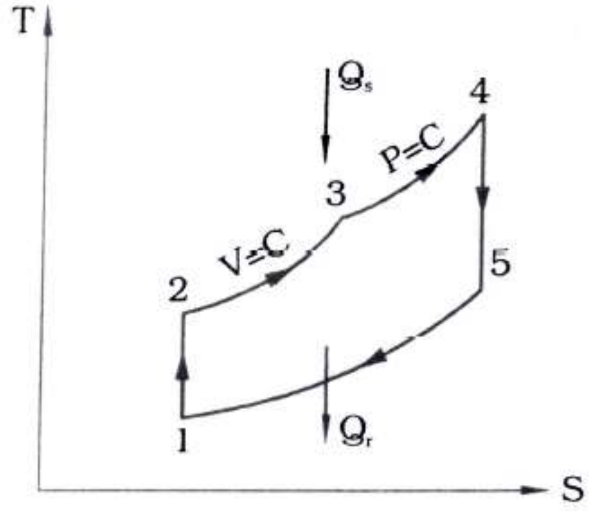
$$MEP = \frac{P_1 R_C \left\{ \gamma R_C^{\gamma-1}(\rho - 1) - \rho^{\gamma} - 1 \right\}}{(\gamma - 1)(R_C - 1)}$$



Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)

Expression for air standard efficiency:





Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)

Process 1-2: Adiabatic compression

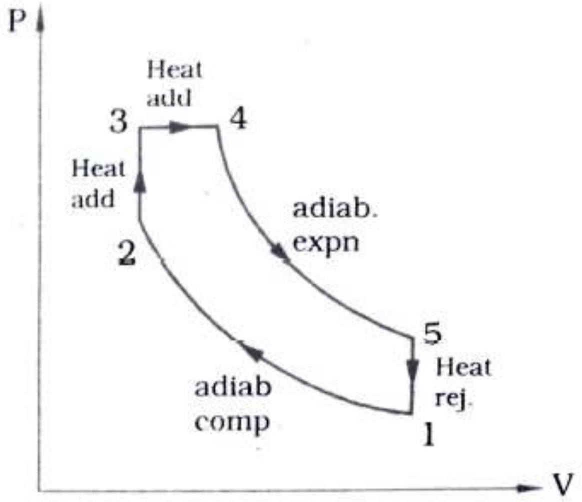
heat transfer Q = 0, and $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$ -----(1)

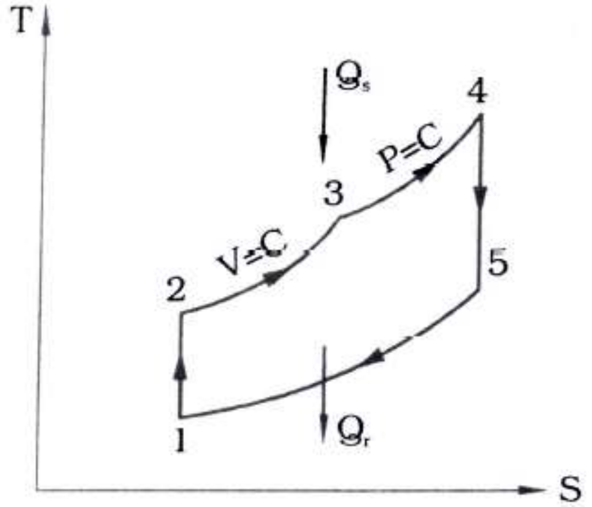
Process 2-3: constant volume heat addition

Heat supplied $(Q_s)_{2-3} = mC_v (T_3 - T_2)$

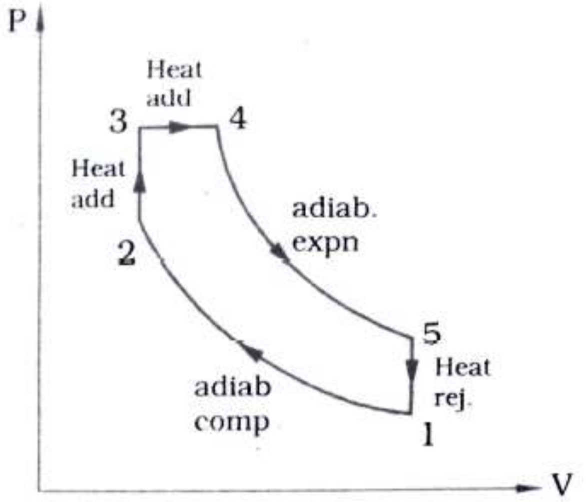
Process 3-4: constant Pressure heat addition

Heat supplied $(Q_s)_{3-4} = mC_P (T_4 - T_3)$





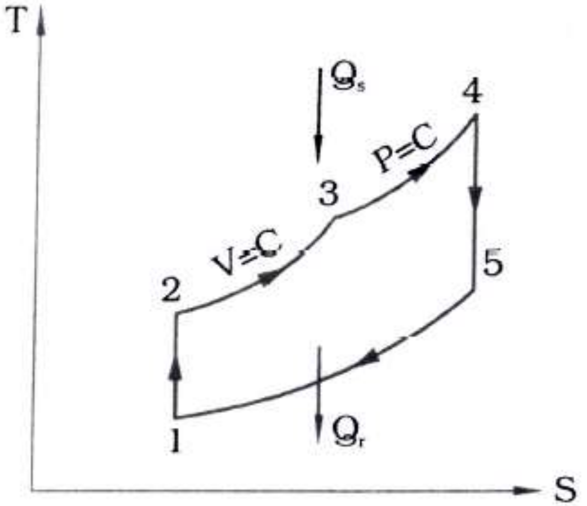
Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)



Process 4-5: Adiabatic Expansion

w.k.t. for adiabatic process, heat transfer, Q = 0,

$$\frac{T_4}{T_5} = \left(\frac{V_5}{V_4}\right)^{\gamma-1}$$



Process 5-1: constant volume heat rejection

$\therefore$ Heat rejected $Q_r = mC_V (T_5 - T_1)$

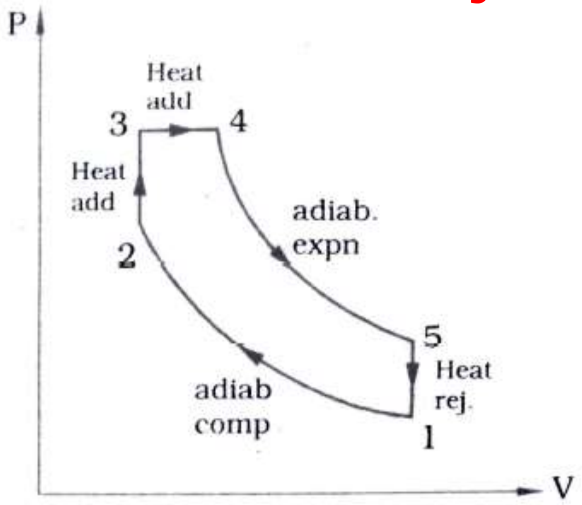
Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)

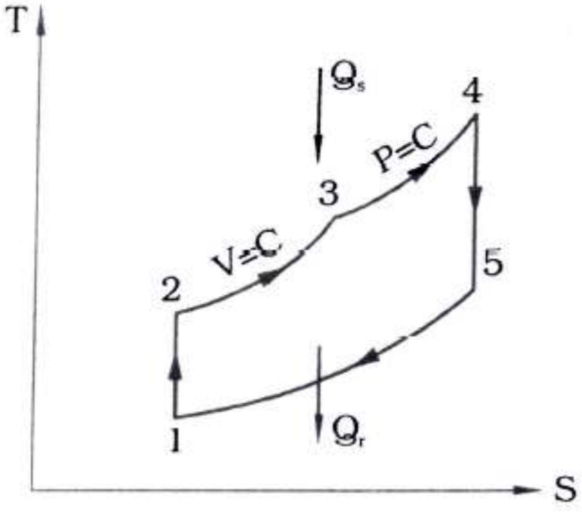
$$\text{w.k.t.}\quad \eta_{air} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s} = 1 - \frac{Q_r}{(Q_s)_{2-3} + (Q_s)_{3-4}}$$

$$,\ \eta_{air} = 1 - \frac{mC_V(T_5 - T_1)}{mC_V(T_3 - T_2) + mC_P(T_4 - T_3)}$$

$$= 1 - \frac{C_V(T_5 - T_1)}{C_V(T_3 - T_2) + C_P(T_4 - T_3)}$$





Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)

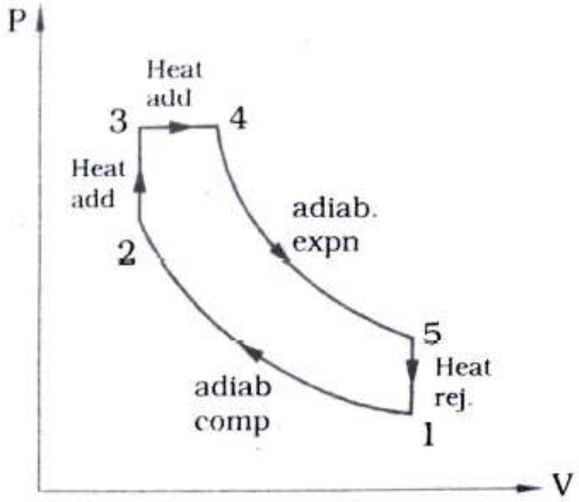
Express all temperatures in terms of T_1

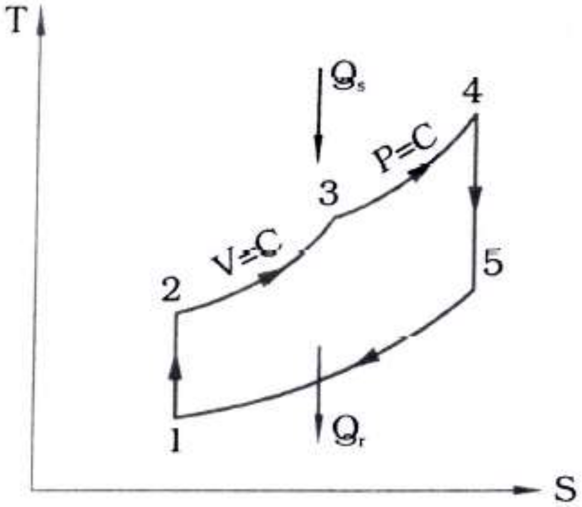
we have $\frac{T_1}{T_2} = \left(\frac{1}{R_C}\right)^{\gamma-1}$ where $R_C = \frac{V_1}{V_2}$ = compression ratio

we have $\frac{T_4}{T_5} = \left(\frac{V_1}{V_4}\right)^{\gamma-1}$ $\because V_5 = V_1$

$$\frac{T_4}{T_5} = \left(\frac{V_1}{V_2} \times \frac{V_2}{V_4}\right)^{\gamma-1}$$

$$\frac{T_4}{T_5} = \left(\frac{V_1}{V_2} \times \frac{V_3}{V_4}\right)^{\gamma-1}$$ $\because V_2 = V_3$





Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)

$$\frac{T_4}{T_5} = \left(R_C \times \frac{1}{\rho}\right)^{\gamma-1}$$

$$\because \frac{V_4}{V_3} = \rho \text{ cut-off ratio}$$

$$T_4 = T_5 \left[R_C^{\gamma-1}.\rho^{1-\gamma}\right]$$

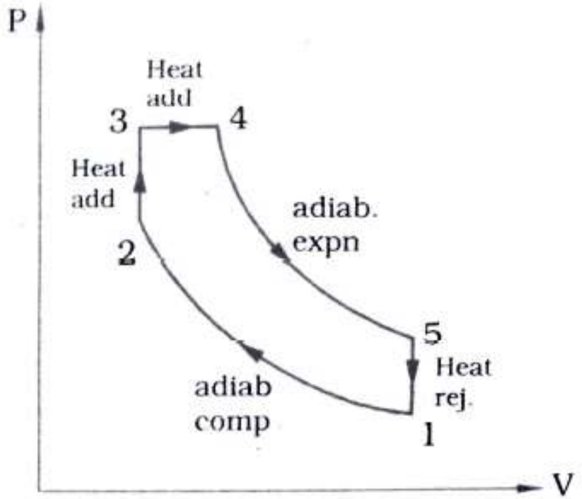
For constant volume process 2-3,

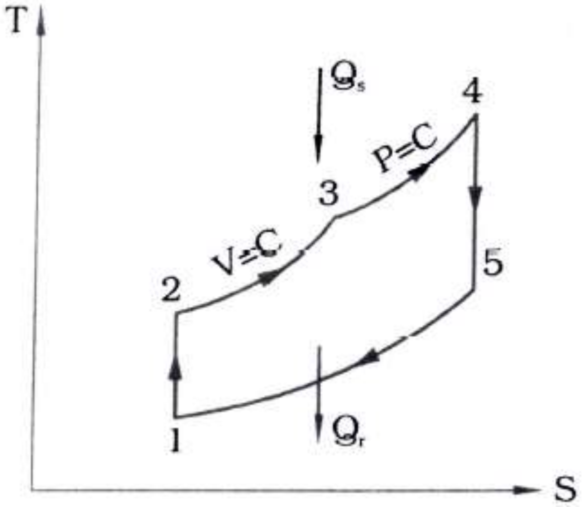
we have $\frac{P}{T} = \text{constant}$

$$\frac{P_2}{T_2} = \frac{P_3}{T_3} \quad \text{or} \quad T_3 = T_2\left(\frac{P_3}{P_2}\right)$$

$$= T_2\,(\alpha)$$

where α = explosion ratio = $\frac{P_3}{P_2}$





Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)

we have, $T_3 = T_1 . (R_C)^{\gamma-1}.\alpha$

For constant pressure process 3-4,

we have $\frac{V}{T}$ = constant.

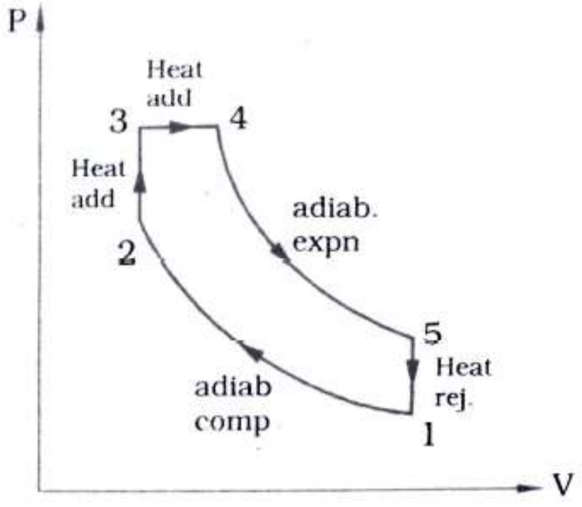
$$T_4 = T_3\left(\frac{V_4}{V_3}\right) = T_3(\rho)$$

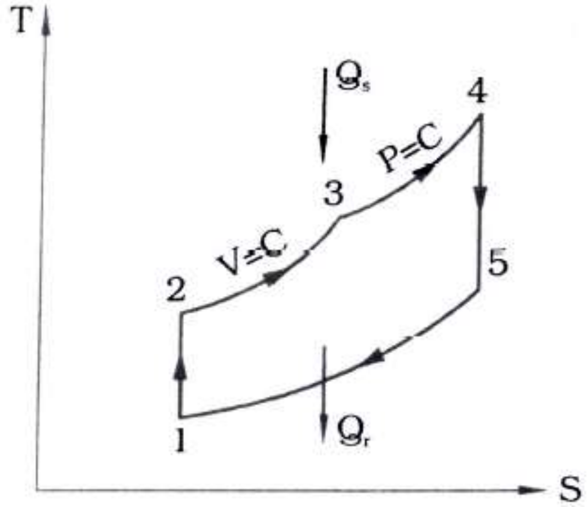
we have $T_4 = T_1 . (R_C)^{\gamma-1}.\alpha.\rho$

we have $T_1 . (R_C)^{\gamma-1}.\alpha.\rho = T_5.(R_C)^{\gamma-1}.\rho^{1-\gamma}$

$$T_5 = \frac{T_1\,\alpha\,\rho}{\rho^{1-\gamma}}$$

$$= T_1\alpha\,\rho^{\gamma}$$





Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)

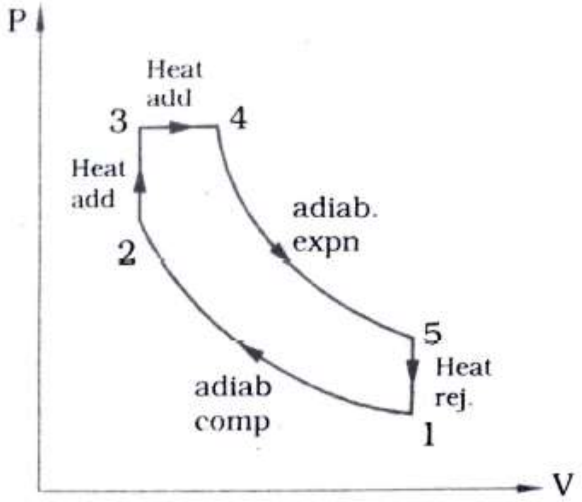
Substituting T_2, T_3, T_4 and T_5 in equation (6), we have

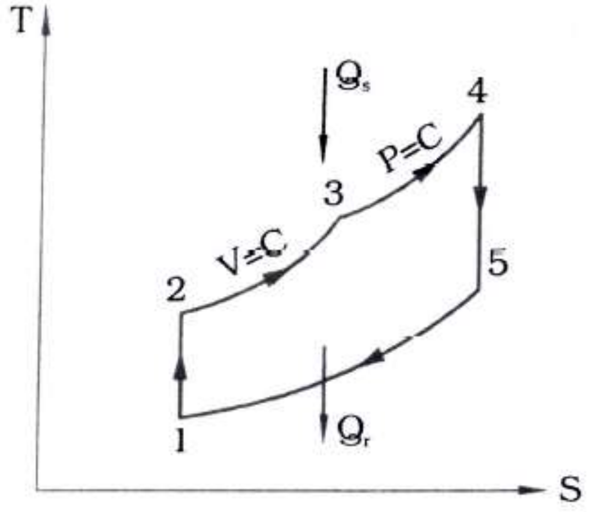
$$\eta_{air} = 1 - \frac{C_V \; T_1 \alpha \rho^{\gamma} - T_1}{C_V \; T_1 R_C^{\gamma-1}.\alpha - T_1 R_C^{\gamma-1} \; + C_p \; T_1 R_C^{\gamma-1}.\alpha\rho - T_1 R_C^{\gamma-1}.\alpha}$$

$$= 1 - \frac{T_1 \; \alpha\rho^{\gamma} - 1}{T_1 \; R_C^{\gamma-1}.\alpha - R_C^{\gamma-1} \; + \frac{C_P}{C_V}.T_1 \; R_C^{\gamma-1}.\alpha\rho - R_C^{\gamma-1}.\alpha}$$

$$= 1 - \frac{\alpha\rho^{\gamma} - 1}{R_C^{\gamma-1}(\alpha - 1) + \gamma . R_C^{\gamma-1} . \alpha(\rho - 1)}$$

$$\eta_{air} = 1 - \frac{1}{R_C^{\gamma-1}} \frac{\alpha.\rho^{\gamma} - 1}{(\alpha - 1) + \alpha\gamma(\rho - 1)}$$





Dual Combustion Cycle (Semi- Diesel/Limited Pressure cycle)

$$MEP = \frac{P_1 R_C}{(R_C - 1)((\gamma - 1))} \; R_C^{\gamma-1}(\alpha - 1) + \alpha.\gamma \; R_C^{\gamma-1}(\rho - 1) - (\alpha.\rho^{\gamma} - 1)$$

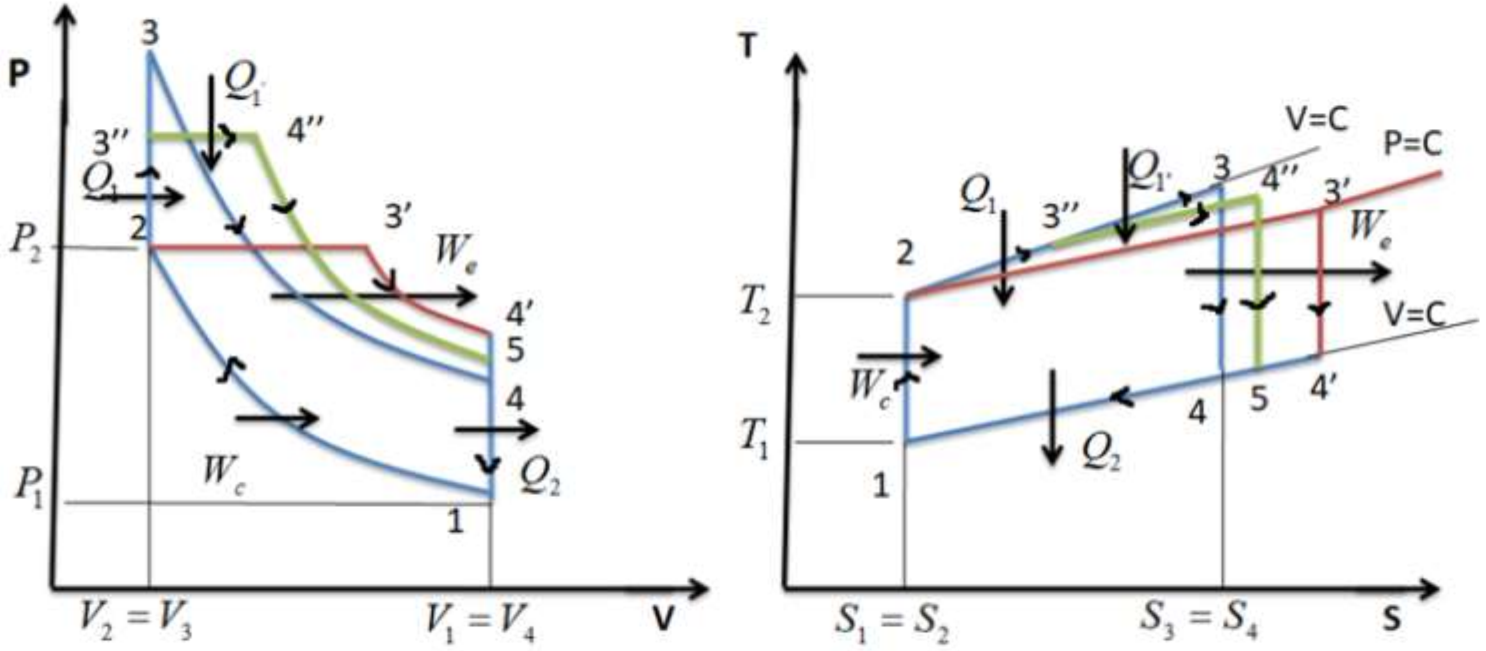
Comparison of Otto, Diesel and Dual Cycles

For same compression ratio and heat supplied

1-2-3-4 -1 is Otto cycle

1-2-3’-4’-1 is diesel cycle

1-2-3’’-4’’-5-1 is dual cycle



w.k.t. $\eta_{air} = \dfrac{\text{Work done}}{\text{Heat supplied}}$

$$= \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s}$$

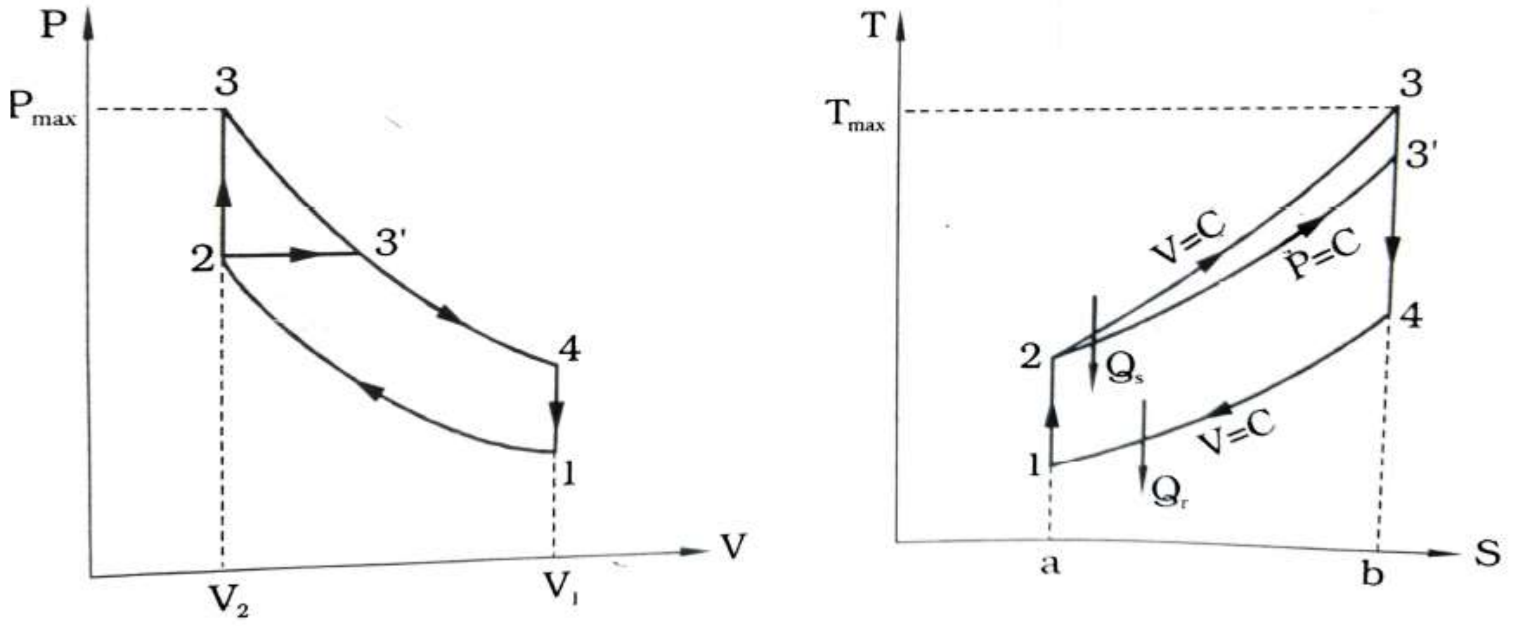
$$\therefore \eta_{otto} > \eta_{Dual} > \eta_{Diesel}$$

Comparison of Otto, Diesel and Dual Cycles

Same compression ratio and heat rejection

w.k.t. $\eta_{air} = \dfrac{\text{Work done}}{\text{Heat supplied}}$

$$= \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s}$$



Otto Cycle : 1-2-3-4
Diesel Cycle : 1-2-3'-4

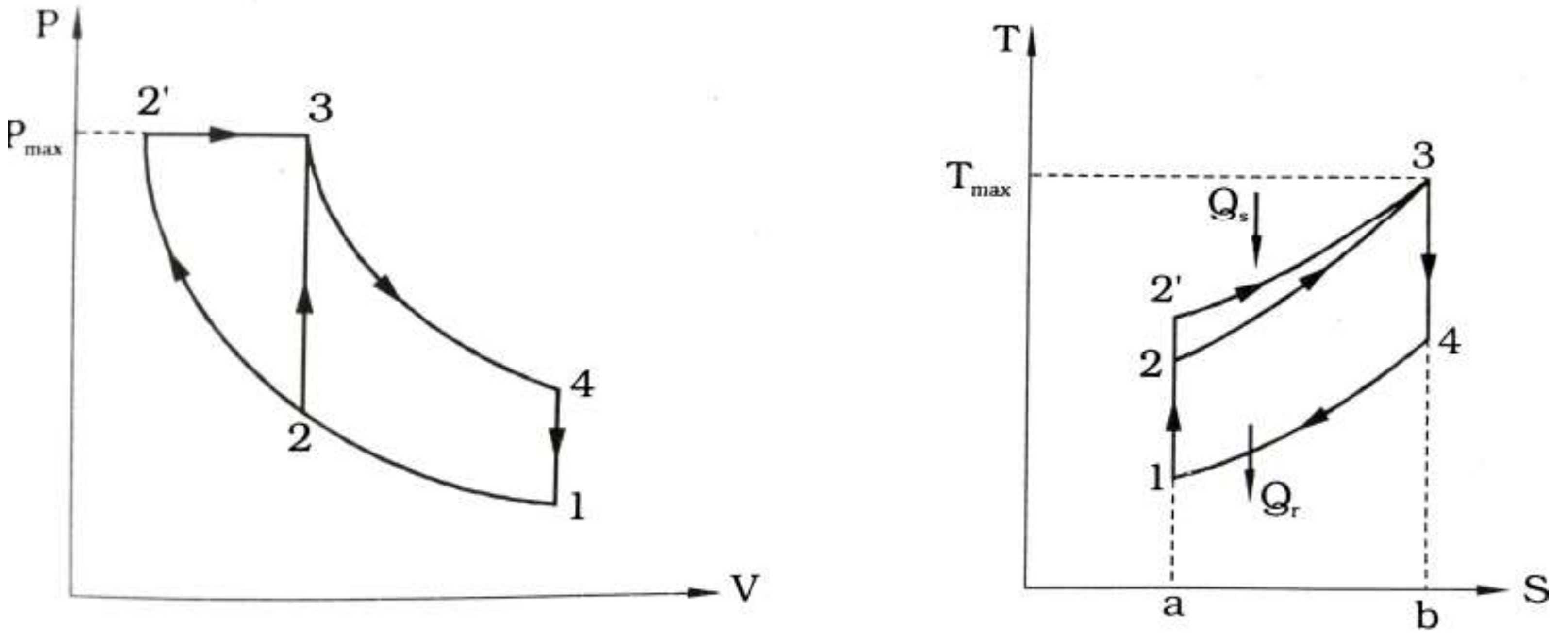
Otto cycle has a comparatively higher efficiency than Diesel cycle

Comparison of Otto, Diesel and Dual Cycles

For Same maximum pressure, maximum temperature and heat rejection

w.k.t. $\eta_{air} = \frac{\text{Work done}}{\text{Heat supplied}}$

$$= \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s}$$



Otto Cycle : 1-2-3-4
Diesel Cycle : 1-2'-3-4

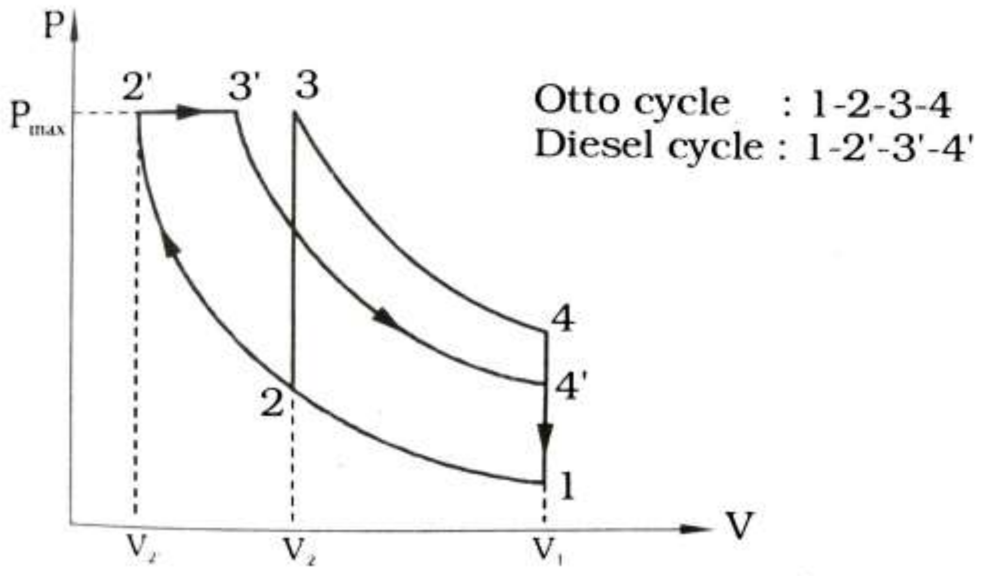
Diesel cycle has a comparatively higher efficiency than Otto cycle

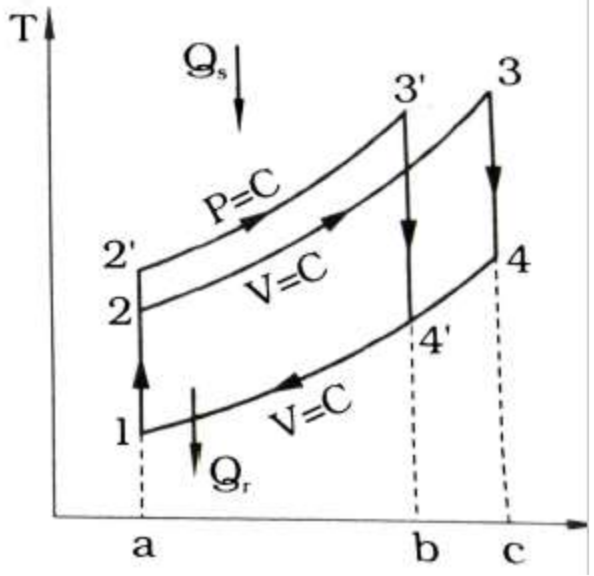
Comparison of Otto, Diesel and Dual Cycles

- **For Same maximum pressure and heat input**

w.k.t. $\eta_{air} = \frac{\text{Work done}}{\text{Heat supplied}}$

$$= \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s}$$





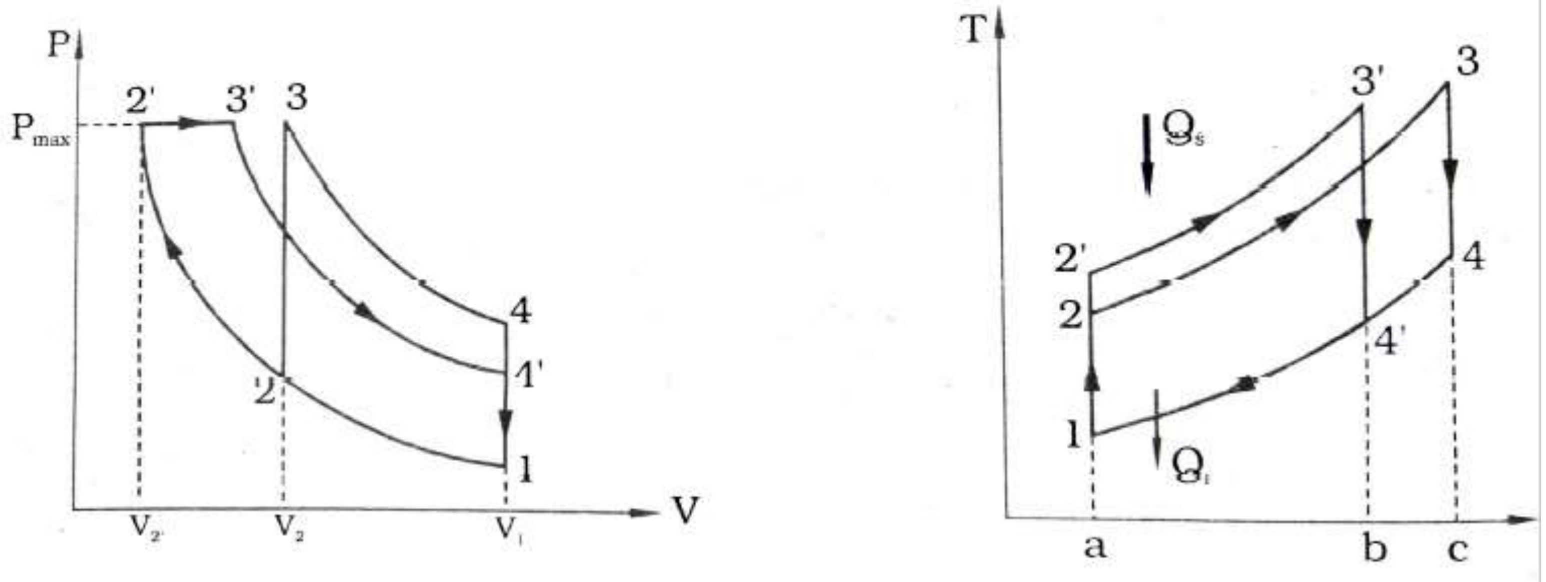
Diesel cycle is more efficient than Otto cycle

Comparison of Otto, Diesel and Dual Cycles

For Same maximum pressure and work output

$$\text{w.k.t.} \quad \eta_{air} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s}$$



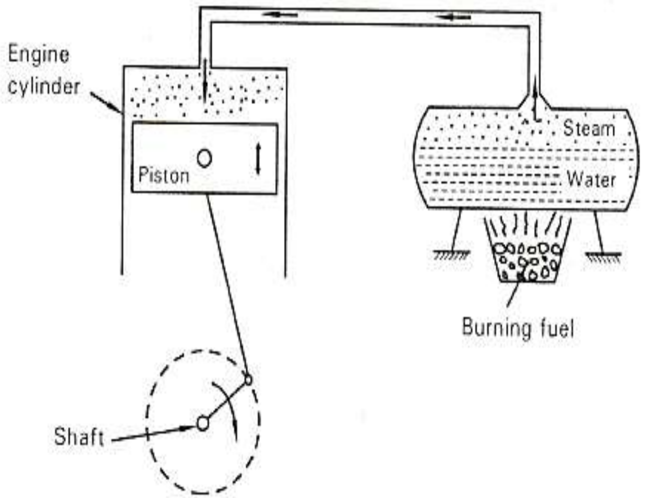
Otto cycle : 1-2-3-4
Diesel cycle : 1-2'-3'-4'

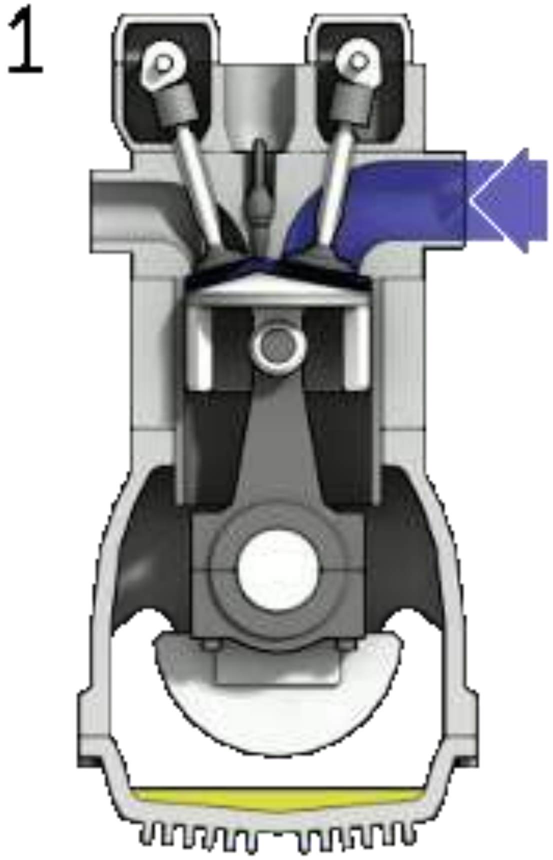
Diesel cycle is more efficient than Otto cycle

I.C ENGINE

Heat engine can be defined as a device or machine that converts the chemical energy of a fuel into heat energy by combustion of fuel, and utilizes this heat energy to perform useful mechanical work (usually in the form of rotation of shaft)

- Internal combustion engine
- External combustion engine





CLASSIFICATION OF IC ENGINE

(1) According to the type of fuel used:

a) Petrol engine

b) Diesel engine

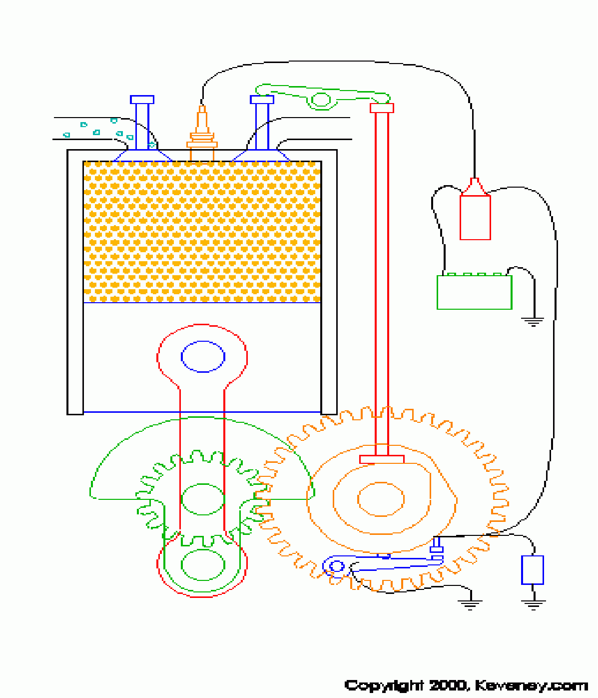
c) Gas engine

d) Bi-fuel (Bio-fuel) engine

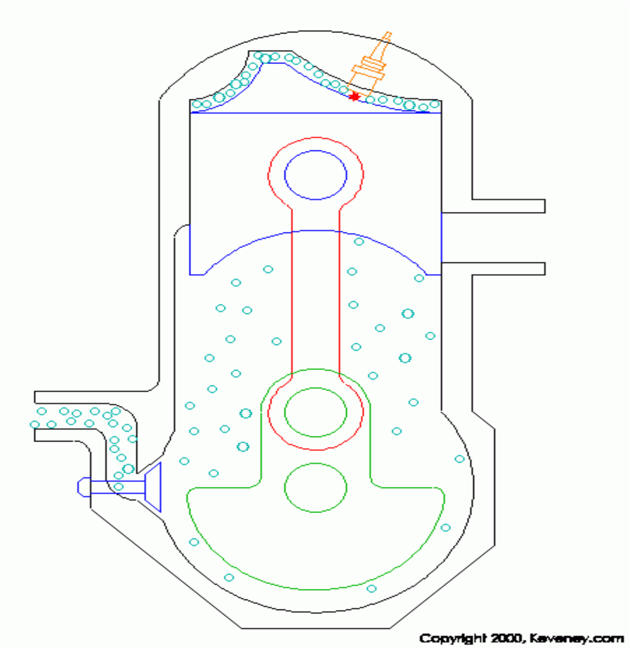
CLASSIFICATION OF IC ENGINE

(2) According to the number of strokes per cycle:

- 4-stroke engine



- 2-stroke engine



CLASSIFICATION OF IC ENGINE

(3) According to the method of ignition:

a) Spark Ignition (SI) engine

b) Compression Ignition (CI) engine

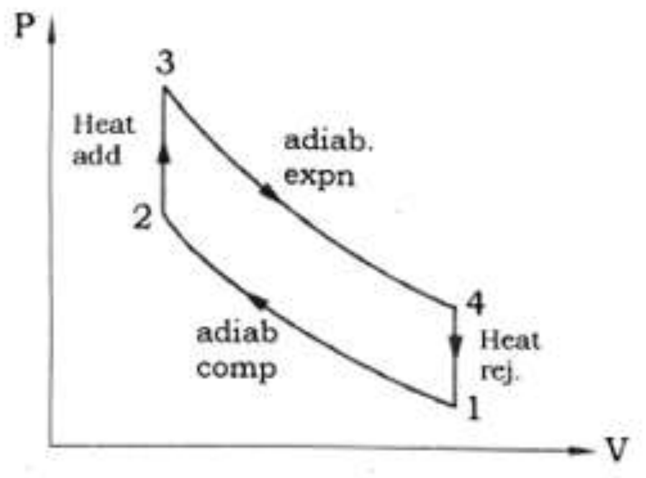
CLASSIFICATION OF IC ENGINE

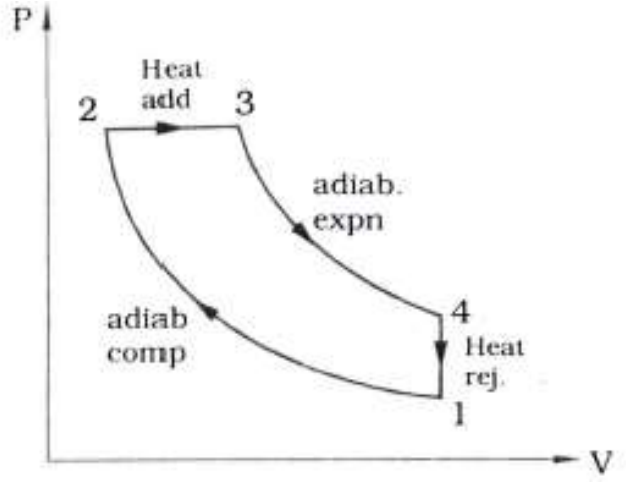
(4) According to the cycle of combustion:

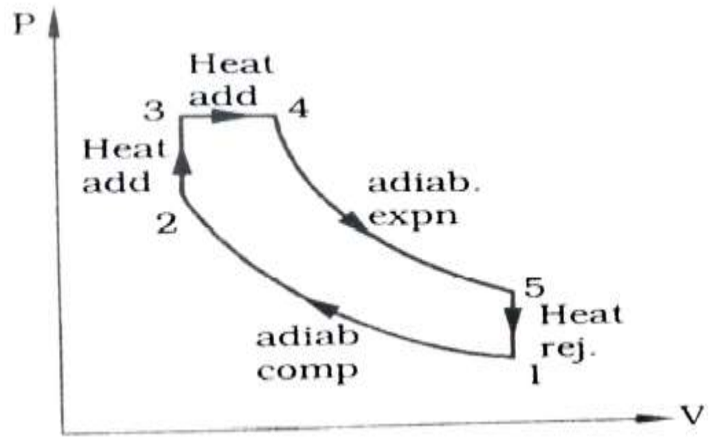
a) Otto cycle engine

b) Diesel cycle engine

c) Dual combustion cycle engine





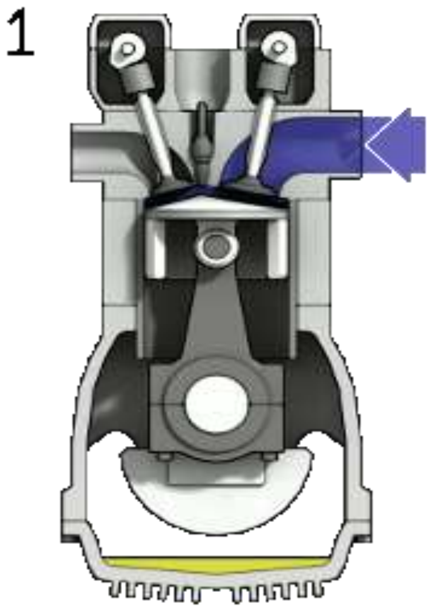


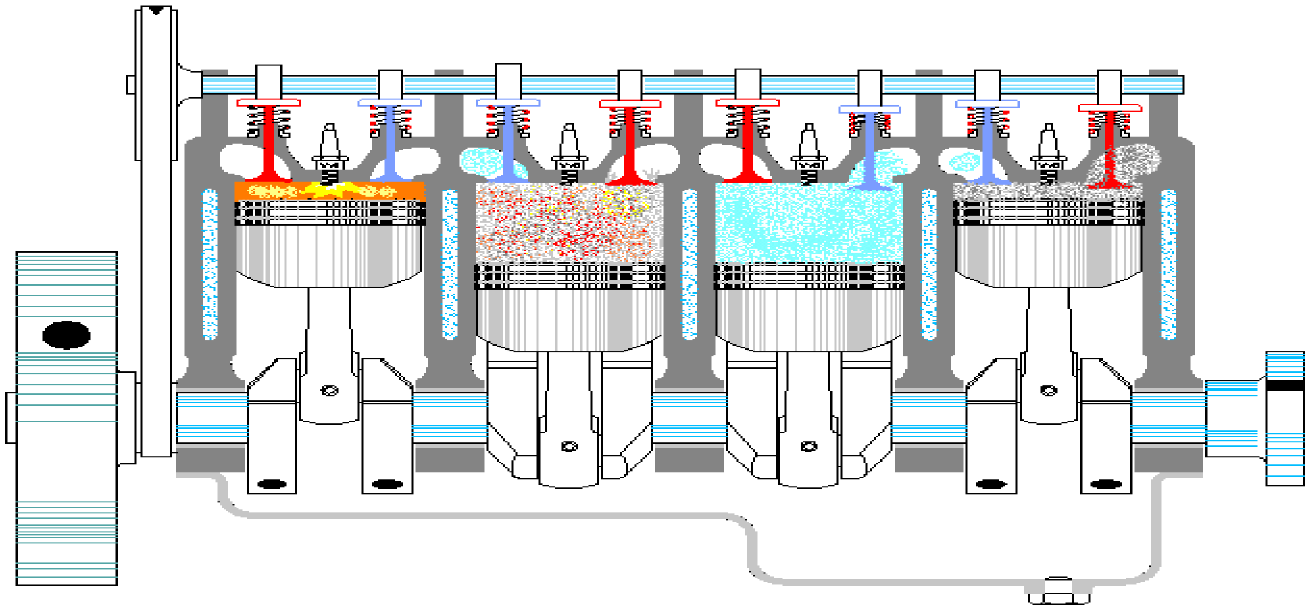
CLASSIFICATION OF IC ENGINE

(5) According to the number of cylinders used:

a) Single cylinder engine

b) Multi-cylinder engine

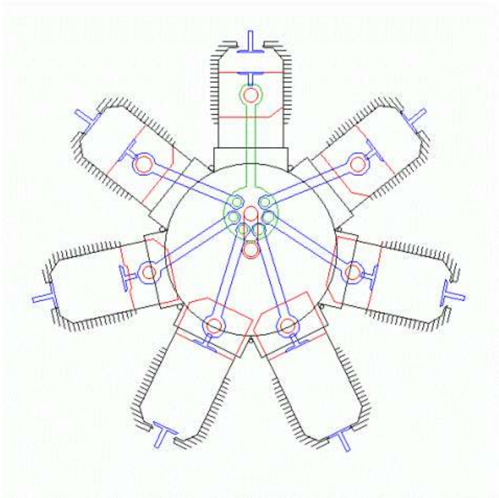




CLASSIFICATION OF IC ENGINE

(6) According to the arrangement of cylinders:

a) Vertical engine
b) Horizontal engine
c) Inline engine
d) Radial engine
e) V-engine
f) Opposed type engine



CLASSIFICATION OF IC ENGINE

(7) According to the method of cooling:

a) Air cooled engine

b) Water cooled engine

(8) According to their uses:

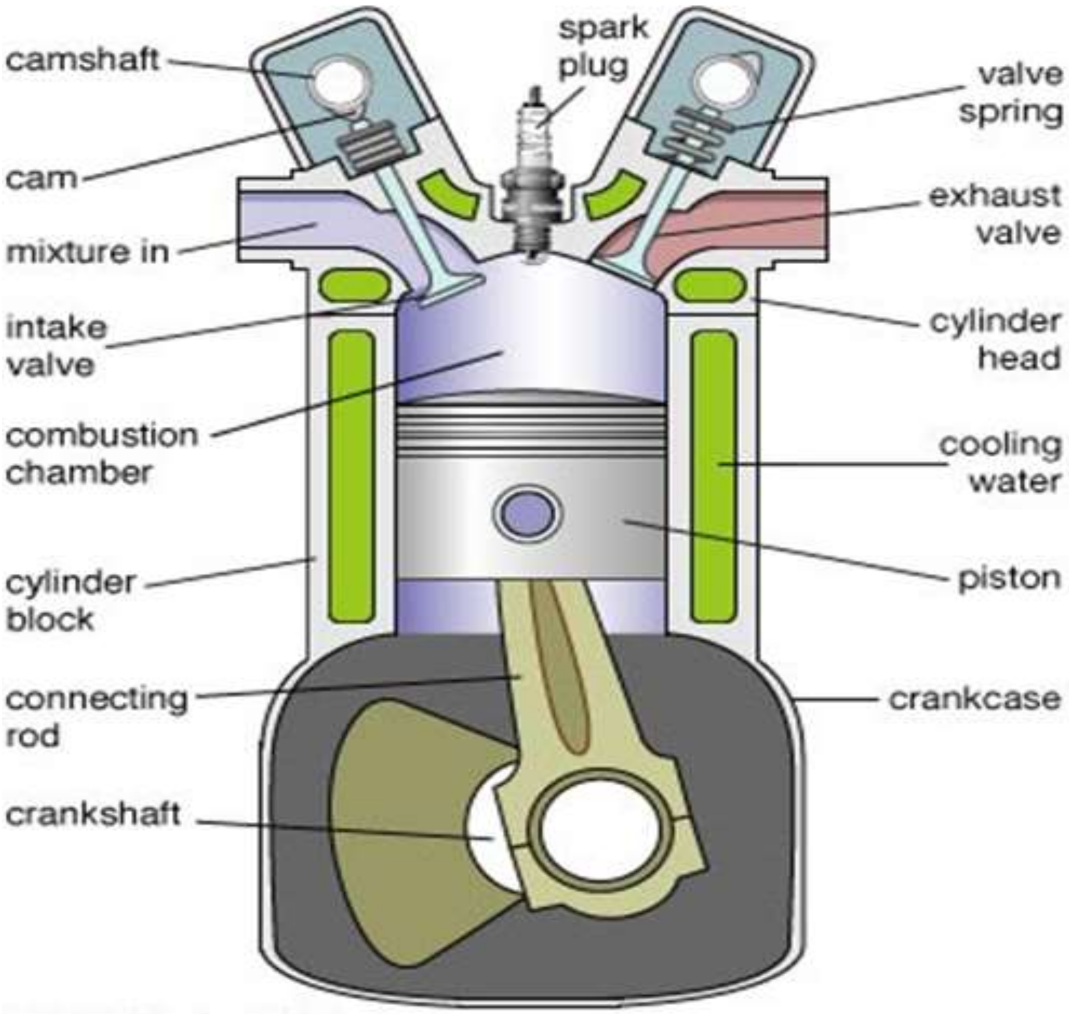
a) Stationary engine

b) Automobile engine

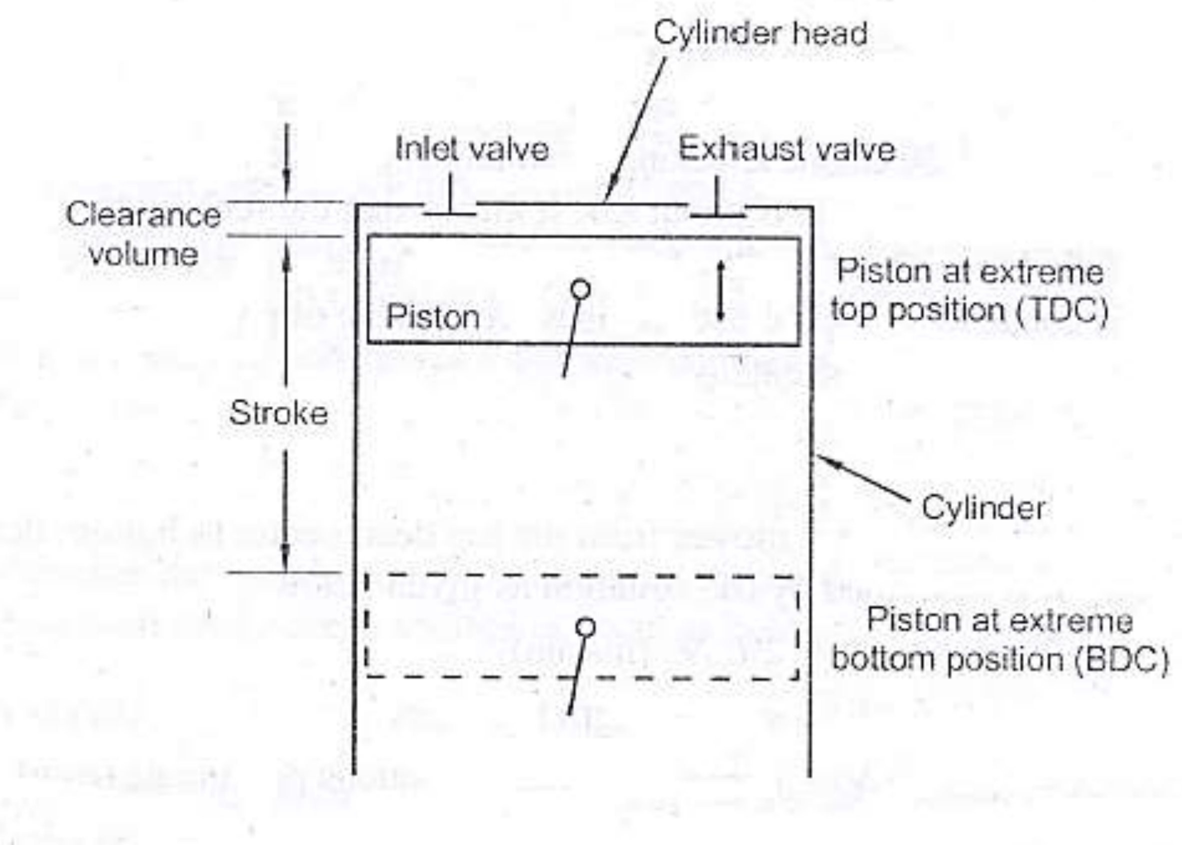
c) Marine engine

d) Aircraft engine, etc

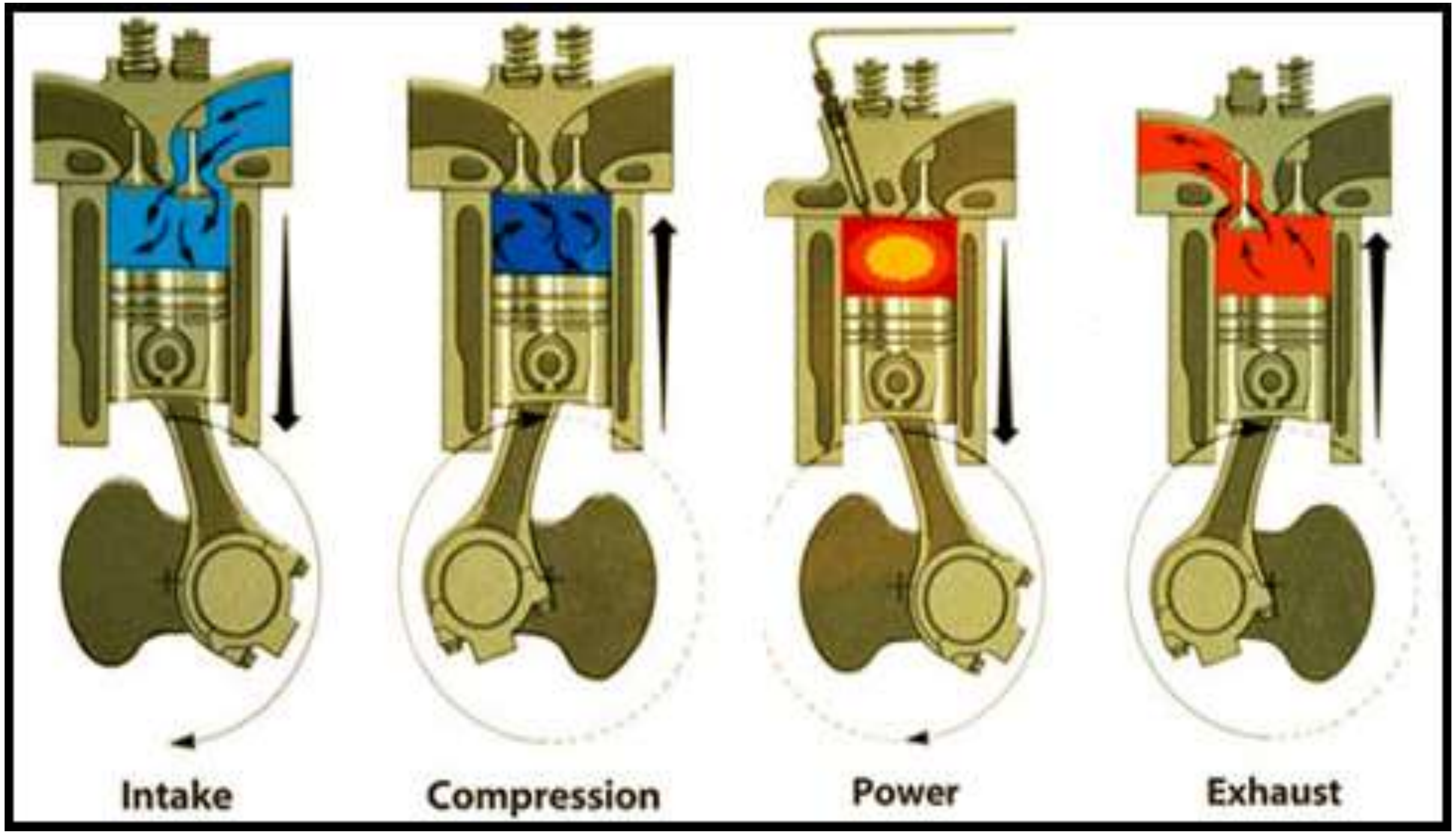
PARTS OF IC ENGINE

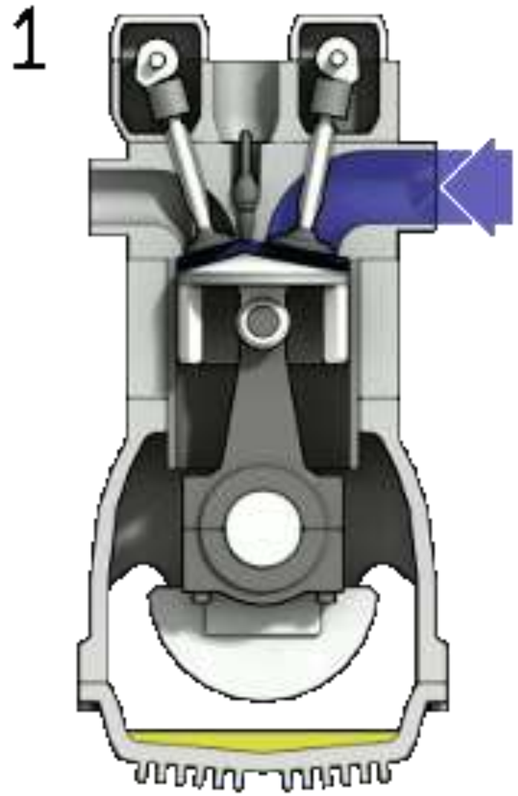


IC ENGINE TERMINOLOGY

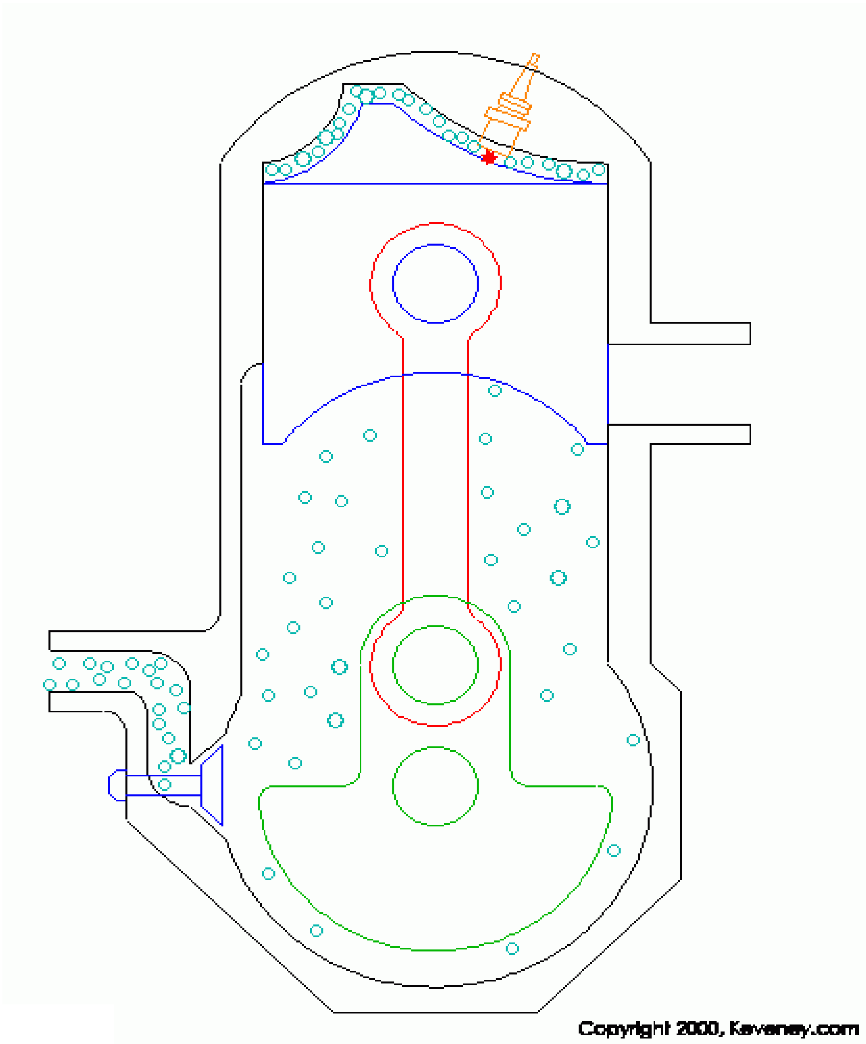


Four - Stroke (4-s) Engine





2-stroke engine



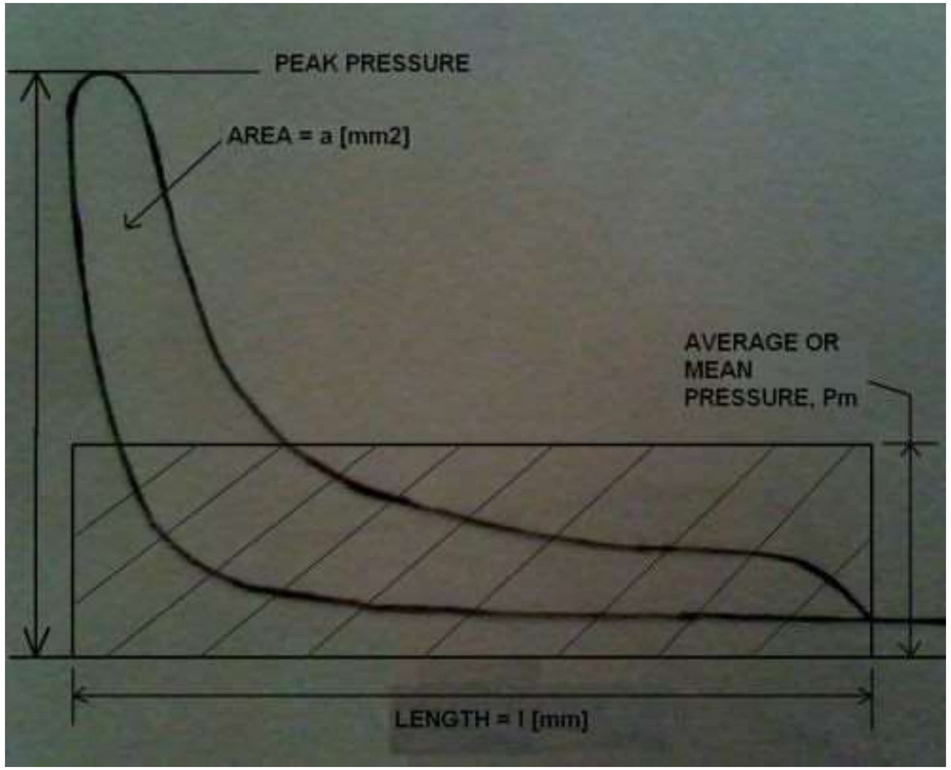
Performance Parameters

- **Mean Effective Pressure (MEP) - P_m**

It is expressed in Bar (1Bar = 10^5 N/m^2)

$$MEP = P_m = \frac{\left(\begin{array}{c}\text{spring value of the spring used}\\ \text{in the indicator }(S)\text{ in bar / m}\end{array}\right) \times \left(\begin{array}{c}\text{net area of the indicator}\\ \text{diagram }(a)\text{ in } m^2\end{array}\right)}{\text{length of the indicator diagram }(l)\text{ in m}}$$

$$P_m = \frac{Sa}{l} \text{ Bar}$$



Performance Parameters

Indicated Power (IP)

$$\text{Indicated Power} = \frac{p_m L A N}{60 \times 2 \times 1000} \text{ kW}$$

p_m	=	Mean Effective Pressure, N/m^2
L	=	Length of Stroke, m
A	=	Area of Cross section of the Cylinder, sq m
N	=	RPM of the Crankshaft.
n	=	Number of cycles per minute.

Brake Power (BP)

BP is given by, $$BP = \frac{2\pi NT}{60\times1000} kW$$

where N = speed of engine in *rpm*

T = Torque in *N-m*

Torque (T) is measured by using either *belt* or *rope brake dynamometer.*

Friction Power (FP)

$$FP = IP - BP \text{ kW}$$

Performance Parameters

Mechanical Efficiency

$$\eta_{mech} = (BP/IP) \times 100$$

Thermal Efficiency

$$\eta_{th} = \frac{\text{power output}}{\text{heat supplied}} \times 100$$

w.k.t. Heat supplied $= (m_f) \times CV$

where m_f = mass of fuel in kg/sec.

CV = calorific value of fuel in kJ/kg.

Indicated thermal effiiciency $= \eta_{ITH} = \frac{IP}{m_f \times CV} \times 100$

Brake thermal efficiency $= \eta_{BTH} = \frac{BP}{m_f \times CV} \times 100$

Performance Parameters

Specific Fuel Consumption

$$\text{i.e., SFC} = \frac{m_f(kg/hr)}{Power\ developed\ (kW)} \quad kg/kW\text{-}hr$$

where m_f = mass of fuel (kg/hr)

Power developed can be based on IP or BP.

SFC based on IP is termed indicated specific fuel consumption (ISFC), and is given by the equation

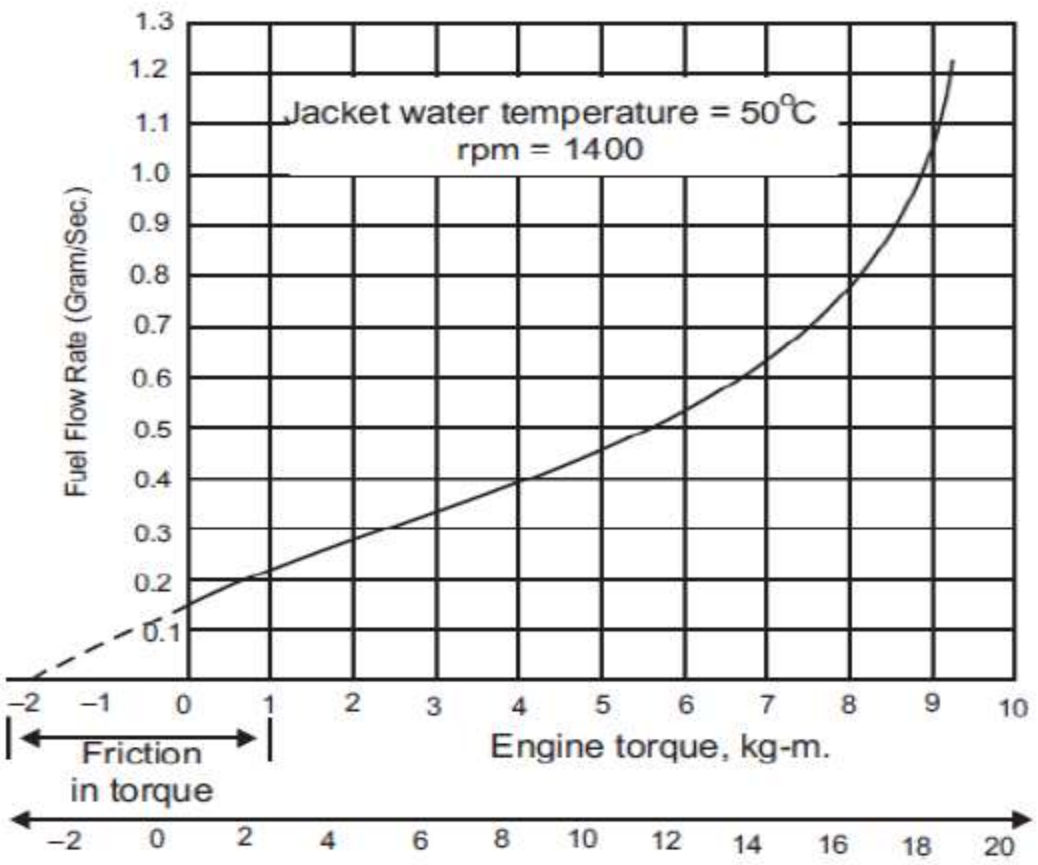
$$\text{ISFC} = \frac{Fuel\ consumed\ in\ kg/hr}{IP\ in\ kW} \quad kg/kWhr$$

While SFC based on BP is termed brake specific fuel consumption (BSFC), and is given by the equation

$$\text{BSFC} = \frac{Fuel\ consumed\ in\ kg/hr}{BP\ in\ kW} \quad kg/kWhr$$

Measurement of Friction power

- *Willan's line method.*
- *•Morse test.*
- *•Motoring test.*



Morse test.

- The Morse test is applicable only to multicylinder engines.

- With all cylinder firing = BP kW
- Cut off at 1st cylinder = BP1 kW
- Cut off at 2nd cylinder = BP2 kW
- Cut off at 3rd cylinder = BP3 Kw

IP1 = BP-BP1, IP3 = BP-BP3

$$IP = IP_1 + IP_2 + IP_3$$

Heat Balance sheet

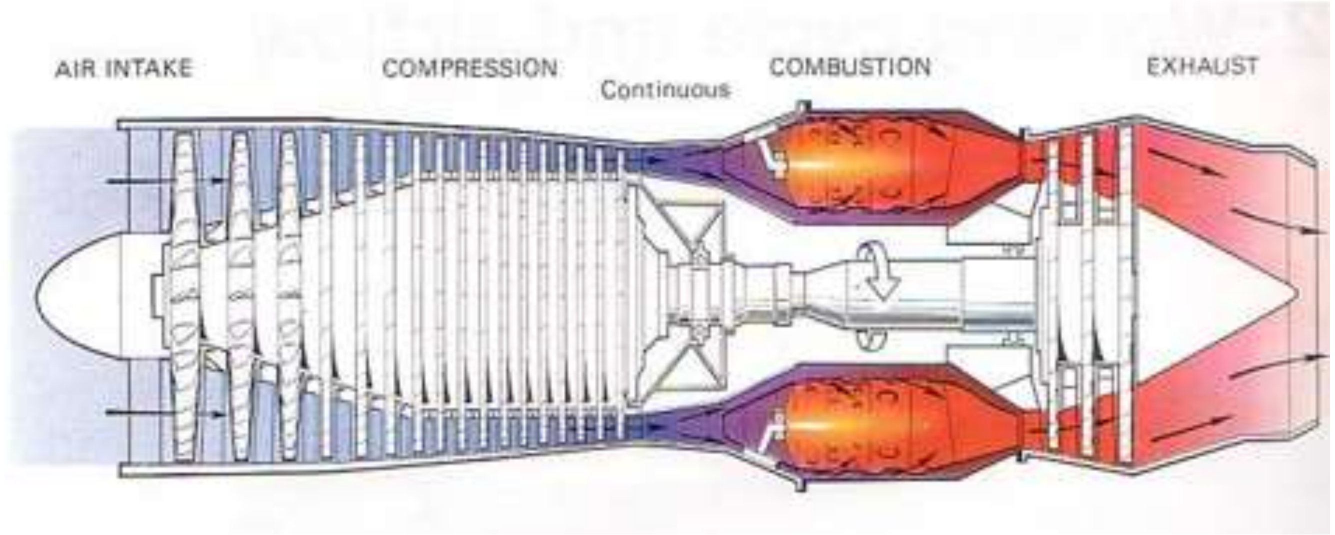
- The heat balance sheet from the above data can be drawn as follows:

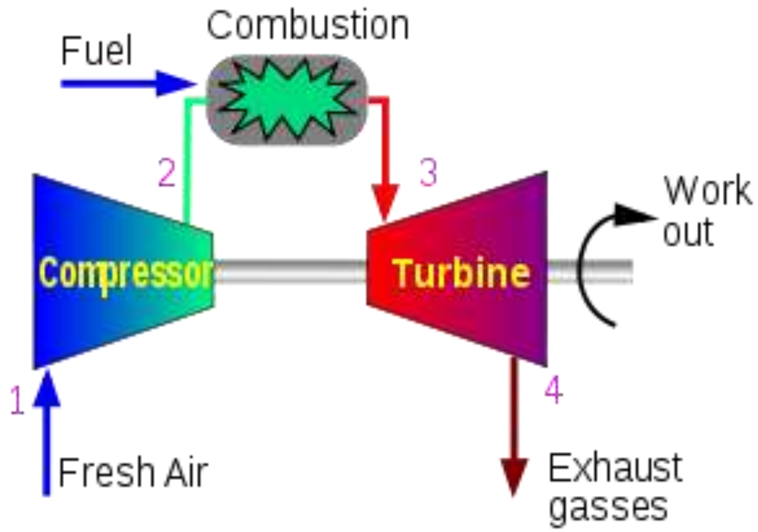
Particulars	*kJ/s or kJ/min or kJ/hr*	*Percent*
a) Heat supplied by fuel	**----**	**------**
b) Heat absorbed in B.P. **c) Heat taken away by cooling water** **d) Heat carried away by the exhaust gases** **e) Heat unaccounted for (a-(b+c+d))**	**----** **----** **----** **----**	**------** **------** **------** **------**
Total	**----**	**------**

Module – 2: Gas Power Cycles

- **Gas-Turbine**
  - Open cycle gas turbine
  - Closed cycle gas turbine
- **Brayton Cycle**
- **Methods to improve Thermal Efficiency of Gas Turbine-**
  Intercooling, Reheat & Regeneration
- **Jet Propulsion System**

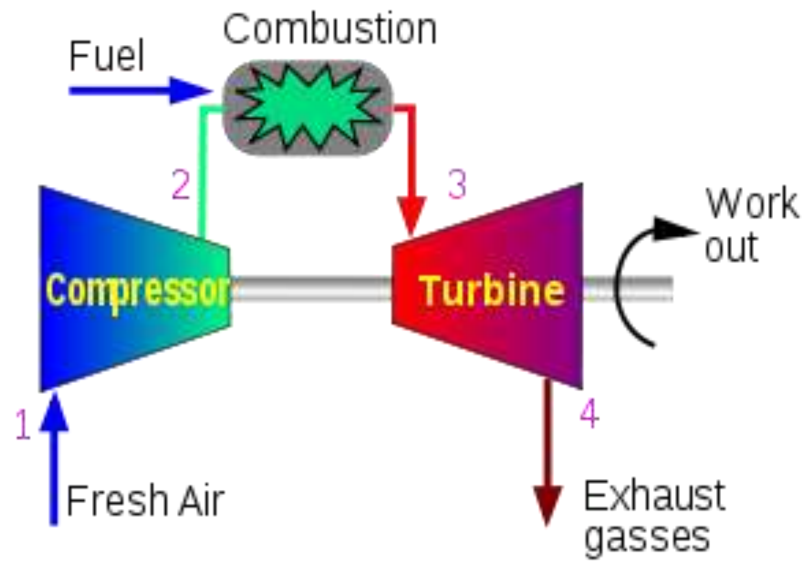
Gas-Turbine


AIR INTAKE
COMPRESSION
Continuous
COMBUSTION
EXHAUST

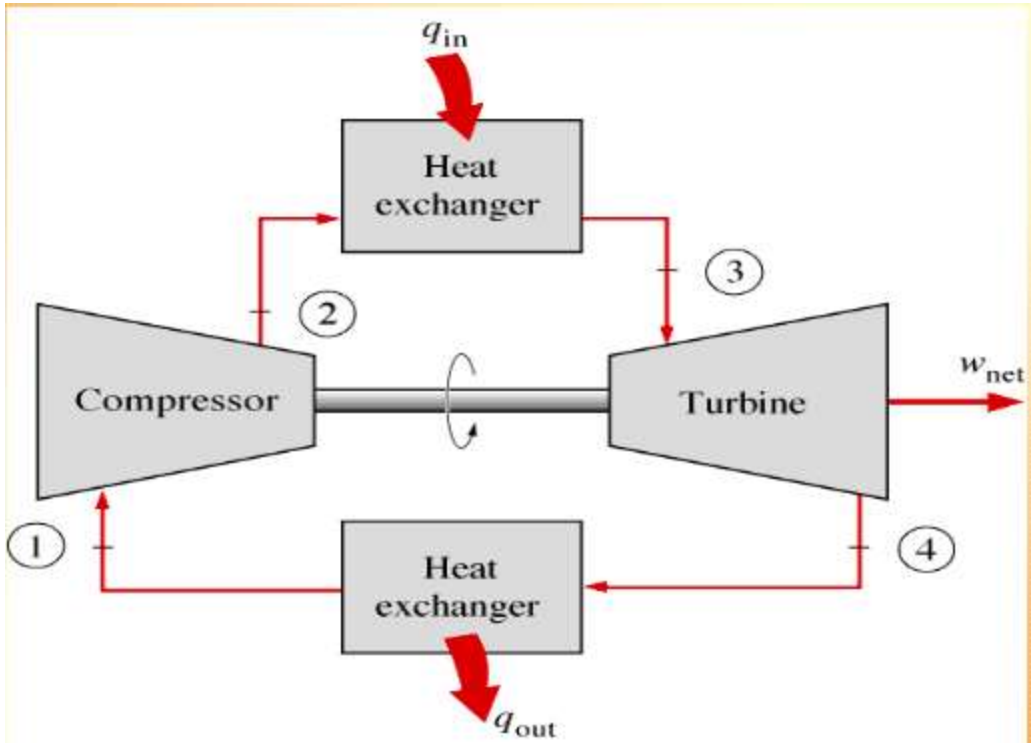

Fuel
Combustion
2
3
Compressor
Turbine
Work out
1
4
Fresh Air
Exhaust gasses

Classification of Gas-Turbine

- Open cycle gas turbine



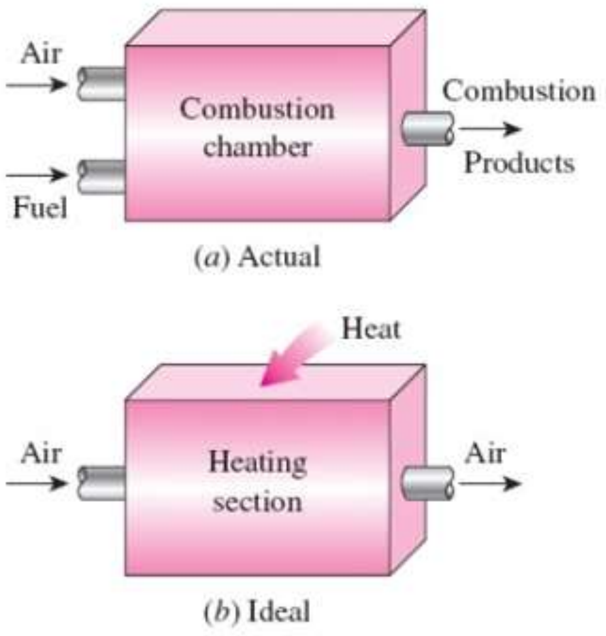
- Closed cycle gas turbine



Comparison between Open cycle gas turbine and Closed cycle gas turbine

Closed Cycle Gas Turbine	Open Cycle Gas Turbine
1. The compressed air is heated in heating chamber.	1. The compressed air is heated in combustion chamber.
2. As the gas is heated by an external source, hence the amount of gas remains same thought the cycle	2. The products of combustion are get mixed up in the heated air hence same gas doesn't remain in cycle.
3. The gas after turbine is passed into the cooling chamber.	3. The gas after turbine is exhausted into the atmosphere.
4. The working fluid is circulated continuously.	4.The working fluid is replaced continuously.
5. Any fluid with better thermodynamic properties can be used.	5. Only air is used as the working fluid.
6. The turbine blades do not wear away earlier, as the enclosed gas does not get contaminated while flowing through heating chamber.	6. The turbine blades wear away earlier, as the air from atmosphere get contaminated while flowing through combustion chamber.
7.The mass of installation per Kwatt is more	7.The mass of installation per Kwatt is less
8. High maintenance cost	8. Maintenance cost is low

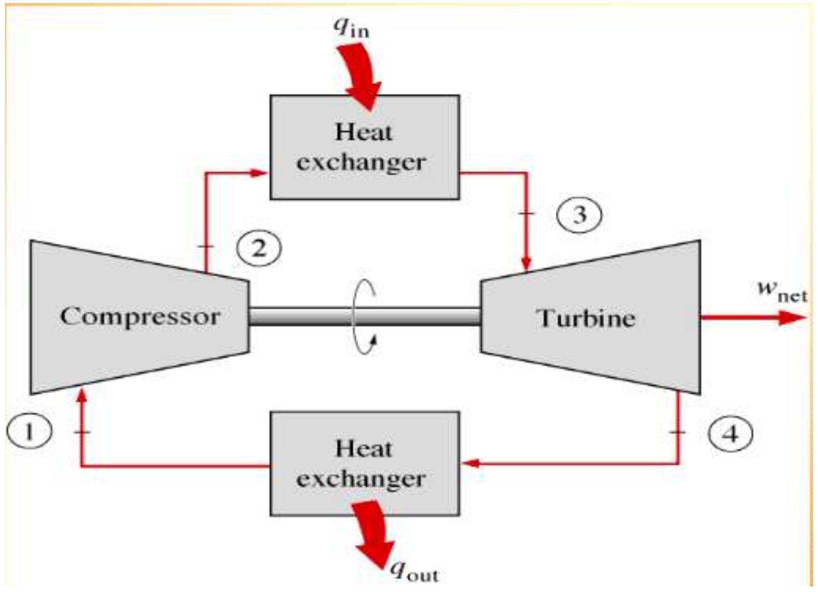
Analysis of Brayton Cycle



The combustion process is replaced by a heat-addition process in ideal cycles.

Air-standard assumptions:

1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
2. All the processes that make up the cycle are internally reversible.
3. The combustion process is replaced by a heat-addition process from an external source.
4. The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.



Analysis of Brayton Cycle

Efficiency of Brayton cycle

1-2 Isentropic Compression (compressor)

$$W_C = C_P (T_2 - T_1)$$

2-3 Constant-pressure heat addition

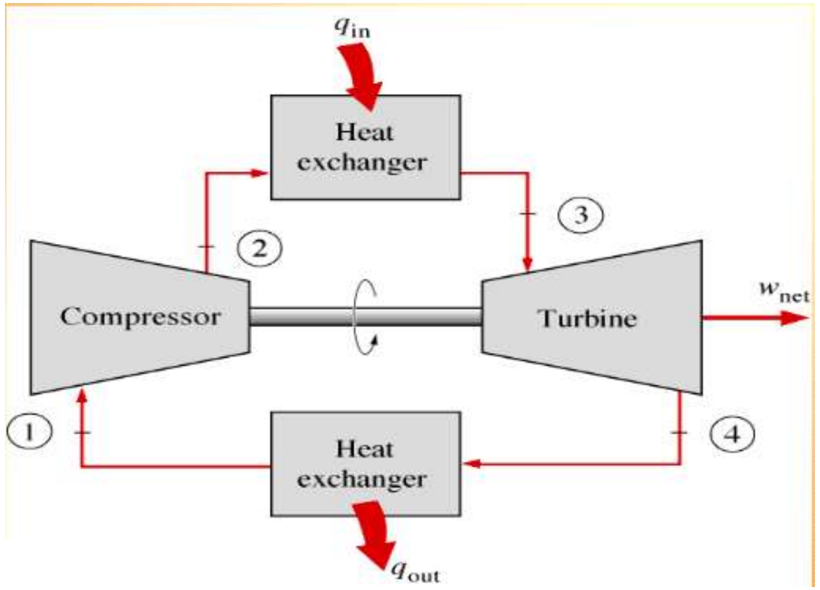
$$Q_S = C_P (T_3 - T_2)$$

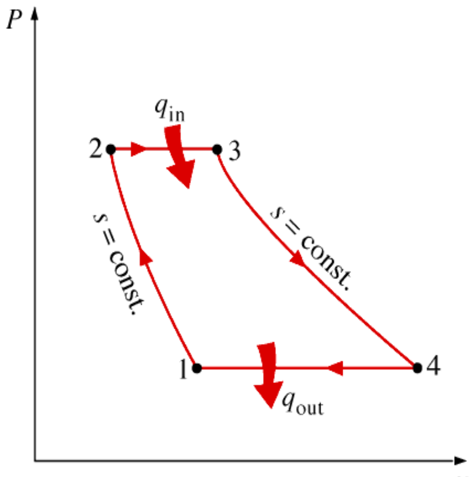
3-4 Isentropic expansion (turbine)

$$W_T = C_P (T_3 - T_4)$$

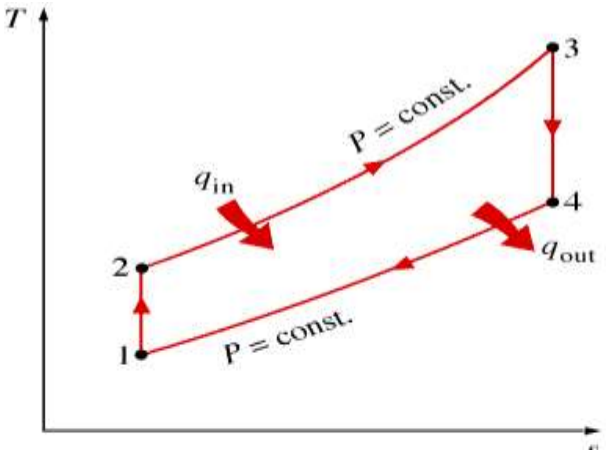
4-1 Constant-pressure heat rejection

$$Q_r = C_P (T_4 - T_1)$$





(b) P- υdiagram



(a) T-s diagram

Analysis of Brayton Cycle

Efficiency of Brayton cycle

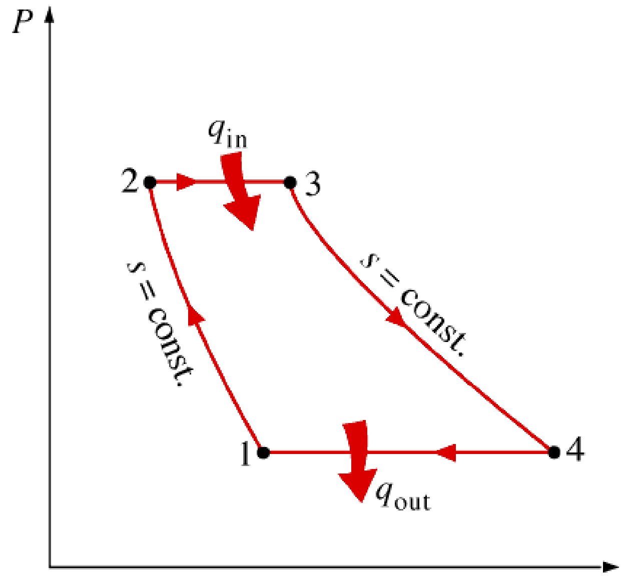
$$\text{efficiency} \ \eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{W_T - W_C}{Q_S}$$

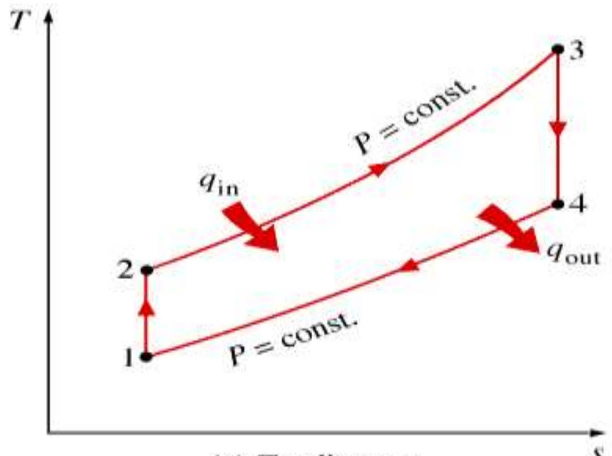
$$= \frac{C_P(T_3 - T_4) - C_P(T_2 - T_1)}{C_P(T_3 - T_2)}$$

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

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



(b) *P*- υdiagram



(a) *T*-*s* diagram

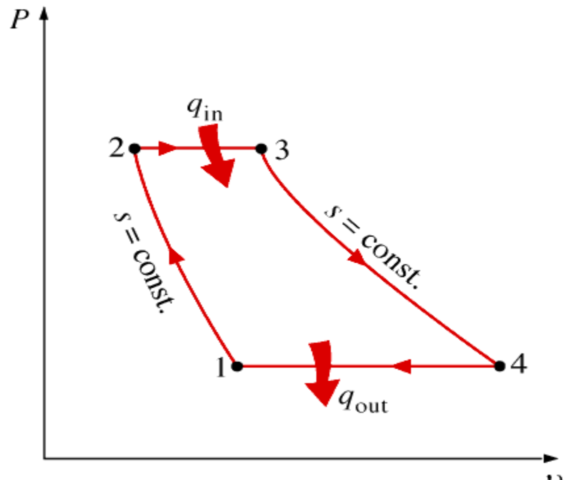
Analysis of Brayton Cycle

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

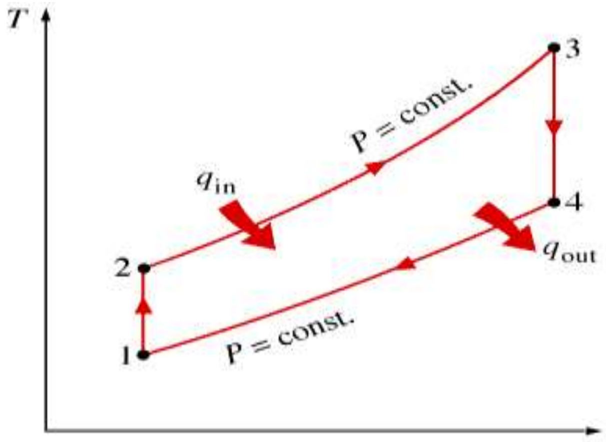
For isentropic (adiabatic) process 1-2,

we have $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

Let $\frac{P_2}{P_1} = R_p$ pressure ratio



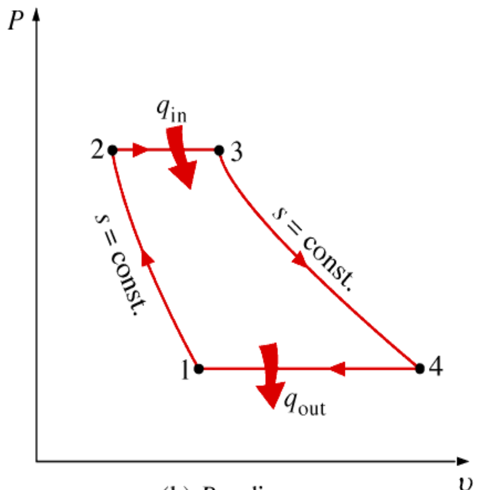
(b) P- υdiagram



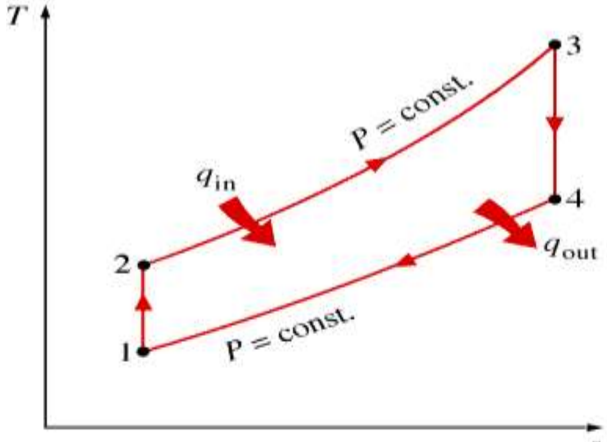
(a) T-s diagram

Analysis of Brayton Cycle

for isentropic process 3-4, we have $\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$



(b) P- υdiagram



(a) T-s diagram

But $P_3 = P_2$ and $P_4 = P_1$

$$\therefore \frac{T_3}{T_4} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{or} \quad \frac{T_3}{T_4} = (R_P)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore T_3 = T_4 (R_P)^{\frac{\gamma-1}{\gamma}}$$

Analysis of Brayton Cycle

Efficiency of Brayton cycle

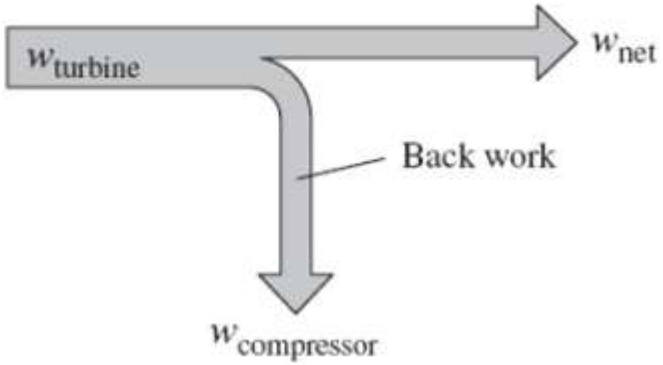
$$\eta = 1 - \frac{(T_4 - T_1)}{T_4 (R_P)^{\frac{\gamma-1}{\gamma}} - T_1 (R_P)^{\frac{\gamma-1}{\gamma}}}$$

$$= 1 - \frac{(T_4 - T_1)}{(T_4 - T_1)(R_P)^{\frac{\gamma-1}{\gamma}}}$$

$$\eta = 1 - \frac{1}{(R_P)^{\frac{\gamma-1}{\gamma}}}$$

Analysis of Brayton Cycle

Work Ratio:



$$\text{i.e., Work ratio} = R_w = \frac{W_{net}}{W_T}$$

$$= \frac{W_T - W_C}{W_T} = 1 - \frac{W_C}{W_T} \quad \text{-----(1)}$$

where, compressor work $W_C = C_P (T_2 - T_1)$ kJ/kg of air

Turbine work $W_T = C_P (T_3 - T_4)$ kJ/kg of air

Work Ratio:

$$\therefore\ R_w = 1 - \frac{C_P(T_2 - T_1)}{C_P(T_3 - T_4)}$$

$$= 1 - \frac{(T_2 - T_1)}{(T_3 - T_4)} = 1 - \frac{T_1}{T_3}\frac{\left(\frac{T_2}{T_1} - 1\right)}{\left(1 - \frac{T_4}{T_3}\right)} \qquad \text{-----(2)}$$

For isentropic (adiabatic) process 1-2, we have $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

But $\frac{P_2}{P_1} = R_p$ pressure ratio

$$\therefore \frac{T_2}{T_1} = (R_P)^{\frac{\gamma-1}{\gamma}} \quad \text{-----(3)}$$

Similarly for isentropic (adiabatic) process 3-4, we have $\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$

But $P_3 = P_2$ and $P_4 = P_1$

$$\therefore \frac{T_3}{T_4} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

or $\frac{T_3}{T_4} = (R_P)^{\frac{\gamma-1}{\gamma}}$

$$\therefore \frac{T_4}{T_3} = \frac{1}{(R_P)^{\frac{\gamma-1}{\gamma}}} \qquad \text{-----(4)}$$

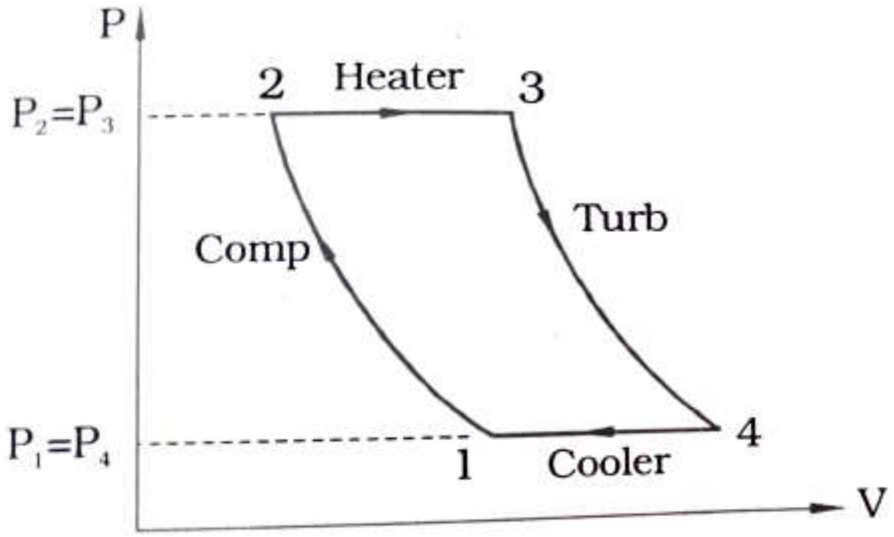
Substituting equations (3) and (4) in (2), we get

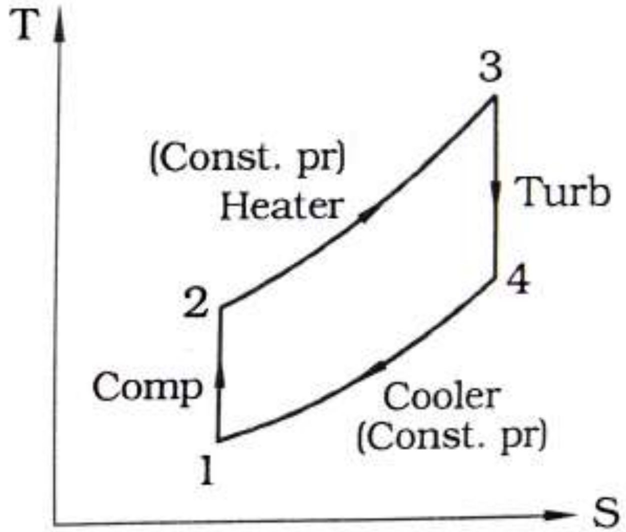
$$R_w = 1 - \frac{T_1}{T_3}\frac{\left[(R_P)^{\frac{\gamma-1}{\gamma}} - 1\right]}{\left[1 - \frac{1}{(R_P)^{\frac{\gamma-1}{\gamma}}}\right]} = 1 - \frac{T_1}{T_3}\frac{\left[(R_P)^{\frac{\gamma-1}{\gamma}} - 1\right]}{\left[(R_P)^{\frac{\gamma-1}{\gamma}} - 1\right]}.(R_P)^{\frac{\gamma-1}{\gamma}}$$

$$R_w = 1 - \frac{T_1}{T_3}(R_P)^{\frac{\gamma-1}{\gamma}}$$

Expression for optimum pressure ratio for maximum net work output

The optimum pressure ratio for maximum net work output is obtained by using the condition $\frac{dW_{net}}{dR_P} = 0$





Expression for optimum pressure ratio for maximum net work output

To find net work done (W_{net})

w.k.t. net work done = $W_{net} = W_T - W_C$

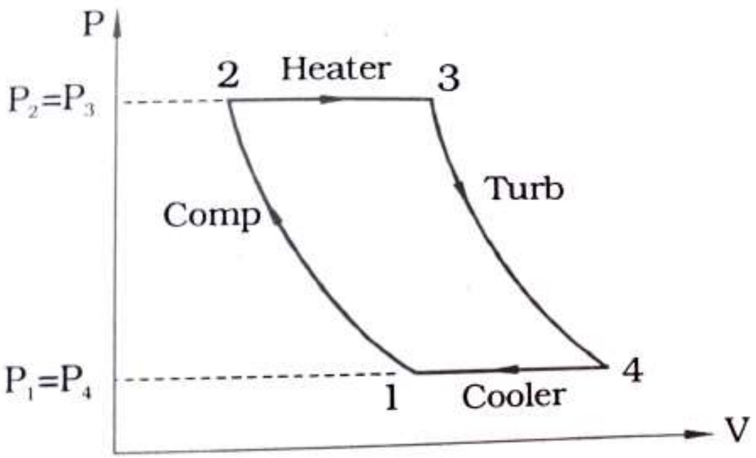
$$= C_P (T_3 - T_4) - C_P (T_2 - T_1) \quad \text{-----(1)}$$

For isentropic (adiabatic) process 1-2, we have, $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

w.k.t. $\frac{P_2}{P_1} = R_P$ pressure ratio

$$\therefore \quad T_2 = T_1 (R_P)^{\frac{\gamma-1}{\gamma}} \quad \text{-----(2)}$$

Also, for isentropic process 3-4, we have $\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$

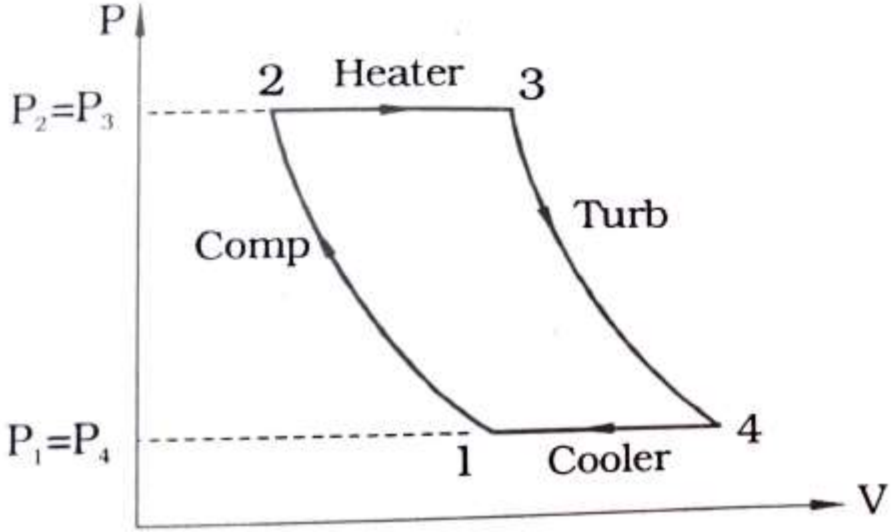


Expression for optimum pressure ratio for maximum net work output

But from p-v diagram, $P_3 = P_2$ and $P_1 = P_4$

$$\therefore \frac{T_3}{T_4} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{or} \quad \frac{T_3}{T_4} = (R_P)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore T_4 = \frac{T_3}{(R_P)^{\frac{\gamma-1}{\gamma}}} \quad \text{----} \ (3)$$



Substituting equations (2) and (3) in (1), we get

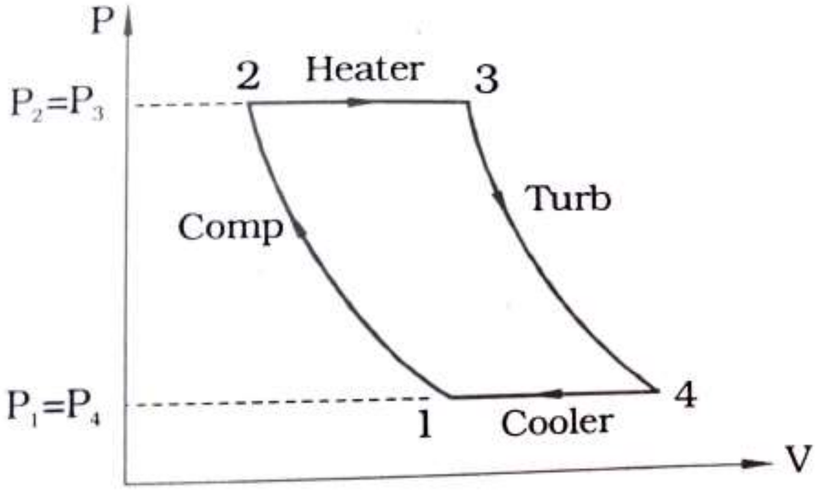
$$W_{net} = C_P\left[T_3 - \frac{T_3}{(R_P)^{\frac{\gamma-1}{\gamma}}}\right] - C_P\left[T_1(R_P)^{\frac{\gamma-1}{\gamma}} - T_1\right]$$

Expression for optimum pressure ratio for maximum net work output

$$= C_P T_3 \left[1 - \frac{1}{(R_P)^{\frac{\gamma-1}{\gamma}}}\right] - C_P T_1 \left[(R_P)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

For simplicity, let $\frac{\gamma - 1}{\gamma} = y$

$$\therefore W_{net} = C_P . T_3 \left[1 - \frac{1}{(R_P)^y}\right] - C_P T_1 \left[(R_P)^y - 1\right] \quad \text{-----(4)}$$



For optimum condition, we have $\frac{dW_{net}}{dR_P} = 0$

$$\therefore \frac{dW_{net}}{dR_P} = C_P . T_3 \left[\frac{(y . R_p^{y-1})}{(R_p^y)^2}\right] - C_P T_1 \left[y . R_p^{y-1}\right] = 0$$

Expression for optimum pressure ratio for maximum net work output

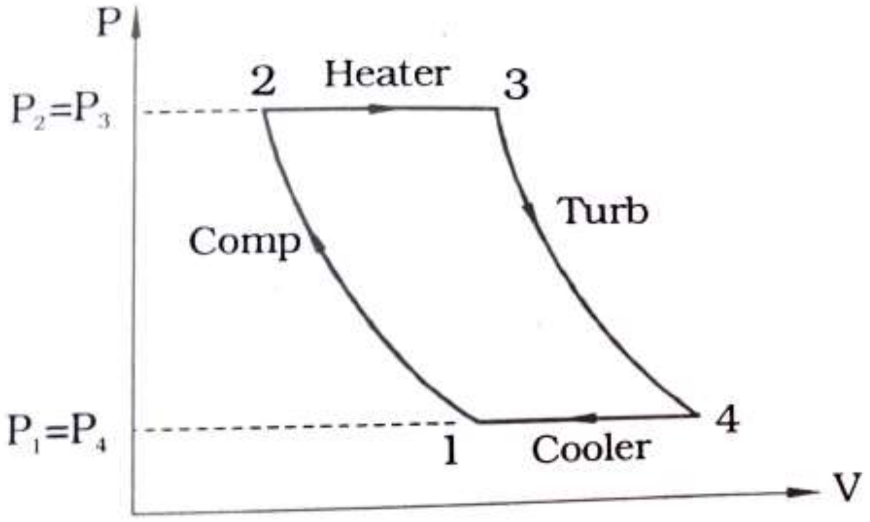
$$\text{or}\quad T_3\left[\frac{1}{(R_p)^{2y}}\right]-T_1=0$$

$$\frac{T_3}{(R_p)^{2y}}=T_1$$

$$\text{or}\quad \frac{T_3}{T_1}=(R_p)^{2y}$$

$$\therefore\ R_p=\left(\frac{T_3}{T_1}\right)^{\frac{1}{2y}}\qquad \text{where}\ \ y=\frac{\gamma-1}{\gamma}$$

$$\text{Thus}\quad (R_p)=(R_p)_{opt}=\left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$$



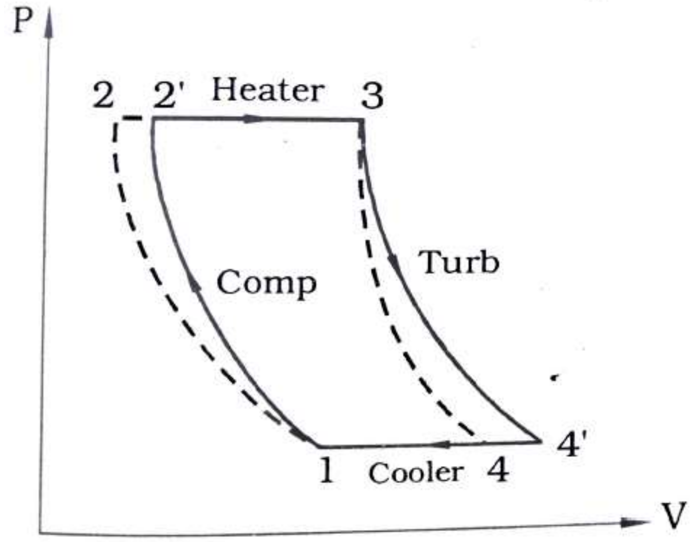
Deviation of Actual Gas-Turbine Cycle From Ideal Brayton cycle

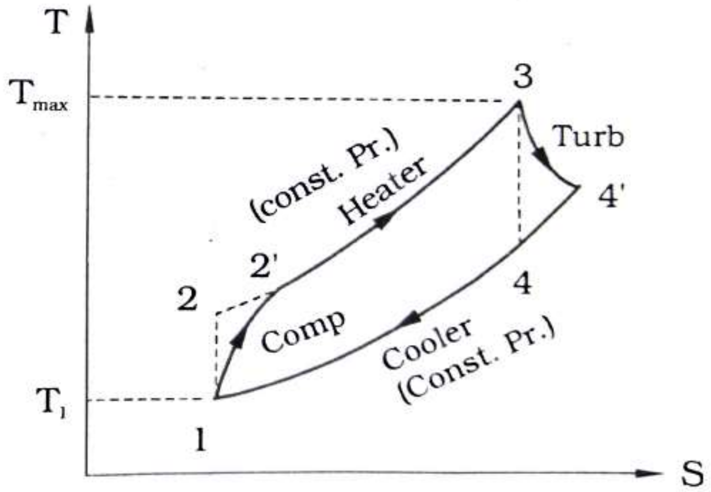
Turbine efficiency = $\dfrac{\textit{Actual workdone by the turbine}}{\textit{Isentropic workdone by the turbine}}$

$$\text{turbine efficiency} \quad \eta_T = \frac{(T_3 - T_{4'})}{(T_3 - T_4)}$$

Compressor efficiency = $\dfrac{\textit{Isentropic workdone to the compressor}}{\textit{Actual workdone to th compressor}}$

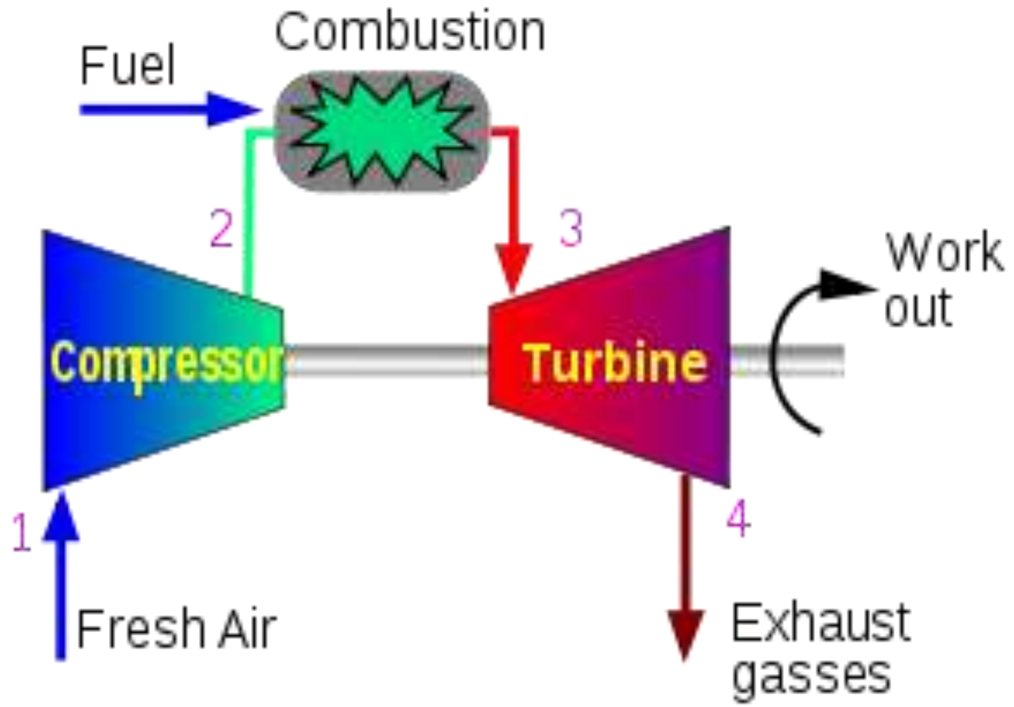
$$\text{compressor efficiency} \quad \eta_C = \frac{(T_2 - T_1)}{(T_{2'} - T_1)}$$



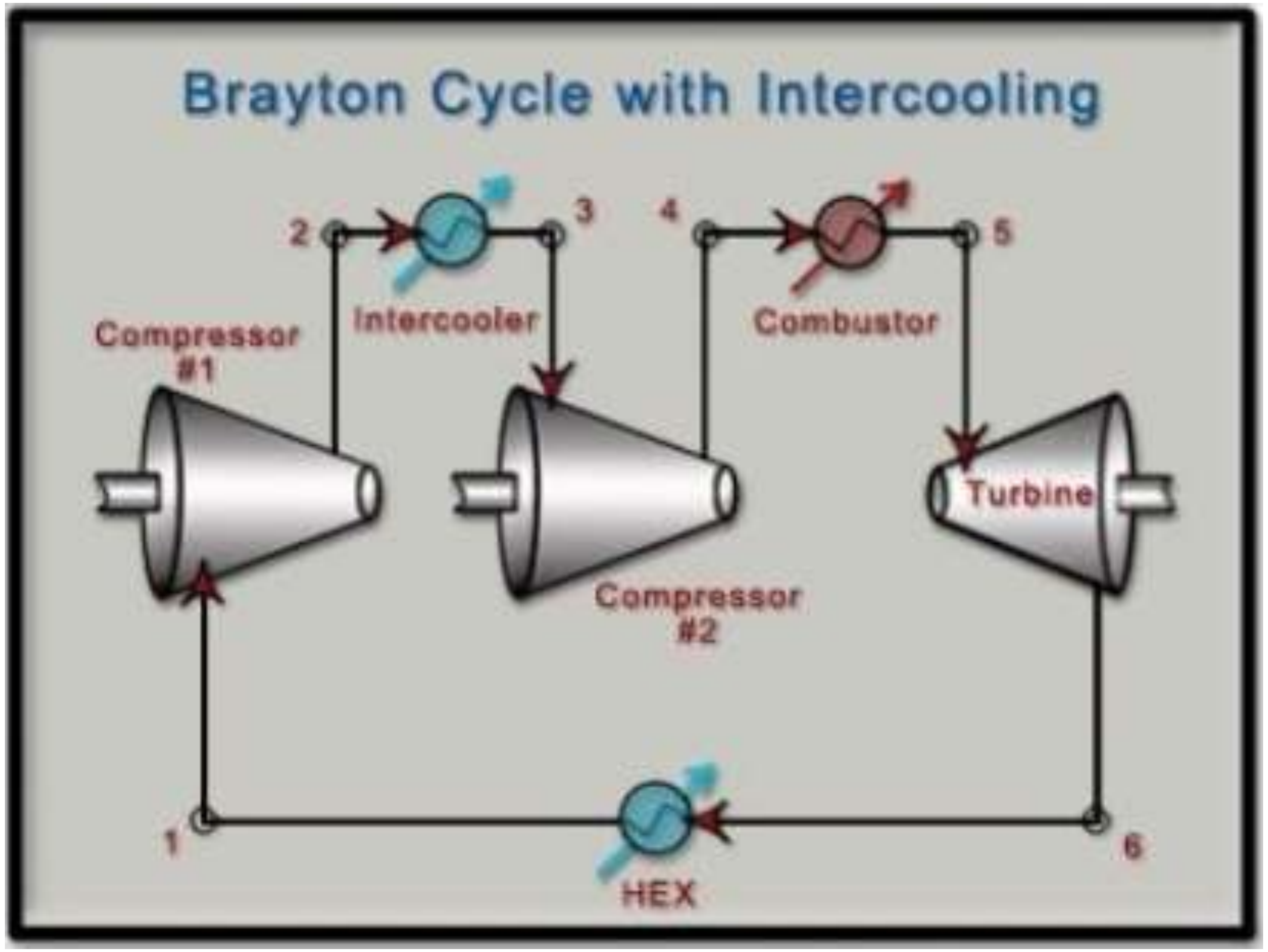


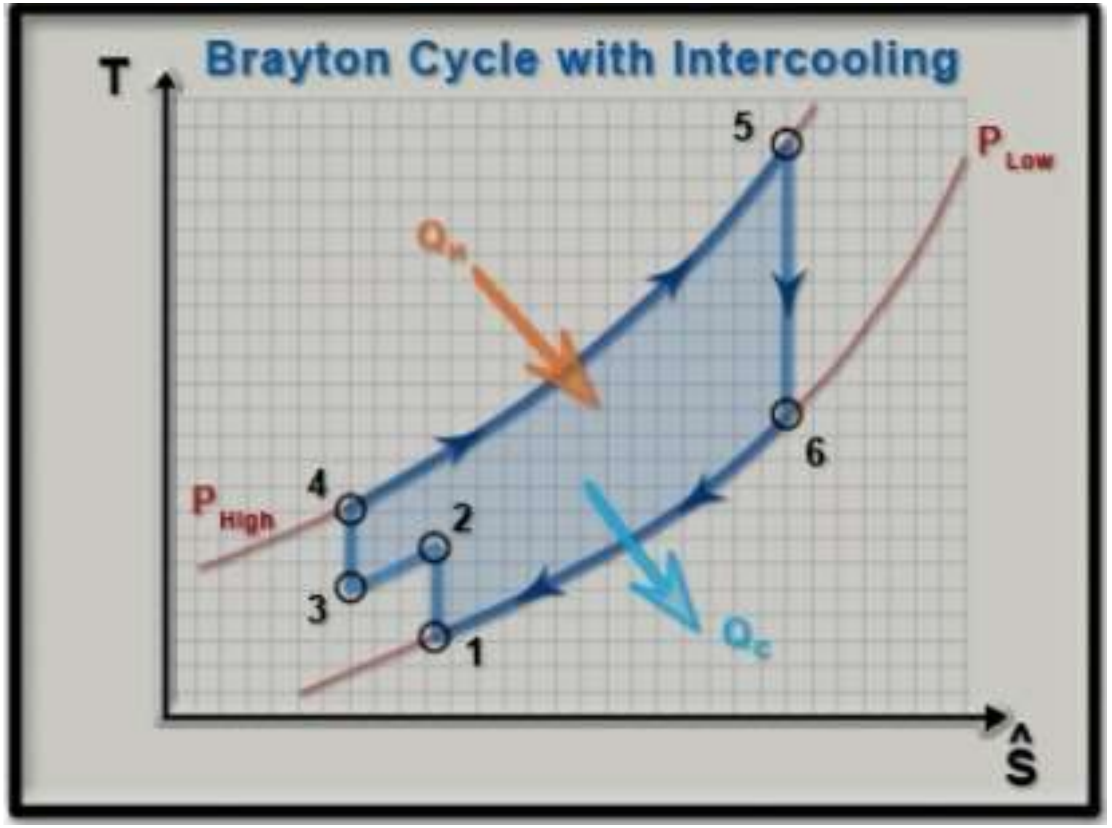
Methods to improve the performance of Gas Turbine

- ➢Intercooling
- ➢Reheating
- ➢Regeneration

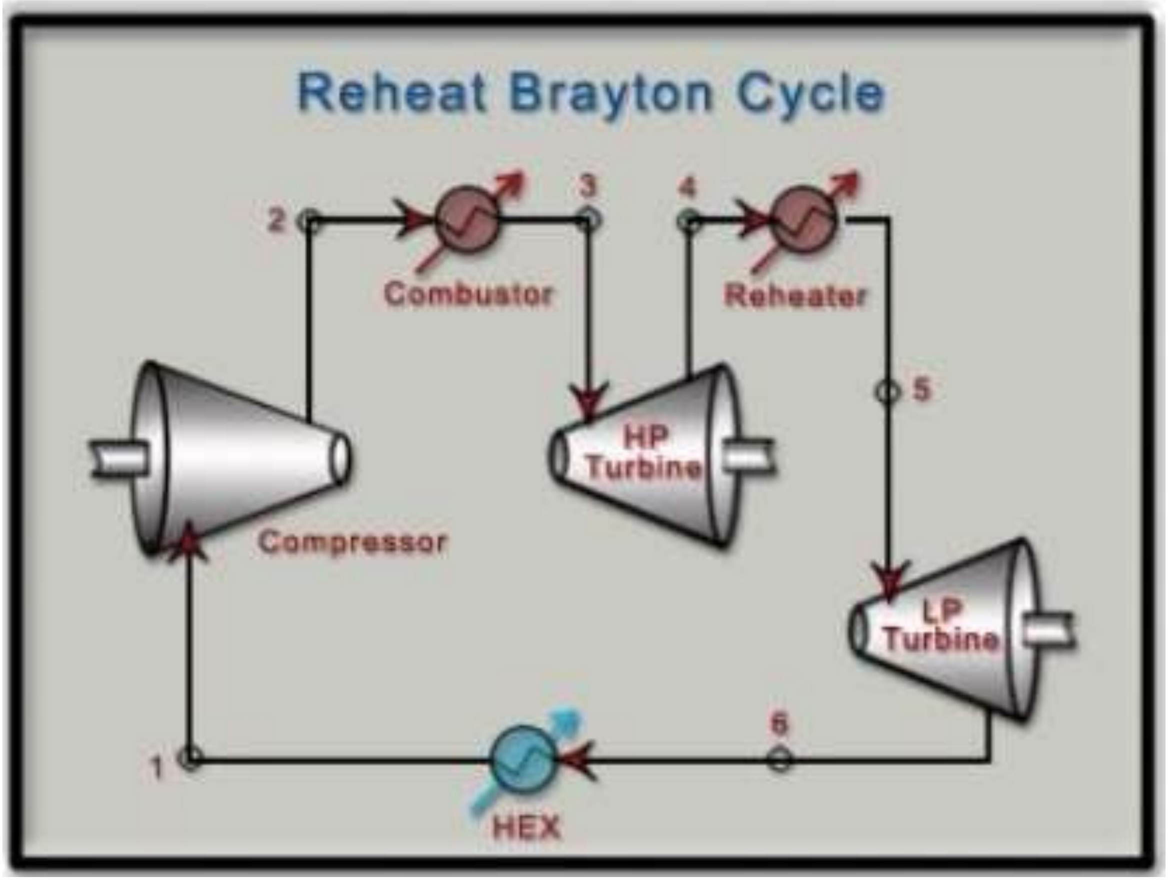


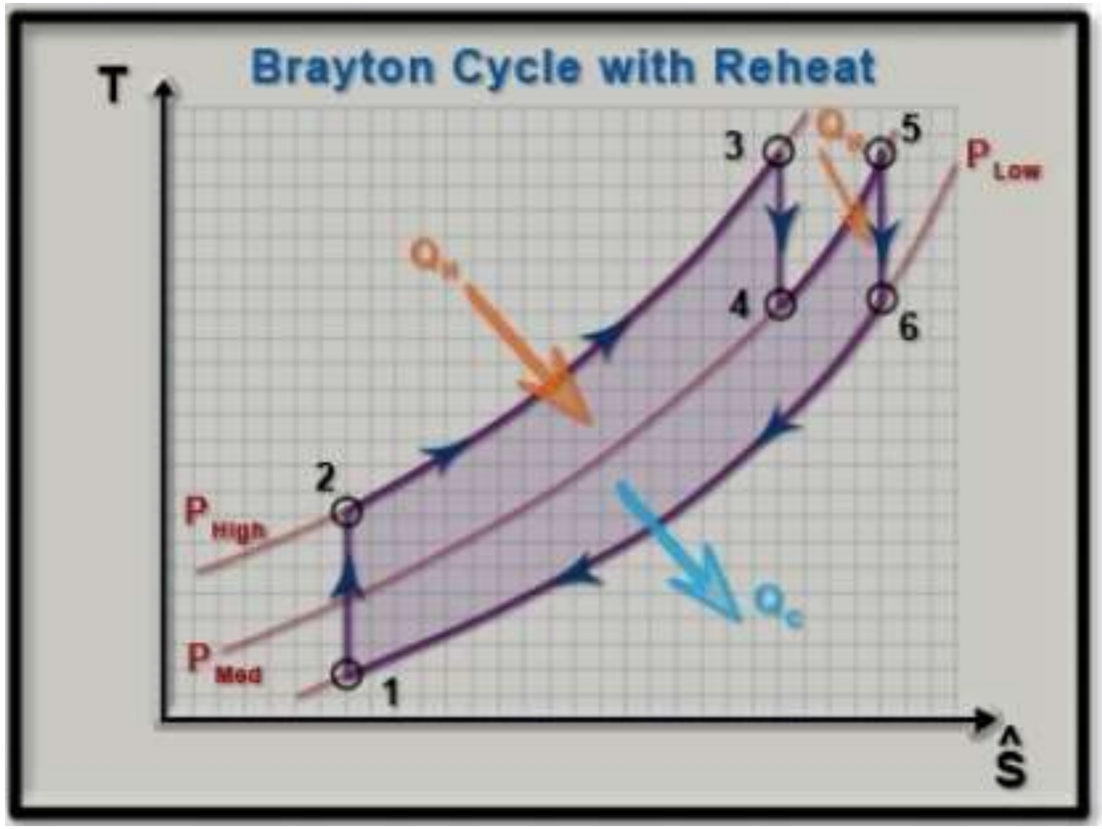
Brayton cycle with Intercooling





Brayton cycle with Reheating





Brayton cycle with Regeneration

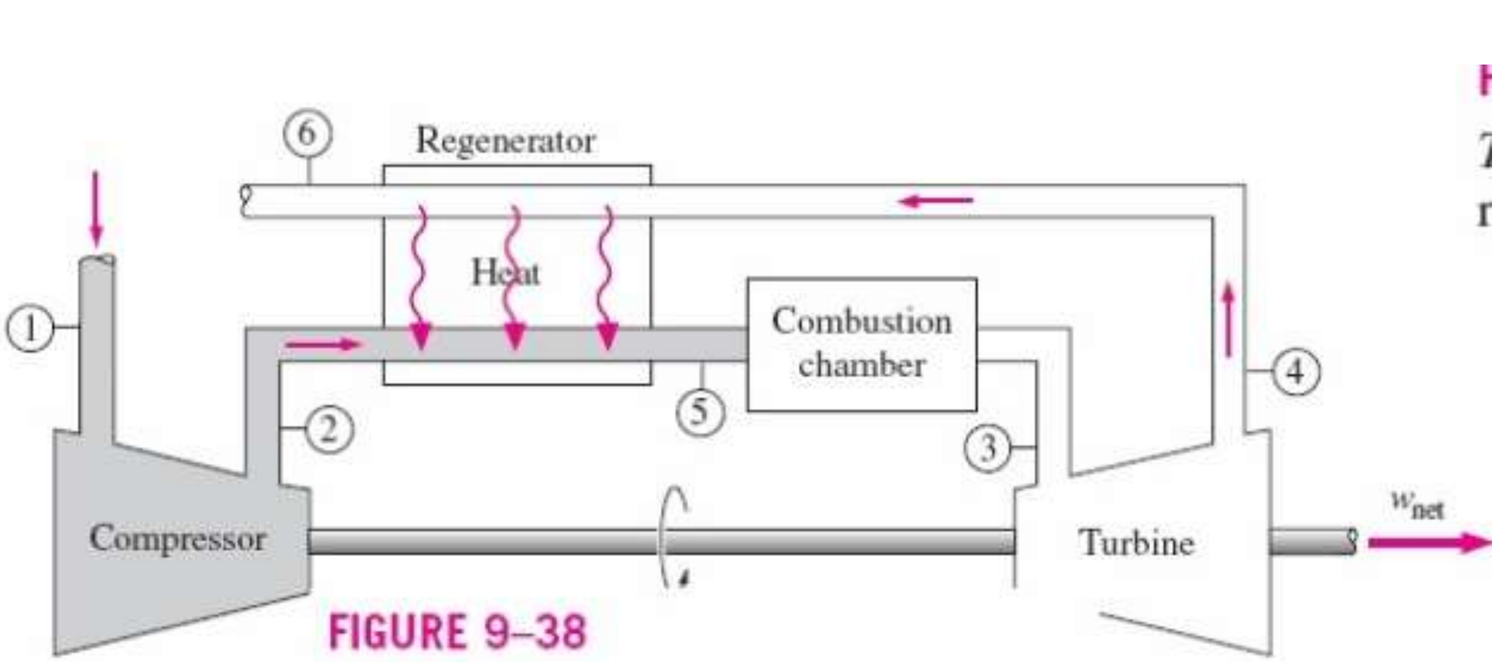
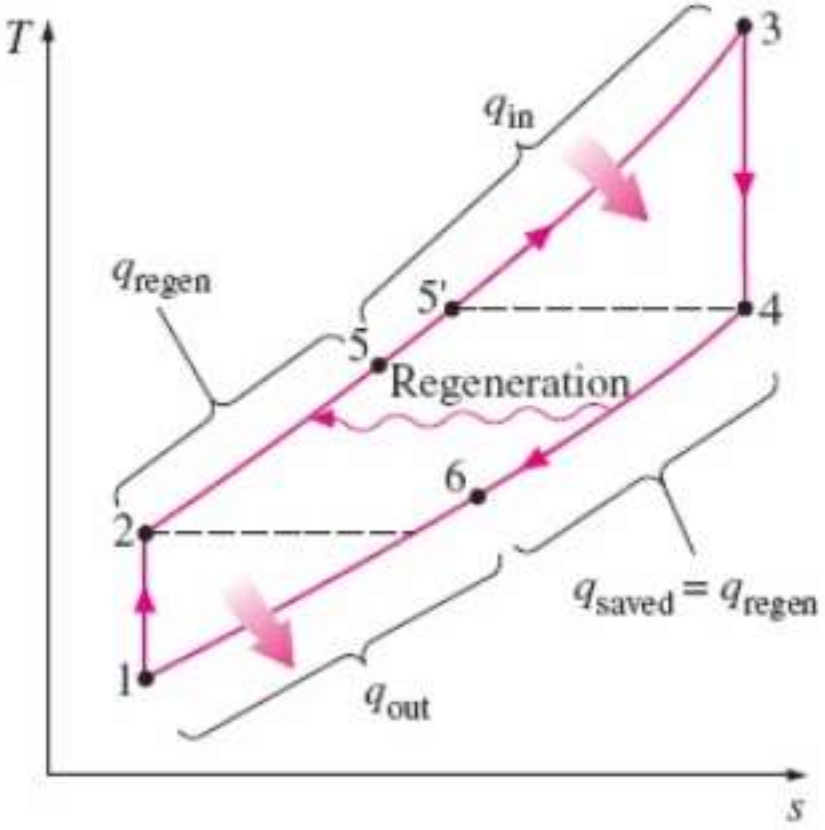


FIGURE 9–38

A gas-turbine engine with regenerator.



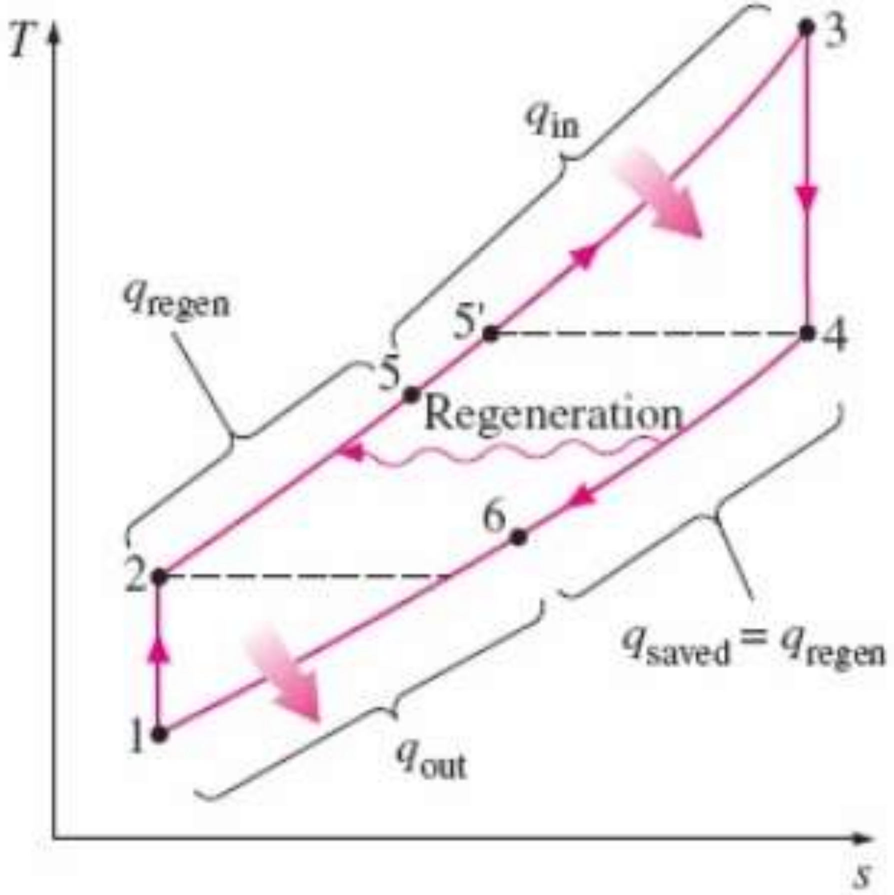
Brayton cycle with Regeneration

Effectiveness of regenerator:

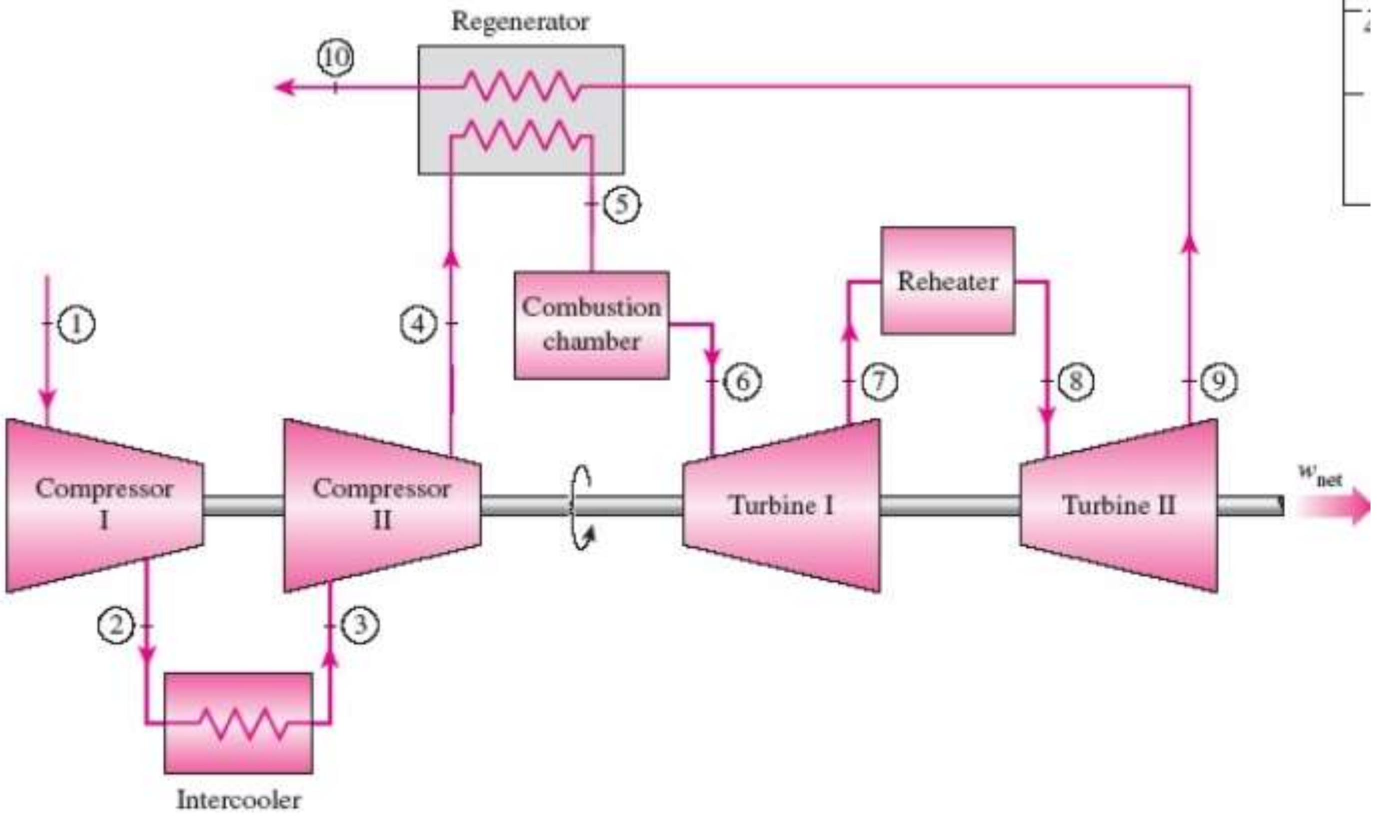
$$q_{regen,act} = h_5 - h_2$$

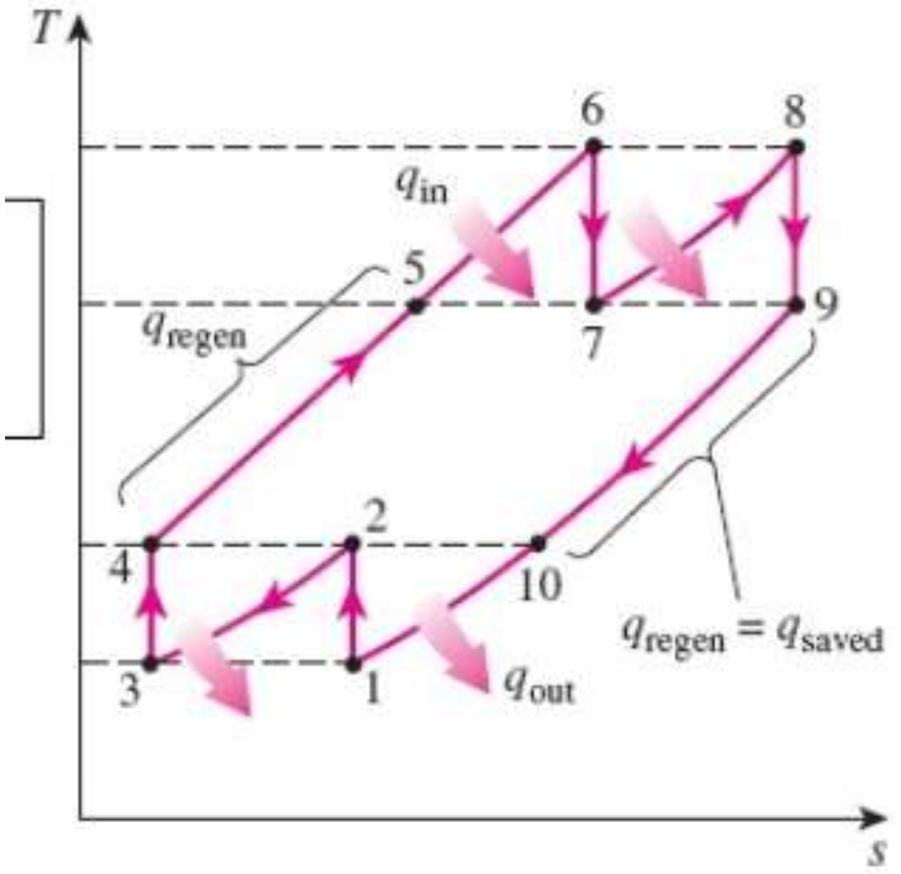
$$q_{regen,max} = h_{5'} - h_2 = h_4 - h_2$$

$$\varepsilon = \frac{q_{regen,act}}{q_{regen,max}} = \frac{h_5 - h_2}{h_4 - h_2} \cong \frac{T_5 - T_2}{T_4 - T_2}$$



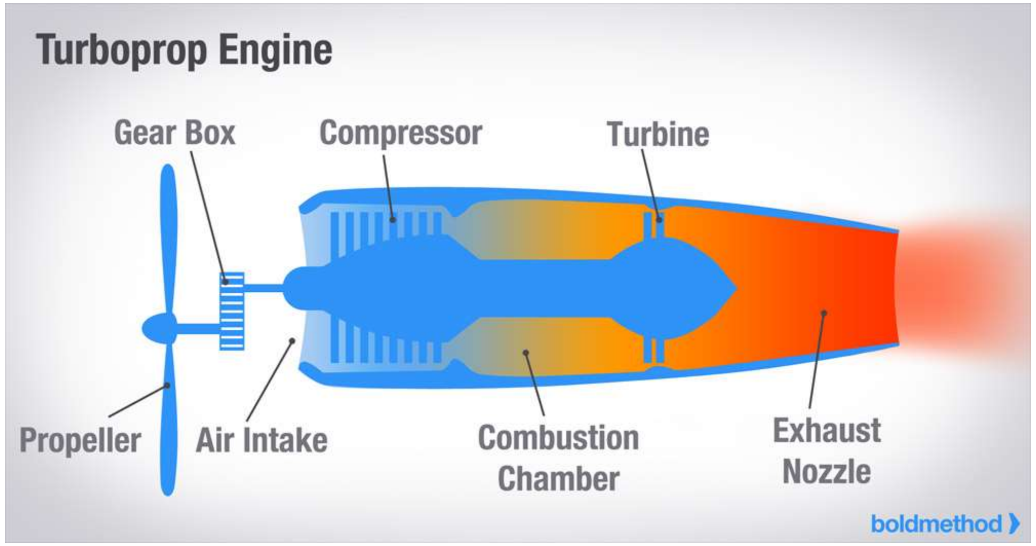
Brayton cycle with Intercooling, Reheating and Regeneration

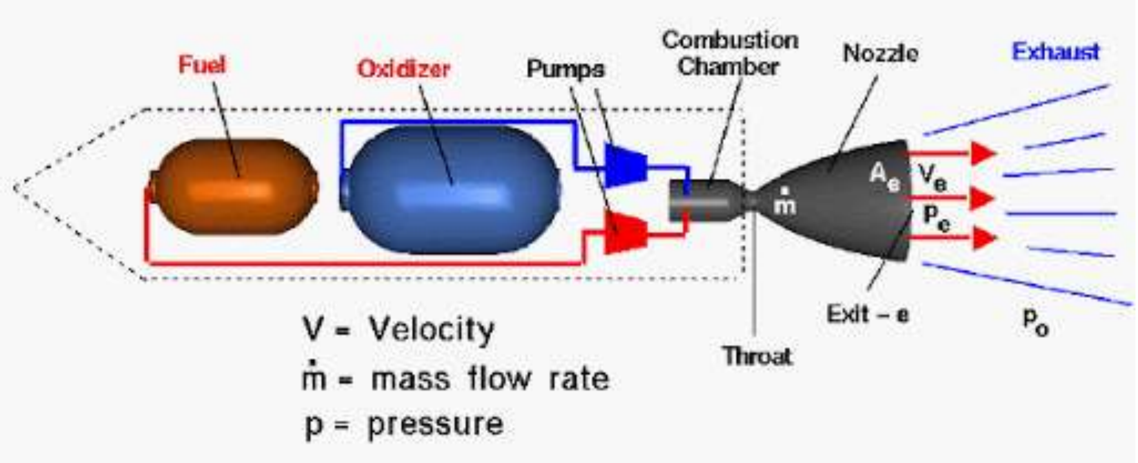




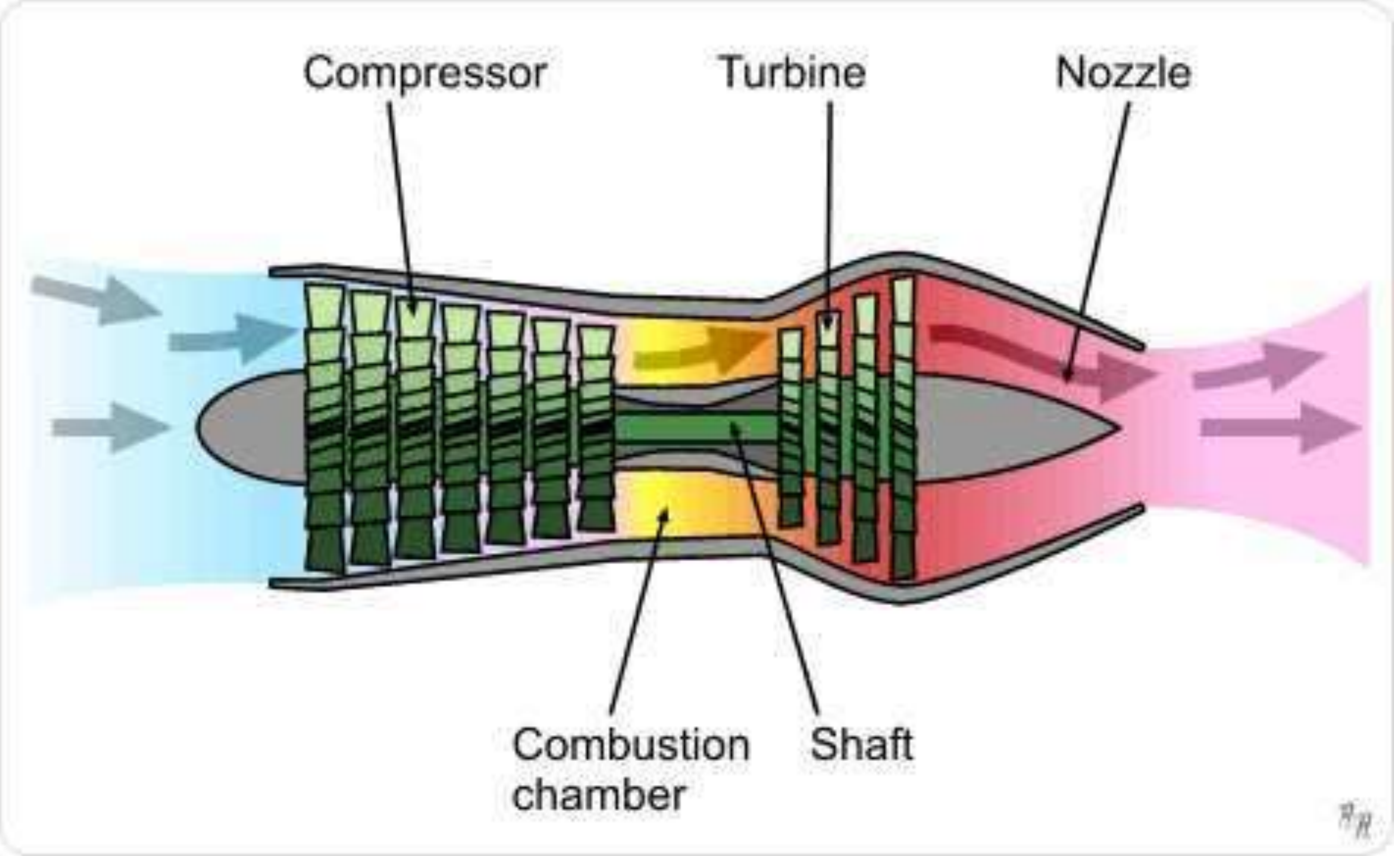
Jet Propulsion System

- **Air-breathing engines**
  - Turbojet engine
  - Turbo-prop engine
  - Turbo-fan engine
  - Ramjet engine
- **Non air-breathing engines**
  - Rocket engine

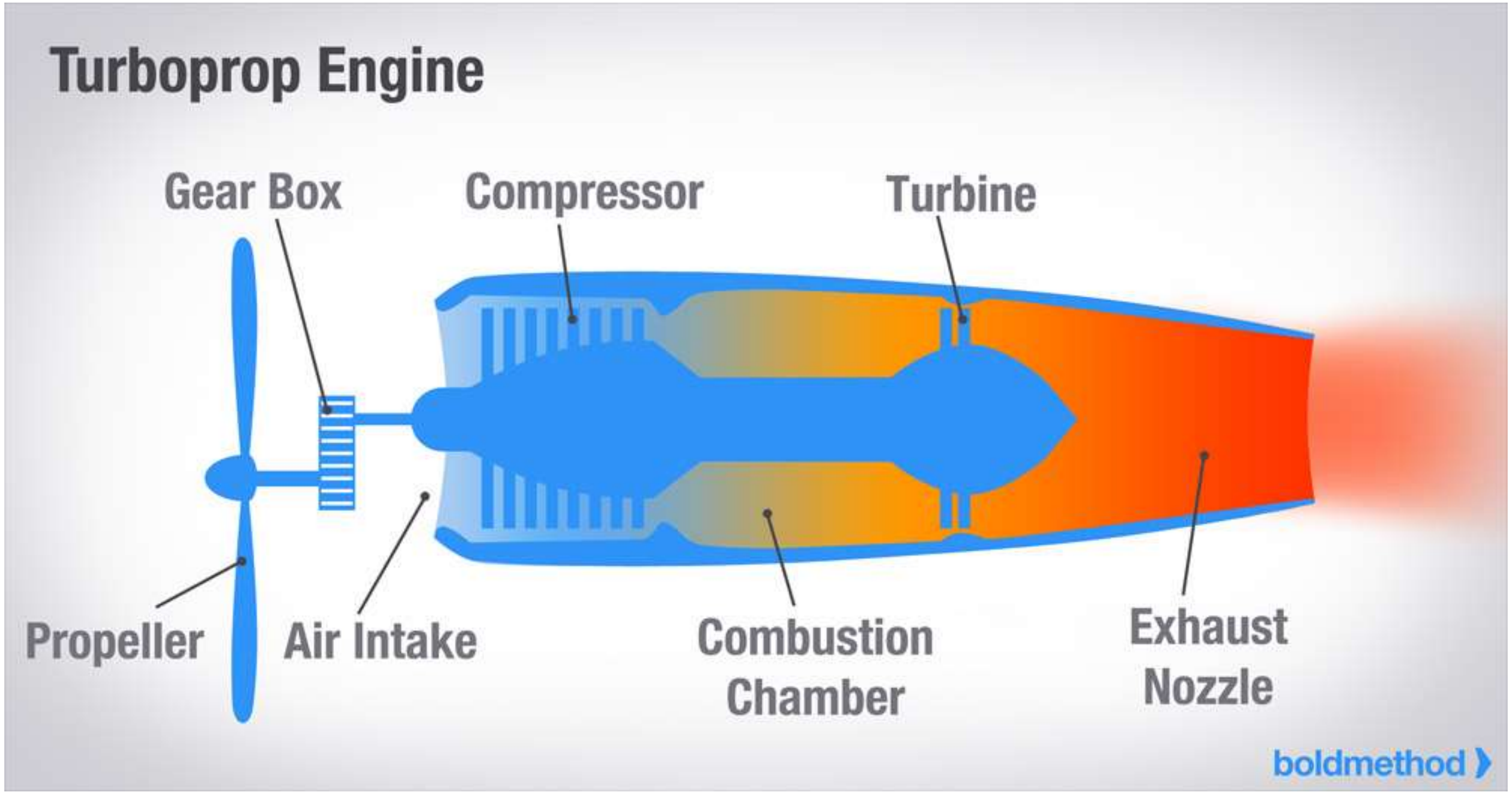




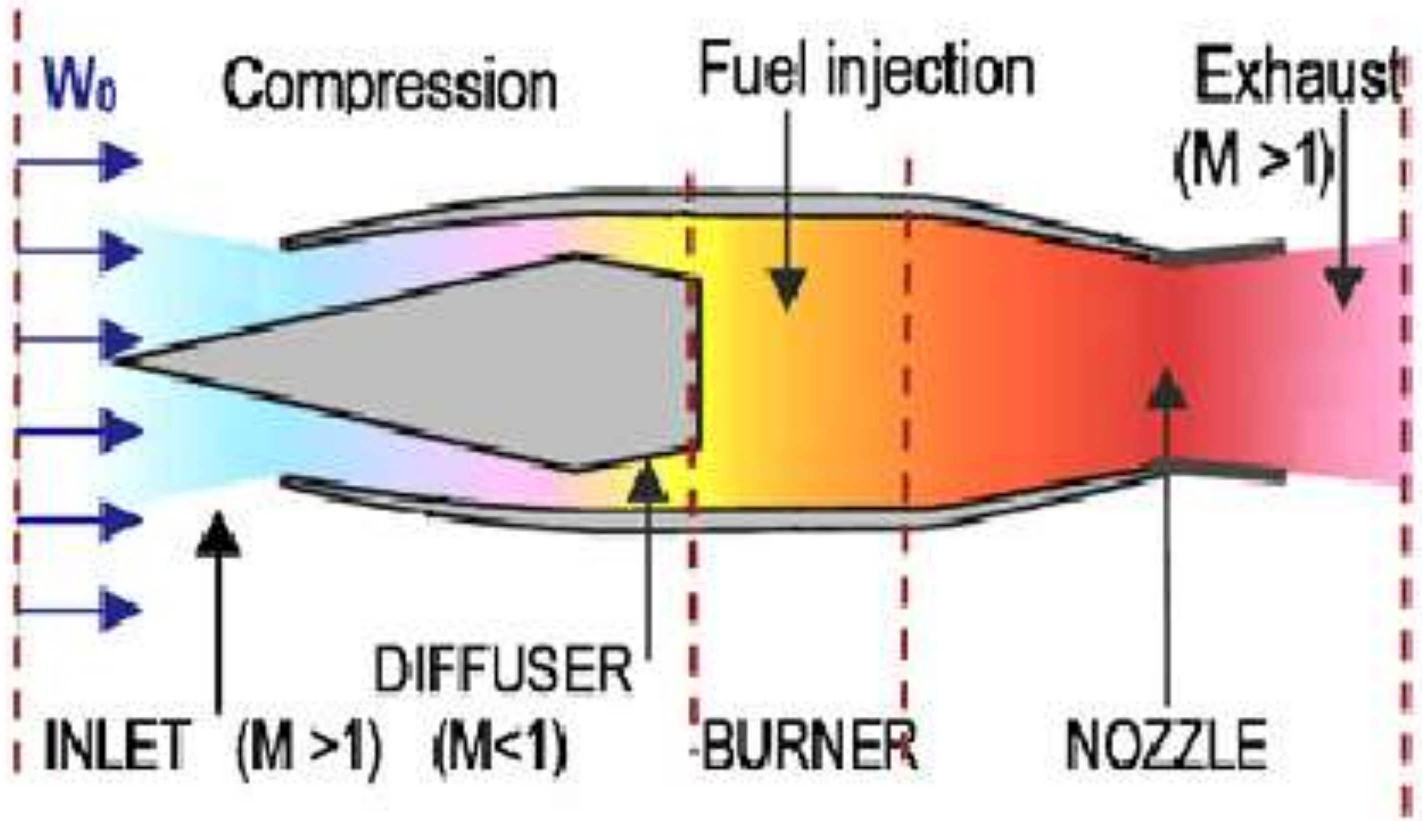
Turbojet engine



Turbo-prop engine



Ramjet engine



Rocket engine