GAS TURBINES

Prime movers:
-Diesel Engine, Petrol Engine
- Steam Turbine, Hydraulic Turbine and Gas Turbine

Advantages of Gas Turbine:

1. The absence of reciprocating and rubbing members which reduces the vibration and balancing problems
2. High reliability
3. Low lubricating oil consumption and
4. High power to weight ratio

Two types of gas turbine:

1. Open cycle gas turbine
2. Closed cycle gas turbine

Open cycle gas turbine:

-Working on Joule cycle or Brayton cycle

-Air is compressed in a rotary compressor and passed into a combustion chamber where fuel is burnt, the products of combustion are made to impinge over rings of turbine blades with high velocity and work is produced. After the work done by the combustion products, rest are given to the atmosphere.

-60% of work produced is used to drive the compressor and rest is available as useful power

-For starting purpose, it is first motored to minimum speed, called coming in speed, before the fuel is turned on

-About 5% power output by the motor is used to start the turbine

To improve the turbine performance intercooler, heat exchanger and reheat cycles are used with simple gas turbine cycle.

Closed cycle gas turbine:

-Working fluid air or other gas is circulated continuously inside the machine

-Working fluid does not come in contact with the atmospheric air or fuel

-Heat to working fluid is given externally by the burning of the fuel that is why it is external combustion engine

-Turbine exhaust rejects heat in a cooler

Advantage of closed cycle gas turbine:

-Due to externally fired, cheaper fuel such as coal can be used

-Products of combustion is not in directly contact with turbine blades, hence fouling and heat transfer from the surface of the blade can be avoided

-Part load efficiency is improved by changing the pressure ratio and varying the quantity of working fluid keeping as cycle temperature constant and at constant speed

-High operating pressure causes low specific volume for the working fluid reducing the size of machines, heat exchangers and piping

-Heat transfer coefficients are higher which reduces the heat exchanger size

Disadvantage of closed cycle gas turbine:

-more complicated and costly system

-Air heaters alone represent over 30% of total mass and cost

-system is not sufficiently strong to resist high pressure

Simple Gas turbine:

Following assumptions are made in analysis of ideal gas turbine,

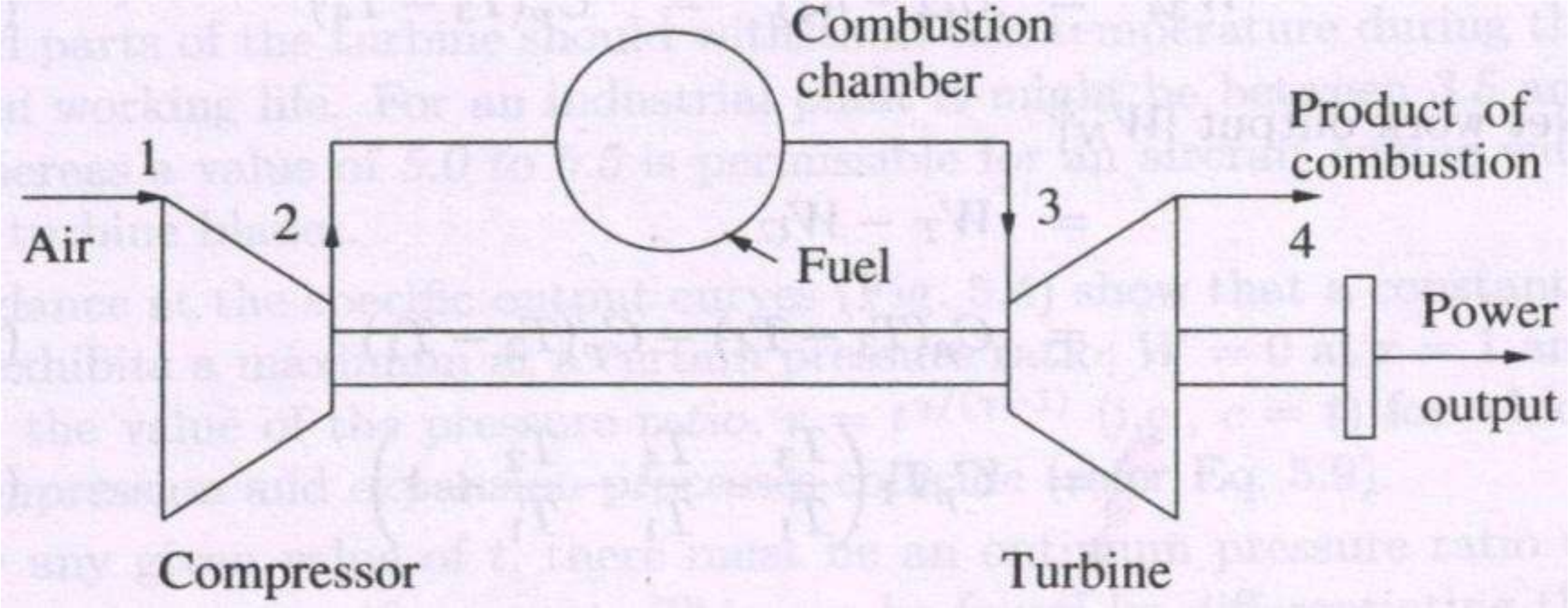
-Compression and expansion process are reversible adiabatic

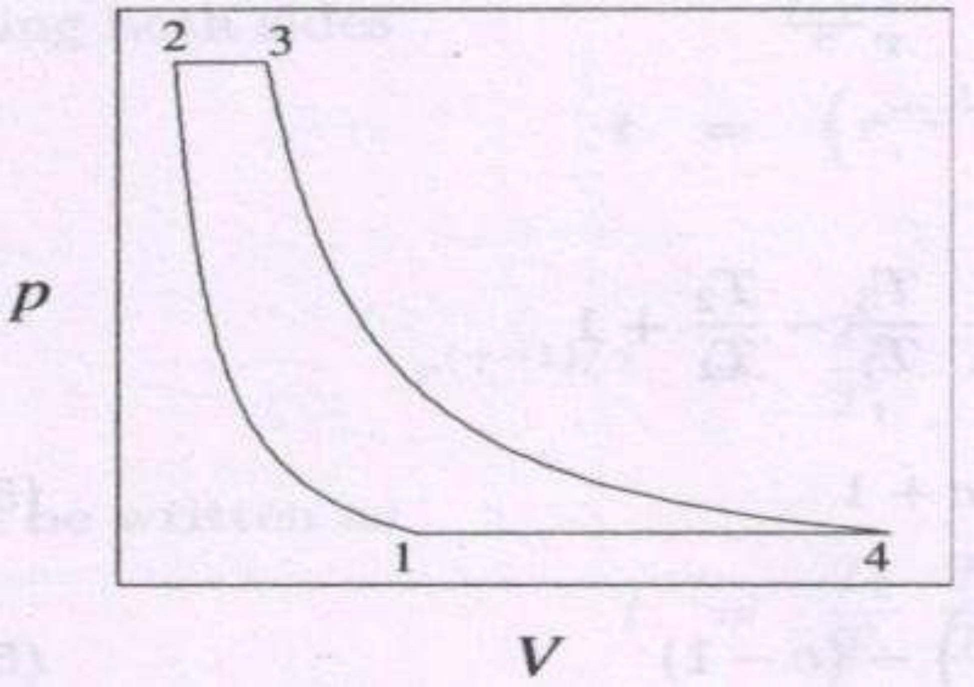
-Kinetic energy does not change at the inlet and exit

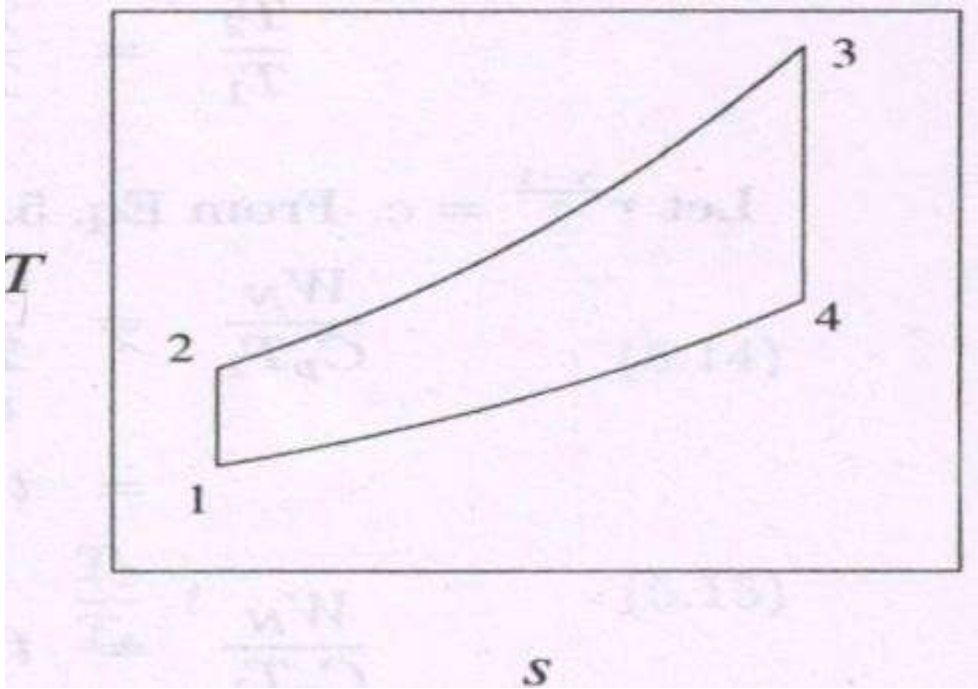
-No pressure loss

-Same chemical composition of working fluid

-Heat exchanger is counter flow type with 100% efficiency







T-S diagram

P-V diagram

Applying the SFEE to each component by considering unit mass flow of working fluid,

Compressor work (W_C),

$$w_{12} = (h_2 - h_1) = C_p(T_2 - T_1)$$

Heat addition (Q),

$$Q_{23} = (h_3 - h_2) = C_p(T_3 - T_2)$$

Turbine work (W_T),

$$w_{34} = (h_3 - h_4) = C_p(T_3 - T_4)$$

Net work output (W_N)= W_T- W_C

$$= C_p(T_3 - T_4) - C_p(T_2 - T_1)$$

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

Let

$\frac{T_3}{T_1} = t$ and $\frac{p_2}{p_1} = r$

Then

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

Let,

$$r^{\frac{\gamma-1}{\gamma}} = c$$

Then equation (1),

$$\frac{W_N}{C_p T_1} = \frac{T_3}{T_1} - \frac{T_4}{T_1}\frac{T_3}{T_3} - \frac{T_2}{T_1} + 1 = t - \frac{t}{c} - c + 1$$

$$\frac{W_N}{C_p T_1} = t\left(1 - \frac{1}{c}\right) - (c - 1)$$

$\eta = \frac{Net\ work\ output}{Heat\ addition} = \frac{W_N}{Q} = \frac{C_p T_1 t\left(1-\frac{1}{c}\right)-(c-1)}{C_p(T_3-T_2)}$=1-1/c

*Heat exchange cycle:

Heat addition,

$$Q_{53} = h_3 - h_5 = C_p(T_3 - T_5)$$

Specific work out put,

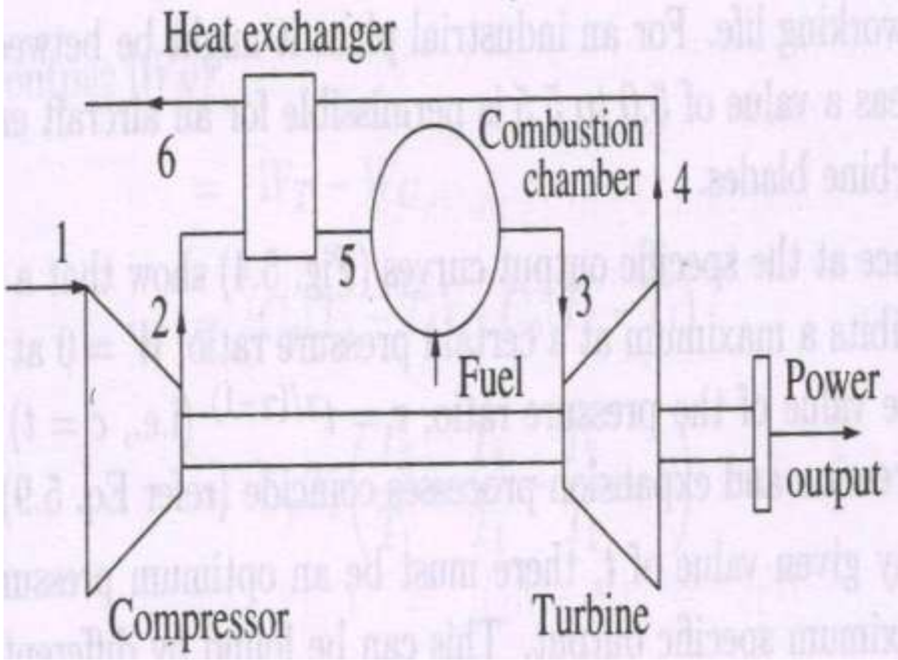
$$\frac{W_N}{C_p T_1} = t\left(1 - \frac{1}{c}\right) - (c - 1)$$

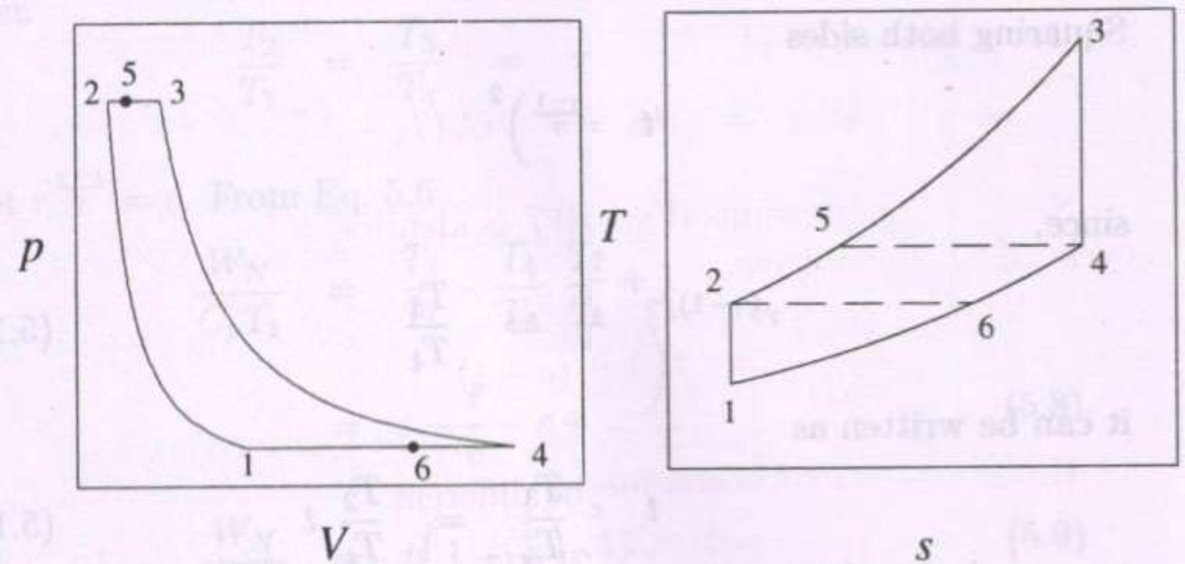
Efficiency,

$$\eta = \frac{Net\ work\ output}{Heat\ input} = \frac{W_N}{Q} = 1 - \frac{c}{t}$$

Efficiency increases with increase in t i.e. it is dependent upon maximum cycle temperature.

Efficiency increases with decrease in pressure ratio.





Reheat cycle:

Heat addition,

$$Q_{23} = h_3 - h_2 = C_p(T_3 - T_2)$$
$$Q_{45} = h_5 - h_4 = C_p(T_5 - T_4)$$

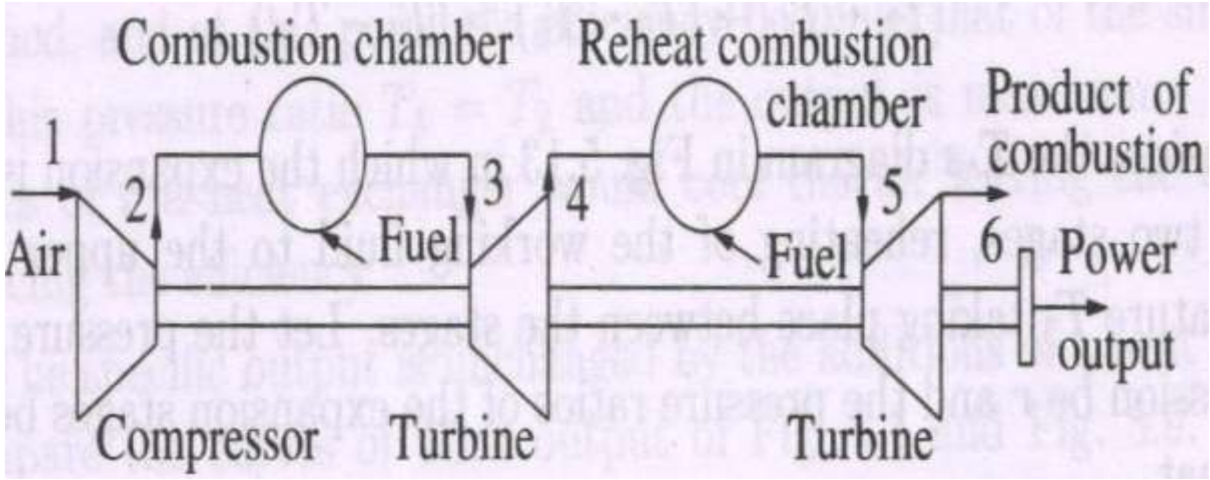
Turbine work,

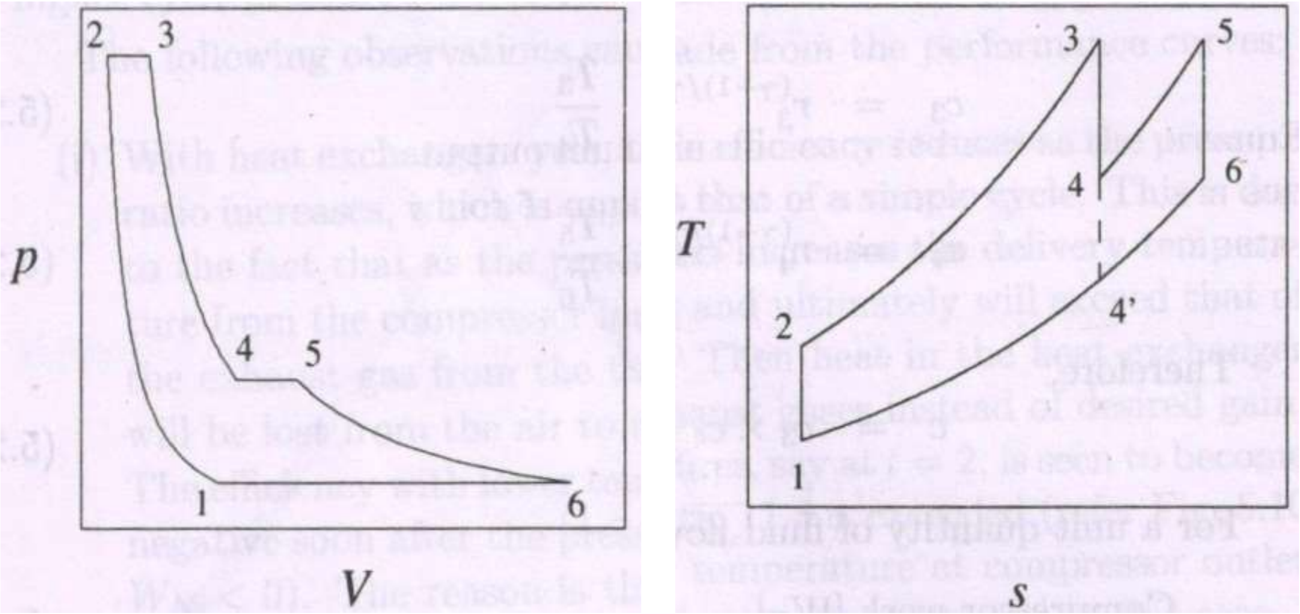
$$W_{34} = h_3 - h_4 = C_p(T_3 - T_4)$$
$$W_{56} = h_5 - h_6 = C_p(T_5 - T_6)$$

Assume that,

$r = r_3 \times r_4$

$$c = r^{\frac{\gamma-1}{\gamma}} = \frac{T_2}{T_1}$$
$$c_3 = r_3^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4}$$
$$c_4 = r_4^{\frac{\gamma-1}{\gamma}} = \frac{T_5}{T_6}$$
$$c = c_3 \times c_4$$
$$T_5 = T_3$$





Specific work out put,

$$\frac{W_N}{C_p T_1} = 2t - \frac{t}{c_3} - \frac{t}{c_4} - c + 1$$

For maximum specific work out put,

$$c_3 = \sqrt{c} = c_4$$

i.e. to obtain maximum specific output stage pressure ratio must be same and equal to square root of overall pressure ratio for two stage expansion.

Then,

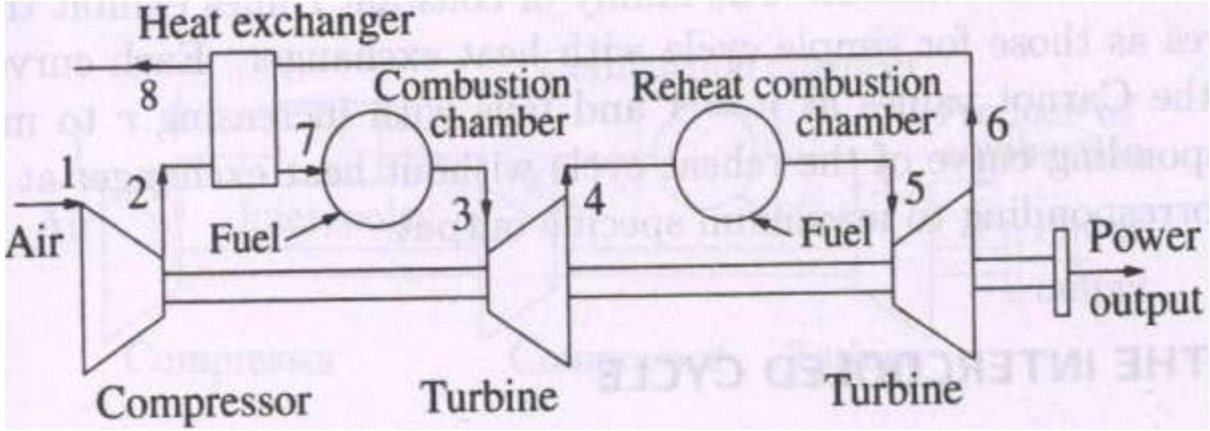
$$\frac{W_{max}}{C_p T_1} = 2t\left(1 - \frac{1}{\sqrt{c}}\right) - (c - 1)$$

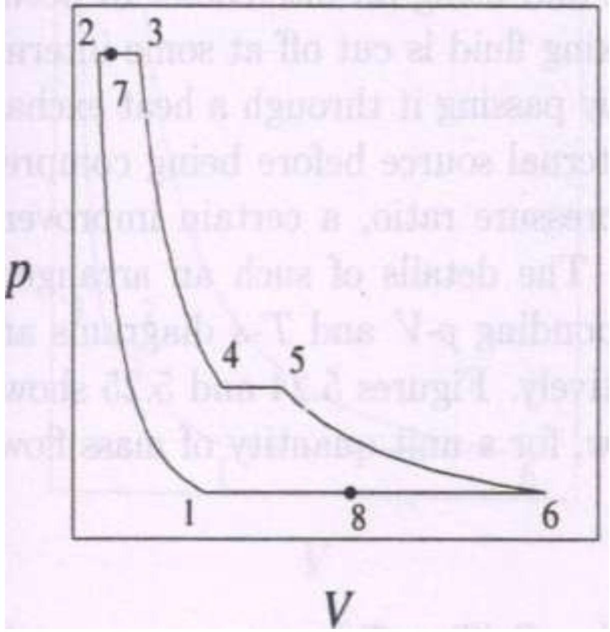
$$\eta_{max} = \frac{2t\left(1 - \frac{1}{\sqrt{c}}\right) - (c - 1)}{2t - c - \frac{t}{\sqrt{c}}}$$

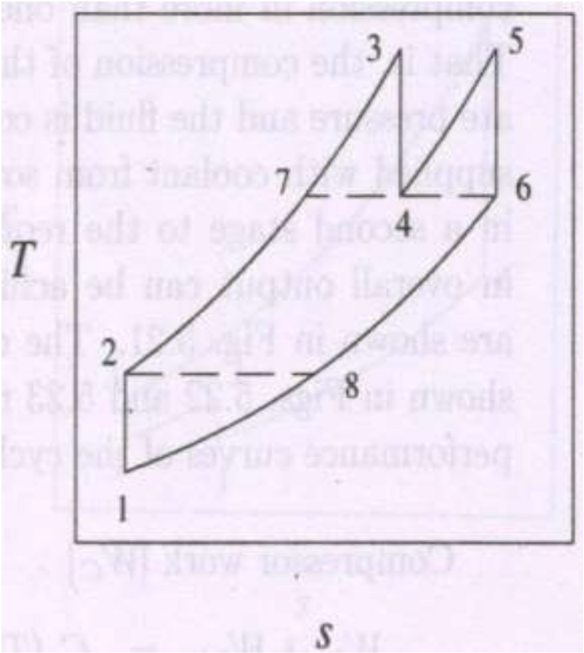
Efficiency is less due to small temperature operating range.

Reheat and Heat exchange cycle:

Specific power output is increased in reheat cycle in the expense of the efficiency and it can be overcome by adding a heat exchanger to reheat cycle.







Heat addition,

$$Q_{73} + Q_{45} = C_p(T_3 - T_7) + C_p(T_5 - T_4)$$

Turbine work,

$$W_{34} + W_{56} = C_p(T_3 - T_4) + C_p(T_5 - T_6)$$

Maximum specific work output is same with reheat cycle, i.e.,

$$\frac{W_{max}}{C_p T_1} = 2t\left(1 - \frac{1}{\sqrt{c}}\right) - (c - 1)$$

But maximum efficiency will change due to heat exchanger,

$$\eta_{max} = \frac{C_p T_1 [2t\left(1 - \frac{1}{\sqrt{c}}\right) - (c - 1)]}{C_p(T_3 - T_7) + C_p(T_5 - T_4)}$$

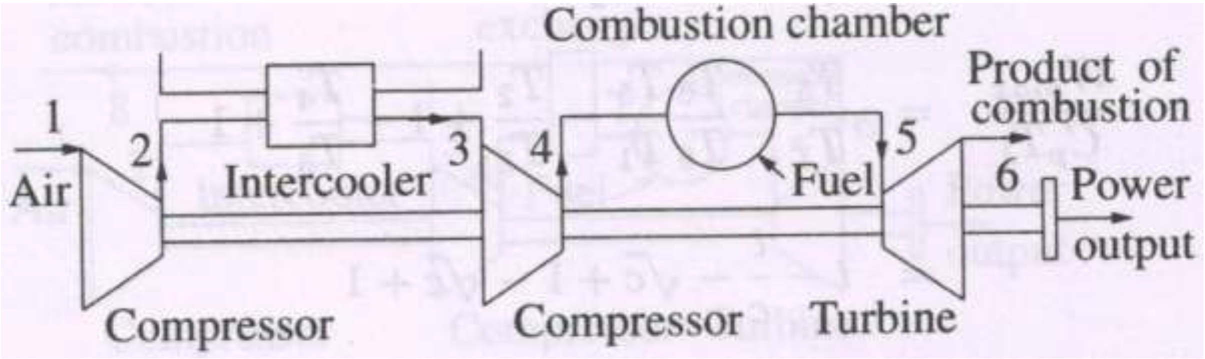
$$= \frac{C_p T_1 \left[2t\left(1 - \frac{1}{\sqrt{c}}\right) - (c - 1)\right]}{\frac{T_3}{T_1} - \frac{T_7}{T_1} + \frac{T_5}{T_1} - \frac{T_4}{T_1}}$$

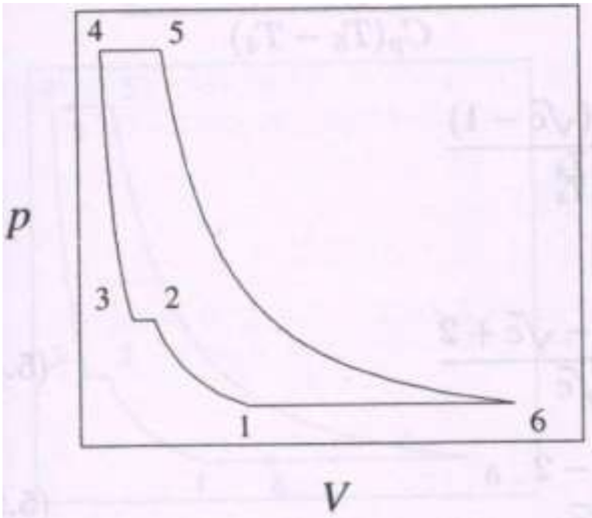
Since, $T_7 = T_4$ and $T_5 = T_3$,

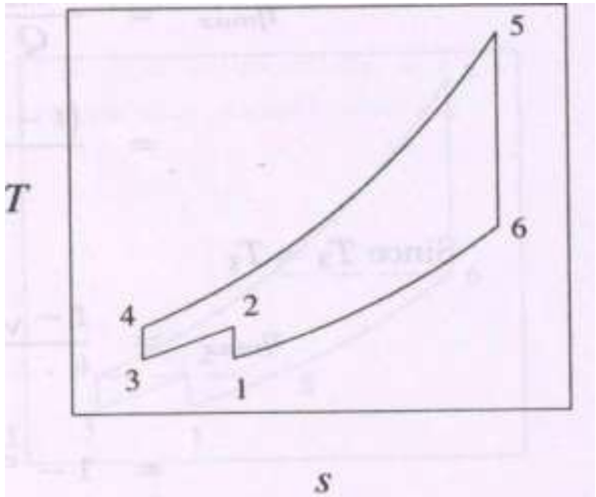
$$\eta_{max} = 1 - \frac{c - 1}{2t - \frac{2t}{\sqrt{c}}}$$

Intercooled cycle:

Another way of increasing the specific work output of gas turbine is reducing the work of compression i.e. compression in more than one stage and using an intercooler in between the compressor.







Compressor work,

$$W_{12} + W_{34} = C_p(T_2 - T_1) + C_p(T_4 - T_3)$$

Heat addition,

$$Q_{45} = h_5 - h_4 = C_p(T_5 - T_4)$$

Turbine work,

$$W_{56} = h_5 - h_6 = C_p(T_5 - T_6)$$

Net work output,

$$W_N = C_p T_1 \left(\frac{T_5}{T_1} - \frac{T_6}{T_1} - \frac{T_2}{T_1} + \frac{T_3}{T_1} - \frac{T_4}{T_1} + 1 \right)$$

Let,

$$\frac{T_5}{T_1} = t, \qquad \frac{T_5}{T_6} = c$$

$\frac{T_2}{T_1} = c_1, \qquad \frac{T_4}{T_3} = c_2$

$T_3 = T_1$

For maximum specific work out put,

$$c_1 = \sqrt{c} = c_2$$

Then,

$$\frac{W_{max}}{C_p T_1} = t - \frac{t}{c} - 2\sqrt{c} + 2$$

$$\eta_{max} = 1 - \frac{\frac{t}{c} + \sqrt{c} - 2}{t - \sqrt{c}}$$

Because of the lower compressor outlet temperature, the fuel flow rate to obtain a given turbine inlet temperature will increase. Therefore, the thermal efficiency of the intercooled cycle will less than that of a simple cycle.

Intercooled cycle with heat exchange and reheat cycle

Compressor work,

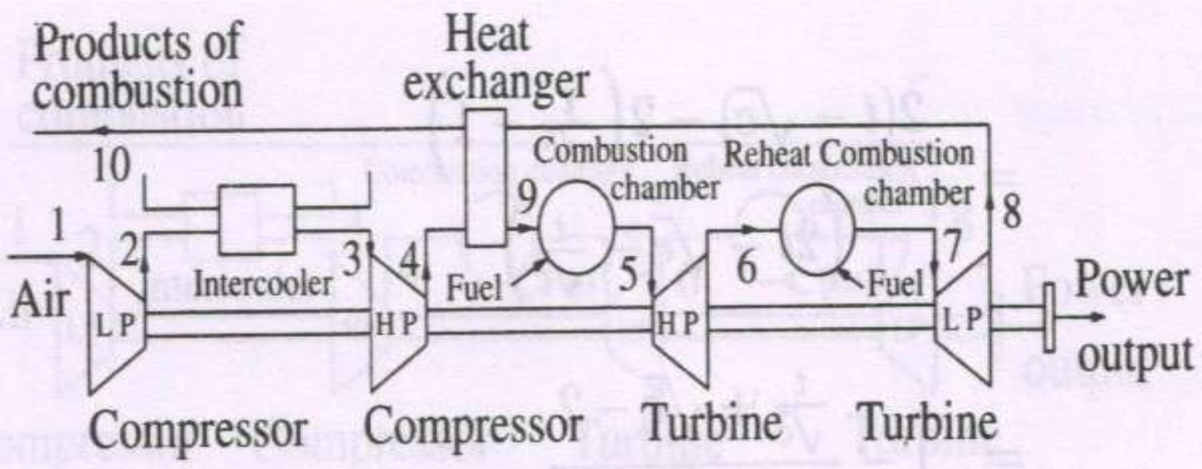
$$W_{12} + W_{34} = C_p(T_2 - T_1) + C_p(T_4 - T_3)$$

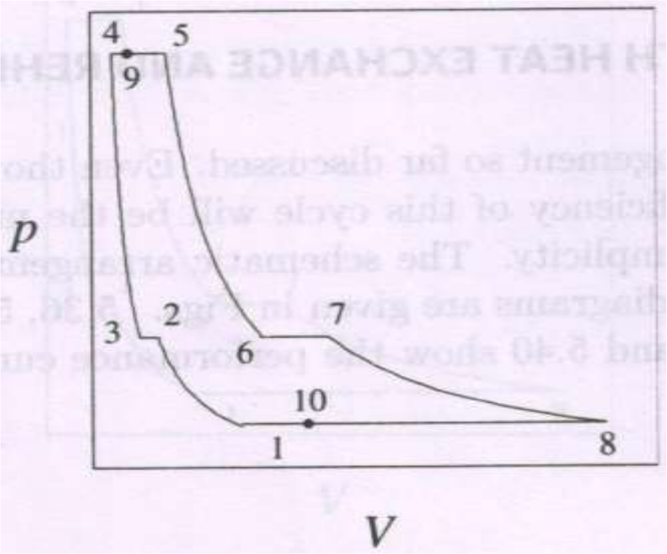
Heat addition,

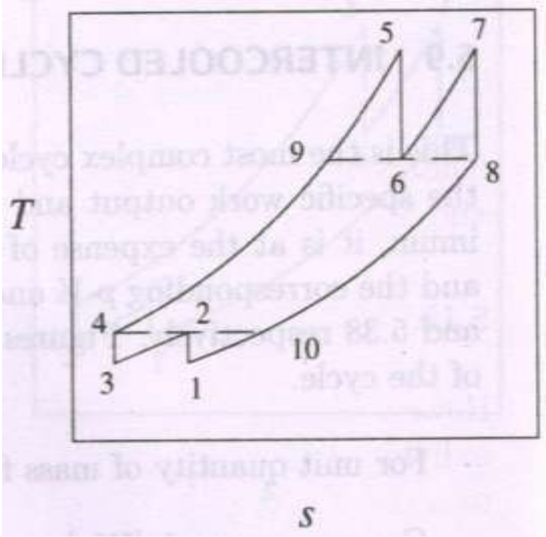
$$Q_{95} + Q_{67} = C_p(T_5 - T_9) + C_p(T_7 - T_8)$$

Turbine work,

$$W_{78} + W_{56} = C_p(T_7 - T_8) + C_p(T_5 - T_6)$$







Maximum specific work out put,

$$\frac{W_{max}}{C_p T_1} = 2\left(t - \frac{t}{\sqrt{c}} - \sqrt{c} + 1\right)$$

Here, $T_6 = T_8$

$$\eta_{max} = 1 - \frac{\sqrt{c}}{t}$$

*Practical cycle:

Assumptions,

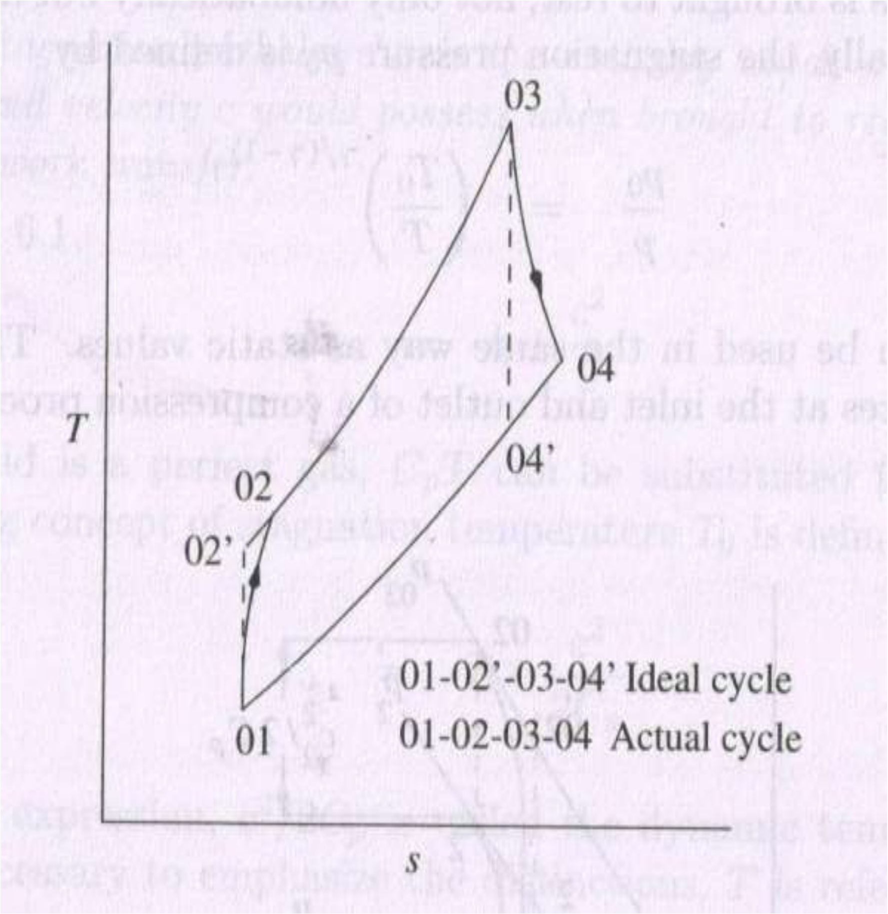
- Fluid velocities are high in turbo-machinery, the change in K.E. change is considered
-compression and adiabatic process are irreversible adiabatic process
-pressure loss in combustion chamber
-complete heat exchange is not possible
-more work required for compression
-C_p and γ values of working fluid change with temperature

Compressor and turbine efficiency:

During compression considerable amount of energy supplied to the compressor is wasted in churning of the working fluid. This energy does not contribute to the pressure rise but is converted into heat by friction.

Compressor efficiency is,

$$\eta_c = \frac{h_{02'} - h_{01}}{h_{02} - h_{01}} = \frac{T_{02'} - T_{01}}{T_{02} - T_{01}}$$



Let, total head pressure ratio or stagnation pressure ratio in the compressor $= r_c$

$$\frac{T_{02'}}{T_{01}} = r_c^{(\gamma-1)/\gamma}$$

Then, $T_{02} - T_{01} = \frac{T_{01}}{\eta_c}\left[{r_c}^{(\gamma-1)/\gamma} - 1\right]$

$$W_{cact} = \frac{C_p T_{01}}{\eta_c}\left[{r_c}^{(\gamma-1)/\gamma} - 1\right]$$

Turbine efficiency is,

$$\eta_T = \frac{h_{03} - h_{04}}{h_{03} - h_{04'}} = \frac{T_{03} - T_{04}}{T_{03} - T_{04'}}$$

Let, r_t= total head pressure ratio in expansion process

$$\frac{T_{03}}{T_{04'}} = {r_t}^{(\gamma-1)/\gamma}$$

$T_{03} - T_{04} = \eta_T T_{03}\left[1 - \frac{1}{{r_t}^{(\gamma-1)/\gamma}}\right]$

$$W_{tact} = C_p \eta_T T_{03}\left[1 - \frac{1}{{r_t}^{(\gamma-1)/\gamma}}\right]$$

Net work done,

$$W_N = W_{tact} - W_{cact} = C_p \eta_T T_{03}\left[1 - \frac{1}{{r_t}^{(\gamma-1)/\gamma}}\right] - \frac{C_p T_{01}}{\eta_c}\left[{r_c}^{(\gamma-1)/\gamma} - 1\right]$$

Work ratio=$\frac{W_N}{W_{tact}} = 1 - \frac{C_p \eta_T T_{03}\left[1 - \frac{1}{{r_t}^{(\gamma-1)/\gamma}}\right] - \frac{C_p T_{01}}{\eta_c}\left[{r_c}^{(\gamma-1)/\gamma} - 1\right]}{C_p \eta_T T_{03}\left[1 - \frac{1}{{r_t}^{(\gamma-1)/\gamma}}\right]}$

If $r_c = r_t = r$,

Work ratio=$1 - \frac{T_{01}\left[r^{(\gamma-1)/\gamma} - 1\right]}{\eta_c \eta_T T_{03}} = 1 - \frac{c}{t}\frac{1}{\eta_c \eta_T}$

Where, c=$r^{(\gamma-1)/\gamma}$ and $t = \frac{T_{03}}{T_{01}}$

Work ratio is increased by high temperature ratio t and low pressure ratio, r.

***Gas turbine combustion chamber:**

2 types of combustion chambers,

(a) Tubular or Can chambers: cylindrical liner is mounted concentrically inside cylindrical casing

-mostly used in jet engines

-with this centrifugal compressor is used

(b) Annular chambers: annular liner is mounted concentrically inside annular casing

-difficult to maintain for air and fuel flow and maintain stable temp.