Gas turbines

Gas turbine is a rotary type of I.C engine. The cyclic events of gas turbine are similar to reciprocating type I.C engine. But each event in gas turbine is carried out in different devices. The simple gas turbine consists of rotary compressor, combustion chamber and turbine unit.

The air is first compressed in a rotary compressor before passing to a combustion chamber where the fuel is injected and ignited. The hot burnt gases expand through the blades of a turbine where the kinetic energy of burnt gases is utilised to produce power. Finally the gases are exhausted from the turbine unit.

Advantages :-

1. Comparatively small weight and size
2. The mechanical efficiency is higher.
3. Torque produced is uniform
4. poor quality of fuels can be used
5. small working pressures are involved.

Limitations :-

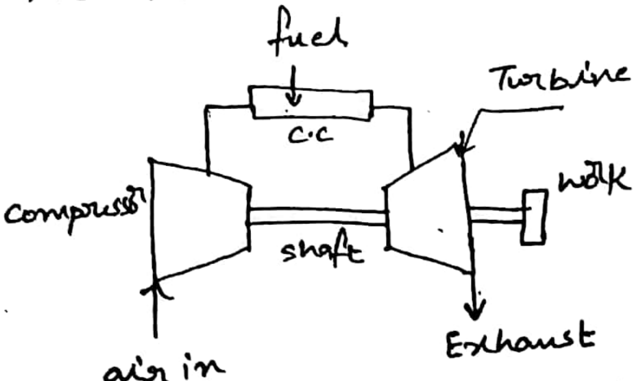
1. part of power produced is utilised for driving the compressor.
2. Not a self-starting unit
3. Relatively low overall efficiency
4. Requires costly reducing gears for normal industrial aplications.

classification of gas turbines :-

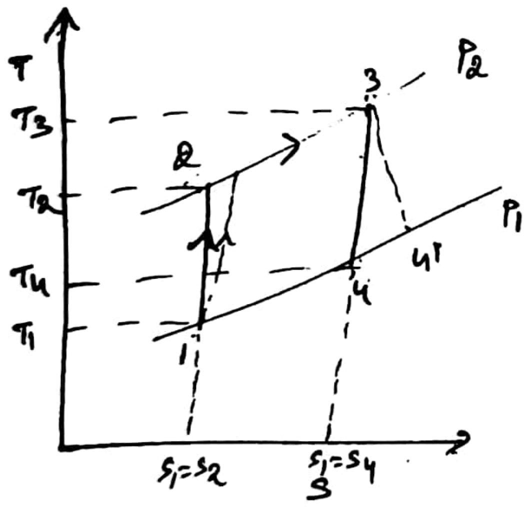
1. According to the path of working fluid
   a) open cycle gas turbine
   b) closed cycle gas turbine
   c) Semi closed cycle gas turbine
2. According to the basis of combustion process
   a) Constant pressure

b) Constant volume

Open cycle gas turbine :-



The open cycle gas turbine in which a rotary compressor and a turbine are mounted on a common shaft. Air is drawn into the compressor and after compression passes a combustion chamber. Energy is supplied in the combustion chamber by spraying fuel into the air stream and resulting hot gases expand through the turbine to the atmosphere. In order to achieve network output from the unit, the turbine must develop more gross work output than is required to drive the compressor and to overcome mechanical losses in drive. The products of combustion coming out from the turbine are exhausted to the atmosphere.



1-2' = Adiabatic compression
2'-3 = constant pressure heat supply
3-4' = Adiabatic expansion
1-2 = Ideal Isentropic Compression
3-4 = Ideal Isentropic expansion.

$$\text{work input (compressor)} = c_p(T_2' - T_1)$$

$$\text{Heat supplied} = c_p(T_3 - T_2')$$

$$\text{work output (turbine)} = c_p(T_3 - T_4')$$

$$\text{Net work output} = \text{work output} - \text{work input}$$

$$= c_p(T_3 - T_4') - c_p(T_2' - T_1)$$

$$\eta_{thermal} = \frac{\text{Network output}}{\text{Heat supplied}}$$

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

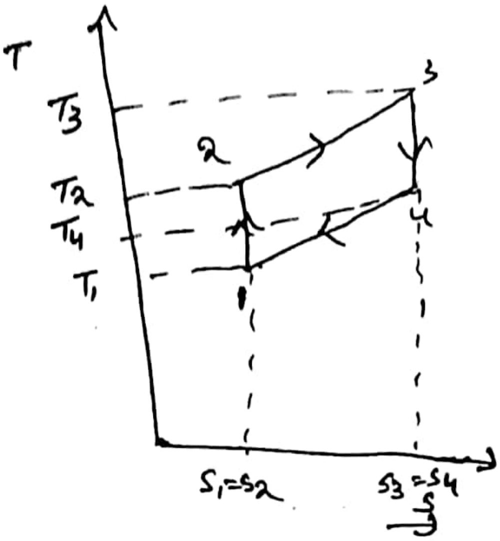
$$\eta_{compressor} = \frac{\text{work input required in Isentropic compression}}{\text{Actual work required.}}$$

$$= \frac{c_p(T_2 - T_1)}{c_p(T_2' - T_1)} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$\eta_{\text{Turbine}} = \frac{\text{Actual work output}}{\text{Isentropic work output}}$$

$$= \frac{c_p(T_3 - T_4')}{c_p(T_3 - T_4)} = \frac{T_3 - T_4'}{T_3 - T_4}$$

1. The simple gas ... has the pressure ratio 6 and the maximum and minimum temperatures of the cycle are 1000K and 288K respectively. Assuming an ideal cycle, calculate the efficiency and specific workout of the plant.



pressure ratio $\frac{P_2}{P_1} = \frac{P_3}{P_4} = 6$

Minimum temperature $(T_1) = 288K$

Maximum temperature $(T_3) = 1000K$

$\gamma = 1.4 \quad C_p = 1.005\ KJ/kg\,K$

$$\eta = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}} = 1 - \frac{1}{6^{\frac{1.4-1}{1.4}}} = 0.401$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 6^{\frac{0.4}{1.4}} = 6^{0.2857}$$

$T_2 = (288)(6^{0.2857}) = 480.53K$

Also $\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$. $T_4 = 1000 \times 0.599 = 599K$

Turbine work $= C_p(T_3 - T_4) = 1.005(1000 - 599) = 403\ KJ/kg$

Compressor work $= (W_c) = C_p(T_2 - T_1) = 1.005(480.53 - 288) = 193.49\ KJ/kg$

Specific workoutput $= W_T - W_c = 403 - 193.49 = 209.51\ KJ/kg$

$$\eta = \frac{W}{Q_{sup}} = \frac{209.51}{1.005(1000 - 480.53)} = 0.401 = 40.1\%$$

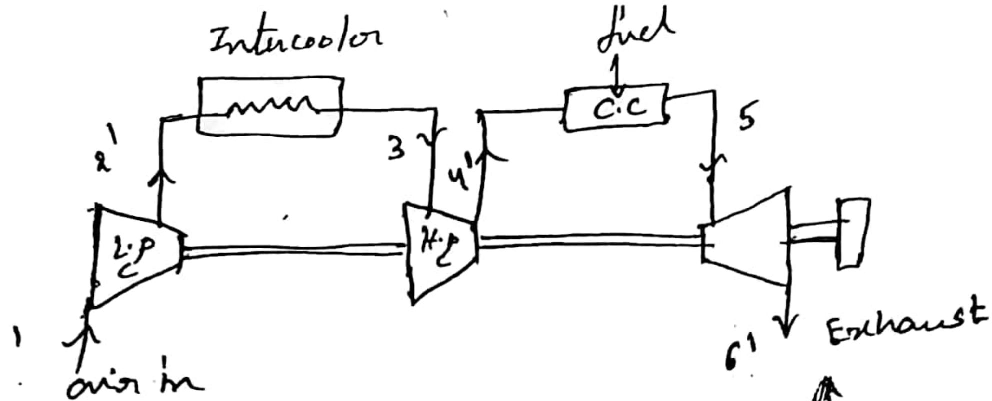
Methods for improvement of thermal efficiency of open cycle gas turbine plant:-

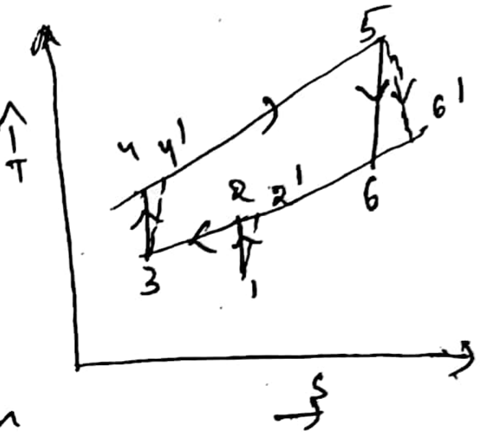
The following methods are employed to increase the specific output and thermal efficiency of plant.

1. Intercooling :- A compressor in a gas turbine cycle utilises the major percentage of power developed by the gas turbine. The work required by the compressor can be reduced by compressing the air in two stages and incorporating an intercooler between the two. The actual processes take place as follows.

1-2' = L.P compression, 3-4' = H.P compression, 5-6' = Turbine expansion.

2'-3 = Intercooling, 4'-5 = C.C heating,





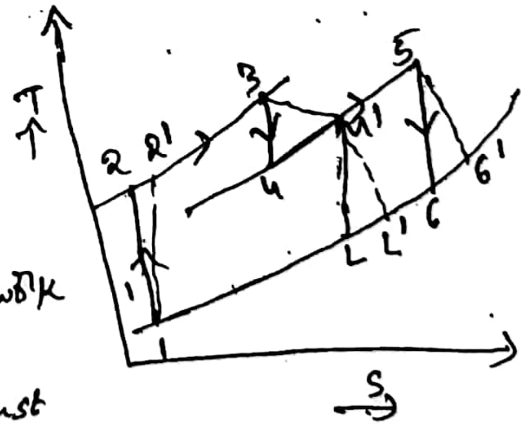
The ideal cycle for this arrangement is 1-2-3-4-5-6

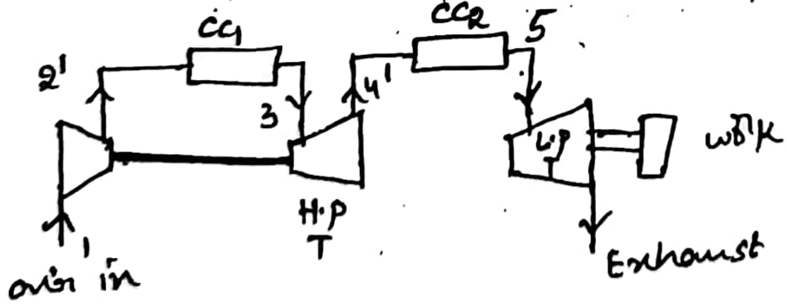
~~now the work output (with intercooling)~~

work ratio = $\dfrac{\text{Net work output}}{\text{Gross work output}}$

$= \dfrac{\text{work of expansion} - \text{work of compression}}{\text{work of expansion}}$

2. Reheating :- The work output of a gas turbine can be amply improved by expanding the gases in two stages with a reheater between the two as shown in fig. The Hp turbine drives the compressor and L.p turbine provides the useful power output.





Neglecting mechanical losses the work output of the H.p turbine must be exactly equal to the work input required for the compressor.

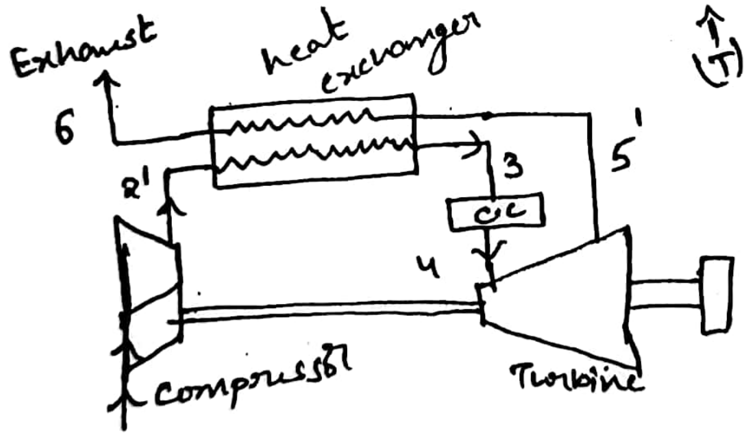
$$c_{pa}(T_2' - T_1) = c_{pg}(T_3 - T_4')$$

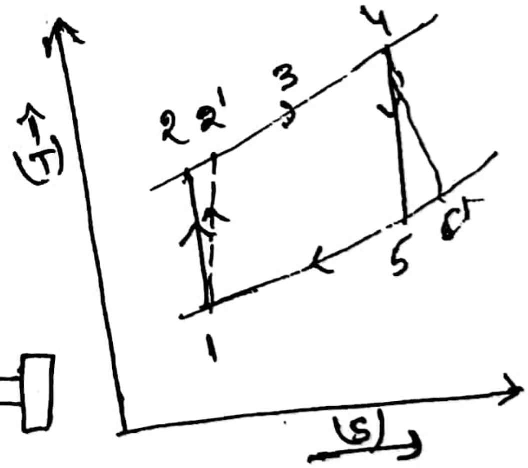
Net work output (with reheating) $= c_{pg}(T_5 - T_6')$

" " (without ") $= c_{pg}(T_4' - T_L)$

From the T-S diagram temperature difference $(T_5 - T_6')$ is always greaterthan $(T_4' - T_2)$ so that reheating increases the workoutput. 4.

3. Regeneration :- The exhaust gases from a gas turbine carry a large quantity of heat with them since their temperature is far above the ambient temperature. They can be used to heat the air coming from the compressor thereby reducing the mass of fuel supplied in the combustion chamber. In a figure 2'-3 represents the heat flow into the compressed air during its passage through the heat exchanger and 3-4 represents the heat taken from the combustion of fuel point 6 represents the temperature of exhaust gases at discharge from the heat exchanger. The maximum temperature to which the air could be heated in the heat exchanger is ideally that of exhaust gases.



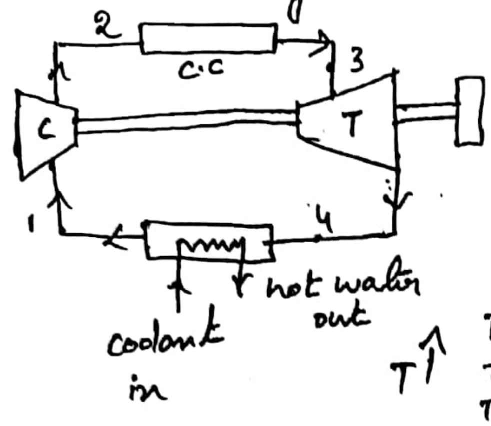


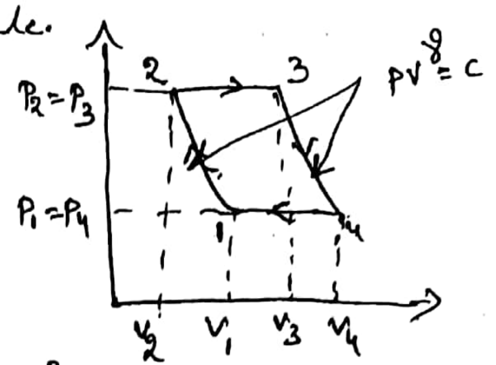
The effectiveness of heat exchanger is given by

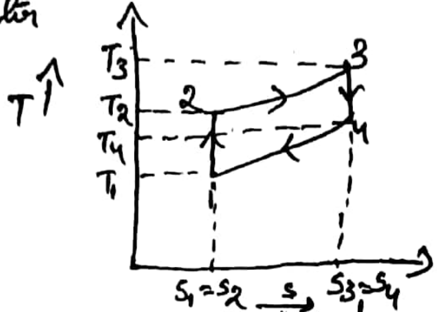
$$= \frac{\text{Increase in enthalpy / Kg of air}}{\text{Available increase in enthalpy / Kg of air}}$$

$$= \frac{T_3 - T_2'}{T_5' - T_2'}$$

Closed cycle gas turbine :- This cycle operates on a constant pressure cycle in which the closed system consists of air behaving as an ideal cycle.







1-2 :- The air is compressed isentropically from the lower pressure P_1 to upper pressure P_2, the temperature raising from T_1 to T_2. No heat flow occurs.

2-3 :- Heat flow into the system increasing volume from V_2 to V_3 and temperature from T_2 to T_3. whilst the pressure remains constant at P_2. Heat received $= mc_p(T_3 - T_2)$

3-4 :- The air is expanded isentropically from P_2 to P_3. The temperature falling from T_3 to T_4. No heat flow occurs.

4-1 :- Heat is rejected from system as the volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at P_1. Heat rejected $= mc_p(T_4 - T_1)$

$$\eta_{\text{air-standard}} = \frac{\text{workdone}}{\text{Heat received}}$$

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

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

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

From 1-2 process:- 5.

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

$P_2 = P_3 = r_p$
$P_1 = P_4 = r_p$

3-4 process:-

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \quad T_3 = T_4\left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

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

$$\eta_{\text{air-standard}} = 1 - \frac{T_4 - T_1}{T_4 (r_p)^{\frac{\gamma-1}{\gamma}} - T_1 (r_p)^{\frac{\gamma-1}{\gamma}}}$$

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

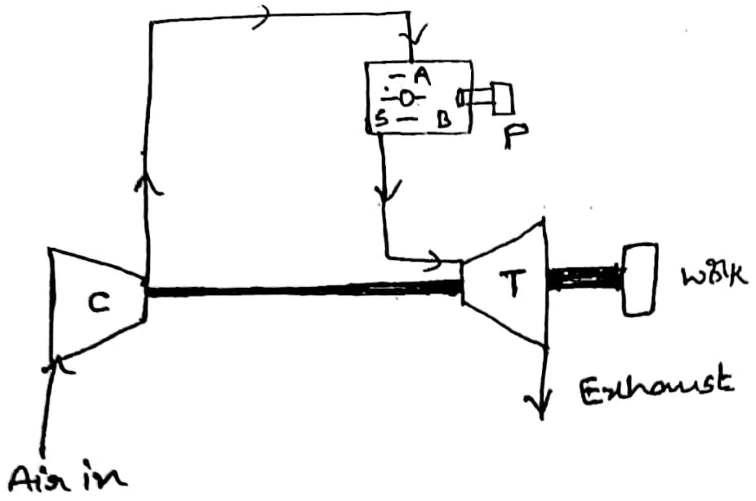
Merits of closed cycle:-

1. Higher thermal efficiency
2. Reduced size
3. No contamination
4. Improved part load efficiency
5. Greater output
6. Inexpensive fuel.

Demerits of closed cycle:-

1. Complexity
2. Dependent system
3. Requires the use of a very large air heater.

Constant volume combustion turbines:- The compressed air from an air compressor C is admitted into the C.C D through the valve A. When valve A is closed, the fuel is admitted into the chamber by means of a fuel pump P. Then the mixture is ignited by means of a spark plug S. The combustion take place at constant volume with increase of pressure. The valve B opens and the hot gases flow to the turbine T and finally they are discharged into atmosphere. The energy of hot gases is thereby converted into mechanical energy. For continuous running of the turbine these operations are repeated.



1. A gas turbine unit received air at 1 bar and 300K and compressess it adiabatically to 6.2 bar. The compressor efficiency is 88%. The fuel has a heating value of 44186 kJ/kg and the fuel air ratio is 0.017 kJ/kg of air. The turbine internal efficiency is 90%. Calculate the work of turbine and compressor / kg of air compressed and thermal efficiency For products of combustion $c_p = 1.147$ kJ/kgK $\gamma = 1.4$

$P_1 = P_4 = 1$ bar, $T_1 = 300$ K $P_2 = P_3 = 6.2$ bar, $\eta_{compressor} = 88\%$

$c = 44186$ kJ/kg, Fuel air ratio $= 0.017$ kJ/kg, $\eta_{turbine} = 90\%$

$c_p = 1.147$ kJ/kgK $\gamma = 1.4$

1-2 process :- $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

$$= 300\left(\frac{6.2}{1}\right)^{\frac{1.4-1}{1.4}}$$

$$= 505.2 \text{ K}$$

$$\eta_{com} = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow 0.88 = \frac{505.2 - 300}{T_2' - 300}$$

$$T_2' = 533.2 \text{ K.}$$

Heat supplied $= m\left(1 + \frac{m_f}{m_a}\right) c_p (T_3 - T_2') = \frac{m_f}{m_a} \times c$

$$(1 + 0.017)\, 1.005\, (T_3 - 533.2) = 0.017 \times 44186.$$

$$T_3 = 1268 \text{ K.}$$

$$\frac{T_3}{T_4} = \cancel{\frac{P_4}{P_3}} \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_4 = \frac{T_3}{\left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}} \Rightarrow 1268 \times 0.634 = 803.9 \text{ K.}$$

$$\eta_{Turbine} = \frac{T_3 - T_4'}{T_3 - T_4}$$ 6.

$$T_4' = 1268 - 0.9\,(1268 - 803.9) = 850.3\,K.$$

$$w_{compressor} = C_p\,(T_2' - T_1) = 1.005\,(533.2 - 300) = 234.4\ kJ/kg$$

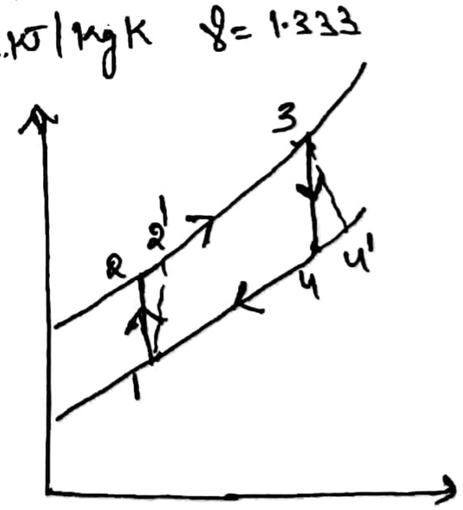
$$w_{turbine} = C_{pg}\,(T_3 - T_4') = 1.147\,(1268 - 850.3) = 479.1\ kJ/kg$$

$$Network = w_{turbine} - w_{compressor} = 244.7\ kJ/kg$$

$$Heat\ supplied/kg\ of\ air = 0.017 \times 44186 = 751.2\ kJ/kg$$

$$\eta_{thermal} = \frac{Network}{Heat\ supplied} = \frac{244.7}{751.2} = 32.57\%$$

A Gas turbine unit receives air at 1 bar and 300K and compresses it adiabatically to 6.2 bar. The Compressor efficiency is 88%. The fuel has heating value of 44186 kJ/kg and the air fuel ratio is 0.017 kJ/kg of air. The turbine efficiency is 90%. Calculate the work of turbine and compressor / kg of air compressed and thermal efficiency. for products of combustion $C_p = 1.147\ kJ/kgK$ $\gamma = 1.333$



Given:-

$P_1 = P_4 = 1$ bar, $T_1 = 300K$

$P_2 = P_3 = 6.2$ bar

$C = 44186\ kJ/kg$

Fuel-air ratio $= 0.017\ kJ/kg$

$\eta_{turbine} = 90\%$

$C_p = 1.147\ kJ/kg\,K$

$\gamma = 1.333$

$\gamma = 1.4$

From 1-2 process:-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow \left(\frac{6.2}{1}\right)^{\frac{1.4-1}{1.4}} \Rightarrow$$

$$T_2 = 300 \times 1.684 = 505.2K.$$

$\gamma = 1.333$

$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$

$0.88 = \frac{505.2 - 300}{T_2' - 300}$

$T_2' = 533.2K.$

$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$

$T_4 = 1268 \times 0.634 = 803.9K.$

$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4}$

$T_4' = 850.3K.$

Heat supplied :-

$(m_a + m_f) C_p (T_3 - T_2') = m_f \times C$

$\left(1 + \frac{m_f}{m_a}\right) C_p (T_3 - T_2') = \left(\frac{m_f}{m_a}\right) C$

$(1 + 0.017) 1.005 (T_3 - 533.2) = 0.017 \times 44186$

$T_3 = 1268 K.$

$W_{compressor} = C_p (T_2' - T_1) = 1.005 (533.2 - 300) = 234.4$ KJ/kg

$W_{Turbine} = C_{pg} (T_3 - T_4') = 1.147 (1268 - 850.3) = 479.1$ KJ/kg

net work output $= W_{Turbine} - W_{compressor} = 479.1 - 234.4 = 244.7$ KJ/kg

Heat supplied / kg of air $= \left(\frac{m_f}{m_a}\right) CV$

$= 0.017 \times 44186$

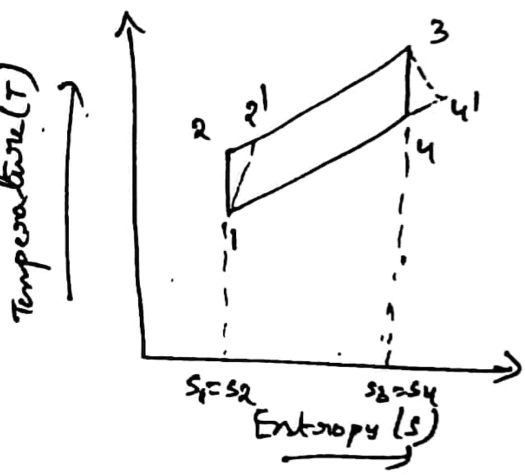
$= 751.2$ KJ/kg

Thermal efficiency $= \frac{\text{Network}}{\text{heat supplied}}$

$= \frac{244.7}{751.2}$

$= 32.57\%.$

1. A gas turbine employs a heat exchanger with a thermal ratio of 72%. The turbine operates between the pressure of 1.01 bar and 4.04 bar and ambient temperature is 20c. Isentropic efficiencies of compressor and turbine are 80% and 85% respectively. The pressure drop on each side of the heat exchanger is 0.05 bar and in the combustion chamber 0.14 bar. Assume combustion efficiency to be unity and calorific value of the fuel to be 41800 kJ/kg. Calculate the increase in efficiency due to heat exchanger over that for simple cycle. $c_p = 1.024$ kJ/kgK. and assume $\gamma = 1.4$, air-fuel ratio = 90:1 and for the heat exchanger cycle the turbine entry temperature is the same as for a simple cycle.



1-2 process :-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.40}{1.01}\right)^{\frac{1.4-1}{1.4}}$$

$$T_2 = (293)(1.486) = 435.4\ K.$$

$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{435.4 - 293}{T_2' - 293}$$

$$T_2' = 471\ K$$

$$(m_a + m_f)\, c_p (T_3 - T_2') = m_f \times C$$

$$T_3 = \frac{m_f \times C}{c_p (m_a + m_f)} + T_2' \Rightarrow \frac{1 \times 41800}{1.024\ (90+1)} + 471 = 919.5\ K$$

3-4 process :-

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_4 = (T_3)\left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow 919.5\left(\frac{1.01}{3.9}\right)^{\frac{1.4-1}{1.4}}$$

$$T_4 = 625\ K$$

$$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4} \Rightarrow T_4' = 919.5 - 0.85(919.5 - 625) = 669\ K$$

$$\eta_{thermal} = \frac{(T_3 - T_4') - (T_2' - T_1)}{(T_3 - T_2')} = \frac{(919.5 - 669) - (471 - 293)}{(919.5 - 471)}$$

$$= 16.16\%$$

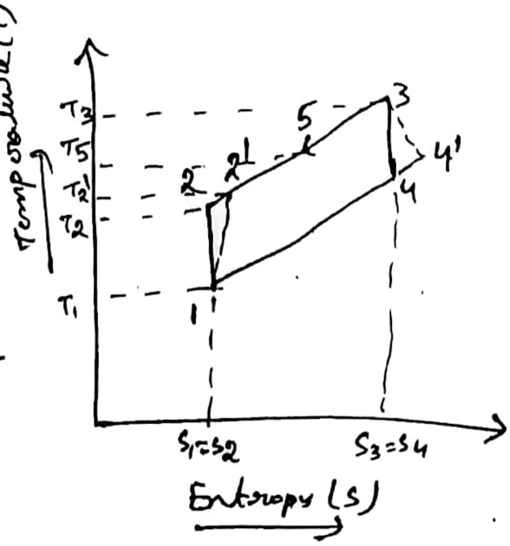
Heat exchanger cycle :-

$P_3 = 4.04 - 0.14 - 0.05 = 3.85$ bar

$P_4 = 1.01 + 0.05 = 1.06$ bar

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow \left(\frac{1.06}{3.85}\right)^{\frac{1.4-1}{1.4}} = 0.69$$

$T_4 = 919.5 \times 0.69 = 634K.$



$$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4} \Rightarrow 0.85 = \frac{919.5 - T_4'}{919.5 - 634}$$

$T_4' = 677K$

Thermal ratio (Effectiveness)

$$\epsilon = \frac{T_5 - T_2'}{T_4' - T_2'} \Rightarrow 0.72 = \frac{T_5 - 471}{677 - 471}$$

$T_5 = 619 K$

$$\eta_{thermal} = \frac{(T_3 - T_4') - (T_2' - T_1)}{(T_3 - T_5)}$$

$$= \frac{(919.5 - 677) - (471 - 293)}{(919.5 - 619)}$$

$$= \frac{64.5}{300.5} = 21.46\%.$$

Increase in thermal efficiency = 21.46 - 16.16 = 5.3%.

2. Air is drawn in a gas turbine unit at 15°c and 1.01 bar and pressure ratio is 7:1. The compressor is driven by the H.P turbine and L.P turbine drives a seperate power shaft. The isentropic efficiencies of compressor, and the H.p and L.p turbines are 0.82, 0.85 and 0.85 respectively. If the maximum cycle temperature is 610°c calculate

1. The pressure and temperature of gases entering the power turbine
2. The net power developed by the unit / kg mass flow.
3. work ratio
4. Thermal efficiency of the unit. Neglect the mass of fuel and assume the following for compression process

$C_{pa} = 1.005$ KJ/kg K, $\gamma = 1.4$ $C_{pg} = 1.15$ KJ/kg and $\gamma = 1.333$

Given :-

$T_1 = 15+273 = 288K$, $\eta_{compressor} = 0.85$, $\eta_{turbine (H.P)} = 0.85$ 8.

$P_1 = 1.01$ bar $\frac{P_2}{P_1} = 7$, $\eta_{turbine (LP)} = 0.85$, Maximum temperature $(T_3) = 610+273 = 883K$

1. 1-2 process :-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (7)^{\frac{1.4-1}{1.4}} = 1.745$$

$$T_2 = 1.745 \times 288 = 502.5K$$

$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow T_2' = 549.6K$$

work of compressor $= C_{pa}(T_2' - T_1) = 1.005\,(549.6 - 288) = 262.9$ KJ/kg

work output of H.p turbine = work input to compressor.

$$C_{pg}\,(T_3 - T_4') = 262.9 \Rightarrow T_4' = 654.4K$$

$$1.15\,(883 - T_4') = 262.2$$

$$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.85 = \frac{883 - 654.4}{883 - T_4} \Rightarrow T_4 = 614K.$$

2. 3-4 process :- (Isentropic expansion)

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$P_4 = \frac{P_3}{4.32} = 1.636 \text{ bar}$$

pressure of gases entering the L.p or power turbine = 1.636 bar

3) Net power developed / kg/s mass flow =

$\boxed{\begin{matrix} P_2 = P_3 \\ P_1 = P_5 \end{matrix}}$

pressure ratio $\frac{P_4}{P_5} \Rightarrow \frac{P_4}{P_3} \times \frac{P_3}{P_5}$

$$= \frac{P_4}{P_3} \times \frac{P_2}{P_5} = \frac{7}{4.32} = 1.62$$

Then

$$\frac{T_4'}{T_5} = \left(\frac{P_4}{P_5}\right)^{\frac{\gamma-1}{\gamma}} = (1.62)^{\frac{0.33}{1.33}} = 1.127$$

$$T_5 = \frac{T_4'}{1.127} = 580.6K$$

Efficiency of turbine (L.p turbine) $= \frac{T_4' - T_5'}{T_4' - T_5}$

$$0.85 = \frac{654.4 - T_5'}{654.4 - 580.6}$$

$T_5' = 654.4 - 0.85\,(654.4 - 580.6) = 591.7\,K$

work of L.P turbine $= C_{pg}\,(T_4' - T_5') = 1.15\,(654.4 - 591.7)$
$= 72.1$ kJ/kg

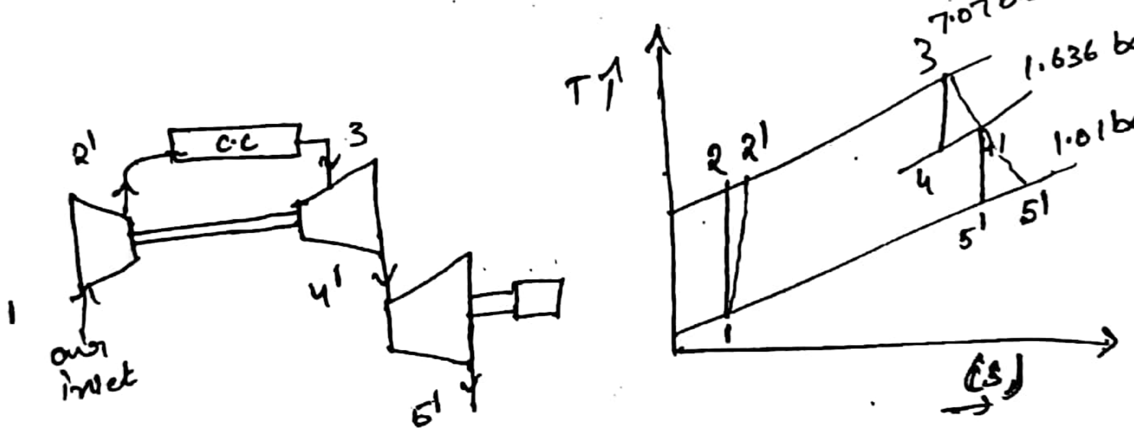
hence net power output $= 72.1$ kW

3) work ratio :- $\dfrac{\text{Net work output}}{\text{Gross work output}} = \dfrac{72.1}{72.1 + 262.9} = 0.215$

4) Thermal efficiency of the unit ($\eta_{thermal}$) :-

Heat supplied $= C_{pg}\,(T_3 - T_2') = 1.15\,(883 - 549.6)$
$= 383.4$ kJ/kg

$\eta_{thermal} = \dfrac{\text{Network output}}{\text{Heat supplied}} = \dfrac{72.1}{383.4} = 18.8\%$



3. The pressure ratio of an open-cycle gas turbine power plant is 5.6. Air is taken at 30°c and 1 bar. The compression is carried out in two stages with perfect intercooling in between. The maximum temperature of the cycle is limited to 700°c. Assuming isentropic efficiency of each compressor stage as 85% and that of turbine as 90%. Determine the power developed and the efficiency of power plant, if the air flow is 1.2 kg/s. The mass of fuel may be neglected, and it may be assumed that $c_p = 1.02$ kJ/kg K and $\gamma = 1.41$

The pressure ratio of the open-cycle gas turbine $= 5.6$
Temperature of intake air (T_1) $= 30°c = 30 + 273 = 303K$
pressure of intake air (P_1) $= 1$ bar
Maximum temperature of cycle $= (T_3) = 700 + 273 = 973\,K$
Isentropic efficiency of each compressor (η_{comp}) $= 85\%$
Isentropic efficiency of turbine ($\eta_{turbine}$) $= 90\%$

mass rate of flow $(m_a) = 1.2$ kg/s, $c_p = 1.02$ kJ/kg $\gamma = 1.4$.

power developed and efficiency of the power plant 9.

assume pressure ratio in each stage is same we have

$$\frac{p_2}{p_1} = \frac{p_4}{p_3} = \sqrt{\frac{p_4}{p_1}} = \sqrt{5.6} = 2.366.$$

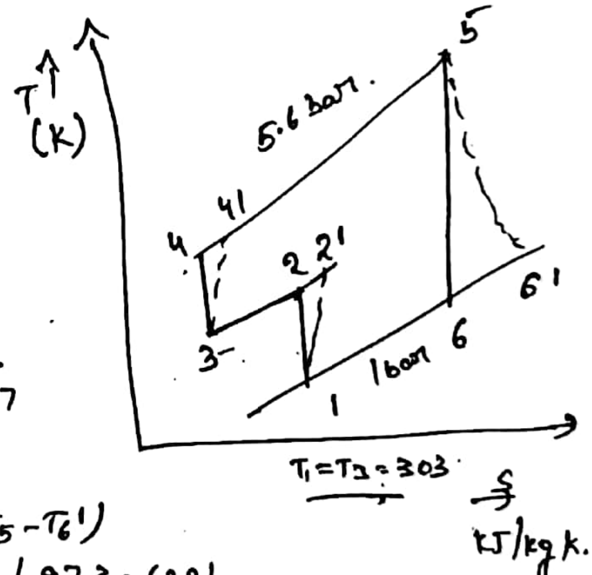
$\eta_{comp_1} = \eta_{comp_2}$ and $\frac{p_2}{p_1} = \frac{p_4}{p_3}$ so that work required for each compressor is same since both the compressors have the same inlet temperature $T_1 = T_3$, $T_2' = T_4'$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = (2.366)^{\frac{1.4-1}{1.4}} = T_2 = (303)(1.2846) = 389.23\,K.$$

$$\eta_{comp} = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow T_2' = \frac{389.23 - 303}{0.85} + 303 = 404.44\,K.$$

2-stage compressor $= 2 \times m \times c_p (T_2' - T_1) = 2 \times 1.2 \times 1.02 (404.44 - 303) = 248.32$ kJ/s

For turbine we have



$$\frac{T_5}{T_6} = \left(\frac{p_5}{p_6}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_6 = \frac{973}{1.65} = 589.7\,K.$$

$$\eta_{turbine} = \frac{T_5 - T_6'}{T_5 - T_6} = 0.9 = \frac{973 - T_6'}{973 - 589.7}$$

$T_6' = 628\,K.$

work output of turbine $= m c_p (T_5 - T_6')$
$= 1.2 \times 1.02 (973 - 628)$
$= 422.28$ kJ/sec.

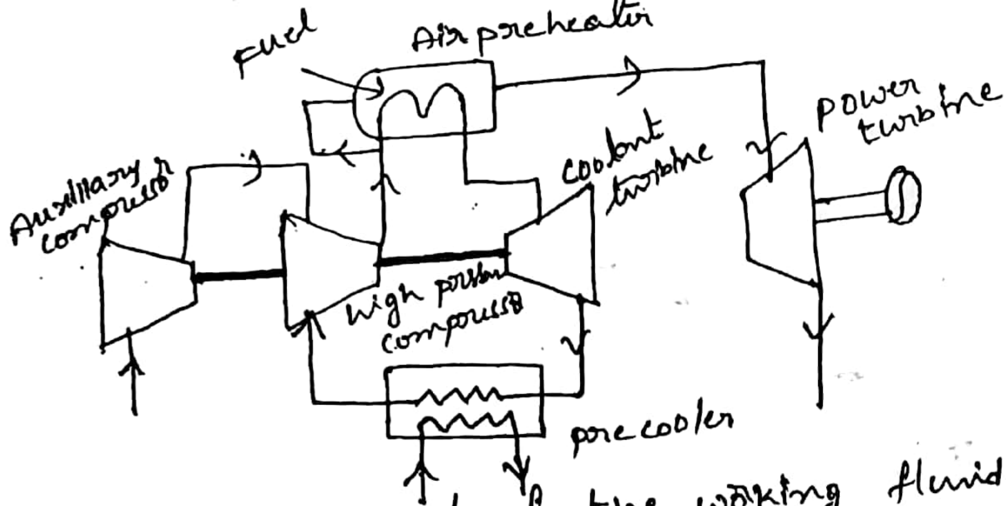
net work output $= w_{turbine} - w_{compressor}$
$= 422.28 - 248.32$
$= 173.96$ kJ/sec.

hence power developed $= 173.9$ kW

heat supplied $(Q_s) = m c_p (T_5 - T_4')$
$= 1.2 \times 1.02 (973 - 404.44)$
$= 695.92$ kJ/sec.

$$\eta_{efficiency} = \frac{W_{net}}{Q_s} = 0.25 = 25\%.$$

Semi closed cycle gas turbine :-



when some part of the working fluid is confined to the plant and another part flows into and from the atmosphere it is called semi cycle. It is basically a high pressure system and the component parts are smaller than an open cycle for the same power output.

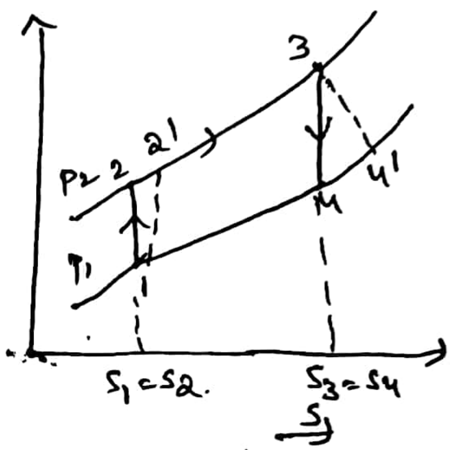
The basic working medium is air. compressed air from auxillary compressor and exhaust air of turbine compressor, passing through the precooler enters the high pressure compressor and is compressed. The high pressure air before entering the air heater is in two parts one part serving the power turbine is used to intial combustion in the air heater and another ~~plant~~ part which does not mix with the fuel is heated by the heat of external combustion so that all the time this part of air may be circulated in a closed system. The exhaust of power turbine goes to atmosphere.

10

The air enters the compressor of an open cycle plant pressure of 1 bar and temperature 20°c The pressure of air after compression is 4 bar. The isentropic efficiency of compressor and turbine are 80% and ~~85%~~ respectively The air fuel ratio used as 90:1. If the flow rate of air is 3.0 kg/s Find power developed, Thermal efficiency of cycle $C_p = 1.0$ KJ/kgK, $\gamma = 1.4$ for air and gases cv of fuel = 41800 KJ/kg

$P_1 = 1$ bar, $P_2 = 4$ bar, $\eta_{compressor} = 0.8$, $\eta_t = 0.85$

$T_1 = 20+273 = 293K$, $A/F = 90/1$, $m_a = 3.0$ kg/sec.



1-2 process:-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = (20+273)(1.486)$$
$$= 435.4\ K.$$

$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$T_2' = \frac{435.4 - 293}{0.8} + 293 = 471\ K$$

3-4 process :- $T_3/T_4 = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$

$$T_4 = 1268 \times 0.634 = 803.9K$$

Heat supplied by fuel = Heat taken by burning gases

$$m_f \times cv = (m_a + m_f)\, C_p (T_3 - T_2')$$
$$cv = \left(\frac{m_a}{m_f} + 1\right) C_p\, (T_3 - T_2')$$
$$41800 = (90+1)\ 1.0\ (T_3 - 471)$$
$$T_3 = 930\ K$$
$$T_4 = 624.9\ K$$

$$\eta_T = \frac{T_3 - T_4'}{T_3 - T_4}$$
$$T_4' = 930 - 0.85(930 - 624.9)$$
$$= 670.6\ K.$$

workdone by turbine $= (m_f + m_a)\, C_p\, (T_3 - T_4')$
$$= m_a\left(\frac{m_f}{m_a} + 1\right) C_p\, (T_3 - T_4')$$
$$= 1\ \left(\frac{1}{90} + 1\right)\ 1.0\ (930 - 670.6)$$

$= 262.28$ kJ/kg of air

$W_{compressor} = m_a c_p (T_2' - T_1)$
$= 1 \times 1.0 \; (471 - 293) = 178$ kJ/kg of air

$W_{net} = W_T - W_C$
$= 262.28 - 178 = 84.28$ kJ/kg of air

power $=$ Wnet $\times$ mass of air
$= 84.28 \times 3 = 252.84$ kW/kg of air

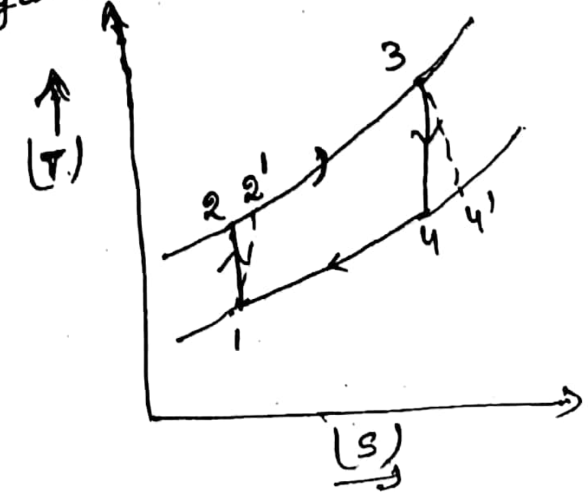
$$\eta_{thermal} = \frac{\text{work output}}{\text{Heat supplied}}$$

Heat supplied $= \left(\frac{m_f}{m_a}\right)$ CV
$= \left(\frac{1}{90}\right) 41800 = 464.44$ kJ/kg of air

$$= \frac{84.28}{464.44}$$

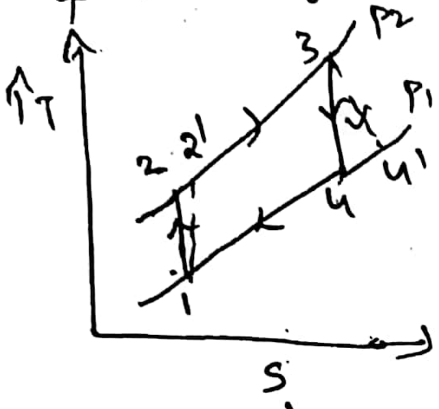
$= 0.1814$ %

In a constant pressure open cycle gas turbine air enters at 1 bar and 20°c and leaves the compressor at 5 bar. Using the following data Temperature of gases entering the turbine 680°c, pressure loss in the combustion chamber 0.1 bar, $\eta_c = 85\%$, $\eta_t = 80\%$, $\eta_{cc} = 85\%$, $\gamma = 1.4$, $c_p = 1.024$ kJ/kgK for the air and gas. Find the quantity of air circulation if the plant develops 1065 kW, Heat supplied/kg of air circulation the thermal efficiency of cycle mass of fuel may be neglected.



Given :-
$P_1 = 1$ bar, $P_2 = 5$ bar
$P_3 = 5 - 0.1 = 4.9$ bar, $P_4 = 1$ bar
$T_1 = 20 + 273 = 293$ K
$T_3 = 680 + 273 = 953$ K
$\eta_c = 0.85$, $\eta_T = 0.8$, $\eta_{cc} = 0.85$
$P = 1065$ kW, $c_p = 1.024$ kJ/kgK
$\gamma = 1.4$

A gas turbine unit has a pressure ratio of 6:1 and maximum cycle temperature of 610°C. The isentropic efficiencies of compressor and turbine are 0.8 and 0.82 calculate power output when the air enters the compressor at 15°c at the rate of 16 kg/sec. Take $C_p = 1.005$ KJ/kgK $\gamma = 1.4$ for compression $C_p = 1.11$ KJ/kgK and $\gamma = 1.333$ for expansion process.



$T_1 = 15 + 273 = 288K$ $\quad \frac{P_2}{P_1} = \frac{6}{1}$

$T_3 = 610 + 273 = 883 K$

$\eta_c = 0.8, \ \eta_T = 0.82$

Air flow rate 16 kg/sec.

$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = 481K.$

$\eta_c = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow T_2' = 529K$

$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_4 = 564K.$

$\eta_T = \frac{T_3 - T_4'}{T_3 - T_4} = 621.4K$

Compressor work input
$= C_p (T_2' - T_1)$
$= 1.005 (529 - 288) = 242.2$ KJ/kg

Turbine work output
$= C_p (T_3 - T_4')$
$= 1.11 (883 - 621.4)$
$= 290.4$ KJ/kg

Network output $= W_T - W_C$
$= 290.4 - 242.2 = 48.2$ KJ/kg

power in KW $= 48.2 \times 16$ mass $= 771.2$ KW

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

$\left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4}$