University of Anbar

College of Engineering

Mechanical Eng. Department

Power Plants

Chapter one

Steam Power Plant

by

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Power Plants

A Power Plant may be defined as a machine or assembly of equipment that generates and delivers a flow of mechanical or electrical energy.

Classification of Power Plants

1. Conventional Power Plants

   - Steam Turbine Power Plant
   - Gas Turbine Power Plant
   - Diesel Power Plant
   - Nuclear Power Plant

2. Non-conventional Power Plants

   - Wind Energy Power System
   - Solar Thermal Power Plant
   - Ocean Thermal Energy Conversion
   - Biomass Energy Power System
   - Geothermal Energy

Energy sources

1. Renewable energy sources

   - Salar energy
   - Wind energy

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- Tidal energy
- Flowing of stream of water

2. Non-renewable energy Sources

- Coal
- Petroleum
- Natural gas
- Nuclear power

Fuels

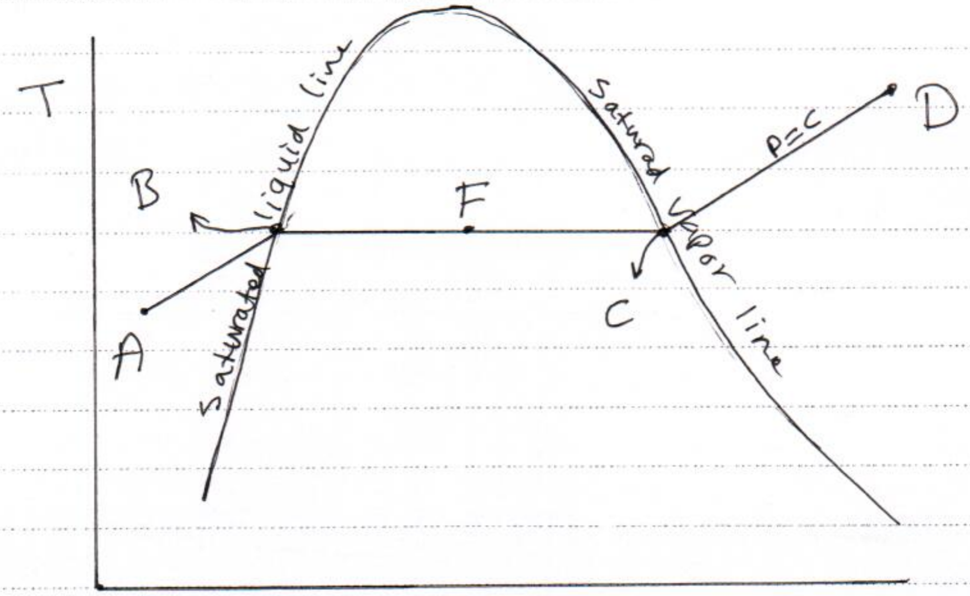
It is defined as any material which when burn will produce heat. Various fuels commonly used are as follows :-

- Solid fuels (Wood, lignite, Coal)
- Liquid fuels (Petroleum)
- Gasous fuels (Natural gas)

Definitions :~

- Subcooled water (A) :~ It refers to water existing below its normal saturation temp.

- Saturated liquid (B) :~ a liquid that exists at the saturation temperature or boiling point that corrosponding to the existing pressure. If any energy is added to the liquid and the pressure remain constant, some of the liquid would boil. During boiling, temp. will remain constant.



- Saturated Vapor (C) :~

A Vapor that exists at the saturation temprature that corrosponding to the existing pressure. If any energy was removed while the pressure is constant, some the vapour would condense and the temp. reamins constant.

- Superheated steam (D) :~

Steam existing at a temp. above the saturation temprature that corrosponding to the existing pressure. The removal of a small amount of energy will not cause the vapor to dendence, its temprature will just decrease.

- Wet Steam (F) :~

It is a mixture of ~~water~~ liquid and vapor. If additional heat is added to the wet steam at constant pressure, the temprature remains constant untill all liquid is evaporated (saturated steam)

- Dryness Fraction:-

It is a ratio of vapor mass to the total mass.

$$X = \frac{m_v}{m_v + m_L}$$

Where m_v: vapor mass
m_L: liquid mass

- Moisture Content:-

It is the ratio of liquid mass to the total mass

$$y = \frac{m_L}{m_L + m_v}$$

$$\therefore \quad X + y = 1$$

h_f : Enthalpy of water (KJ/Kg.K)

h_g : Enthalpy of dry steam (KJ/Kg.K)

h_x : Enthalpy of wet steam (KJ/Kg.K)

$$h_x = h_f + x\, h_{fg}$$

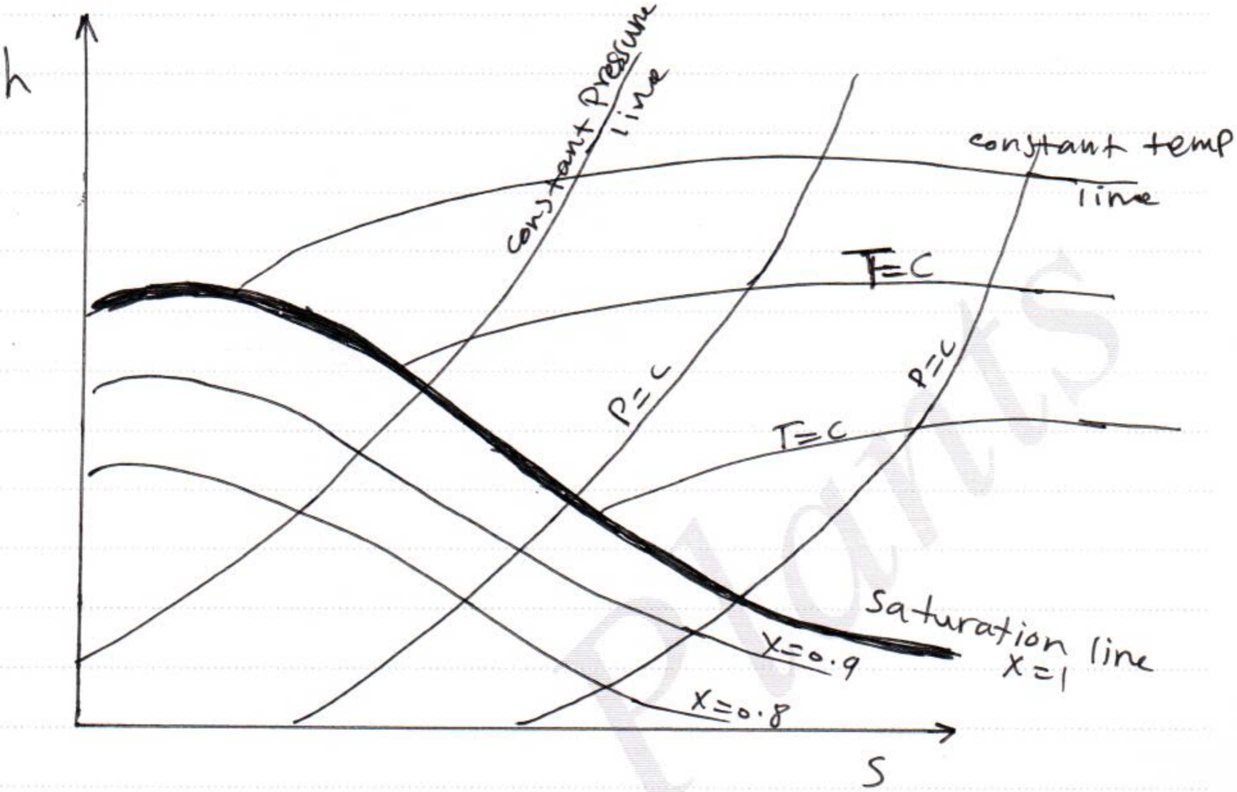
where $h_{fg} = h_g - h_f$

So, $x = \dfrac{h_x - h_f}{h_g}$

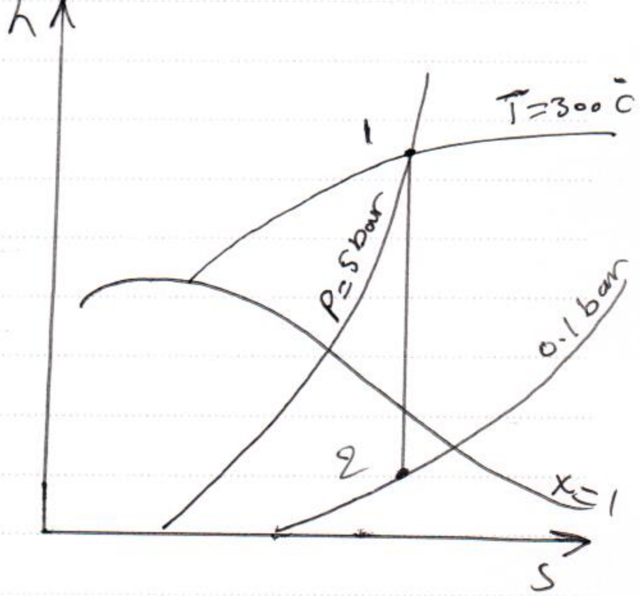
* h-s daigram (Mollier Chart)

The Mollier Chart is a chart on which enthalpy (h) versus entropy (s) is plotted. The chart contains a series of constant tempreture lines, a series of constant pressure, a series of constant quality lines.

The Mollier chart is used when quality (x) is greater than 50% and for ~~sapp~~ super heated steam



Ex/ Find the enthalpy drop when steam expand from 5 bar, 300 °C to 0.1 bar Using Mollier chart



$h_1 = 3070$ KJ/Kg

$h_2 = 2370$ KJ/Kg

$\Delta h = h_1 - h_2$

$= 3070 - 2370$

$= 700$ KJ/Kg

Steam Power Plant Cycles

Steam is most common working fluid used in vapor power plant cycles because of its many desirable characteristics such as :-

- low cost
- availability
- high enthalpy of vaporization

Steam Power Plant are commonly referred to as Coal Plant, nuclear plant, or natural gas plant depending on type of fuel used to apply heat to the steam.

- Vapor Power Cycles Classifications :-

- Carnot vapour Power Plant
- Rankine cycle
- Reheat cycle
- Regenerative cycle

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- Performance Parameters:

✓ - Thermall efficiency:

Thermall efficiency is the parameter which gauges the extent to which the energy input to the device is converted to net work output from it.

$$\text{Thermal efficiency } \eta = \frac{\text{Net Work in cycle}}{\text{Heat added in cycle}}$$

✓ - Work ratio

It refer to the ratio of net work to the Positive work.

$$W_T - \cancel{W_P}$$

$$\text{Work ratio} = \frac{W_{net}}{W_{turbine}}$$

✓ - Specific Steam Consumption (SSC):

It indicates the steam requirment per unit power output, and it is given in Kg/Kw.h

$$SSC = \frac{3600}{W_{net}} \quad , \boxed{Kg/Kwh}$$

* Carnot vapour Power cycle

Carnot cycle can be defined as an ideal cycle having highest thermodynamic efficiency.

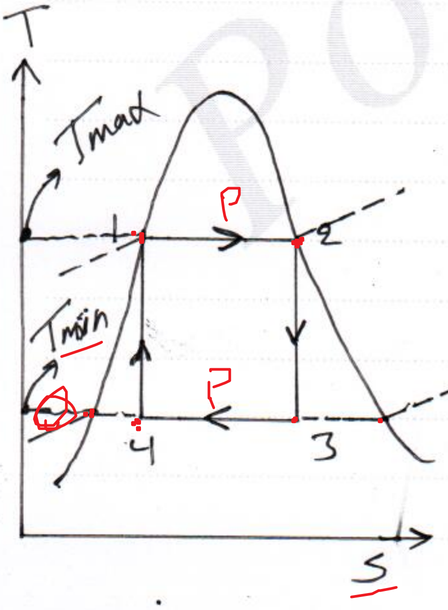
Arrangment proposed for using carnot vapour Power cycle is as follows :-

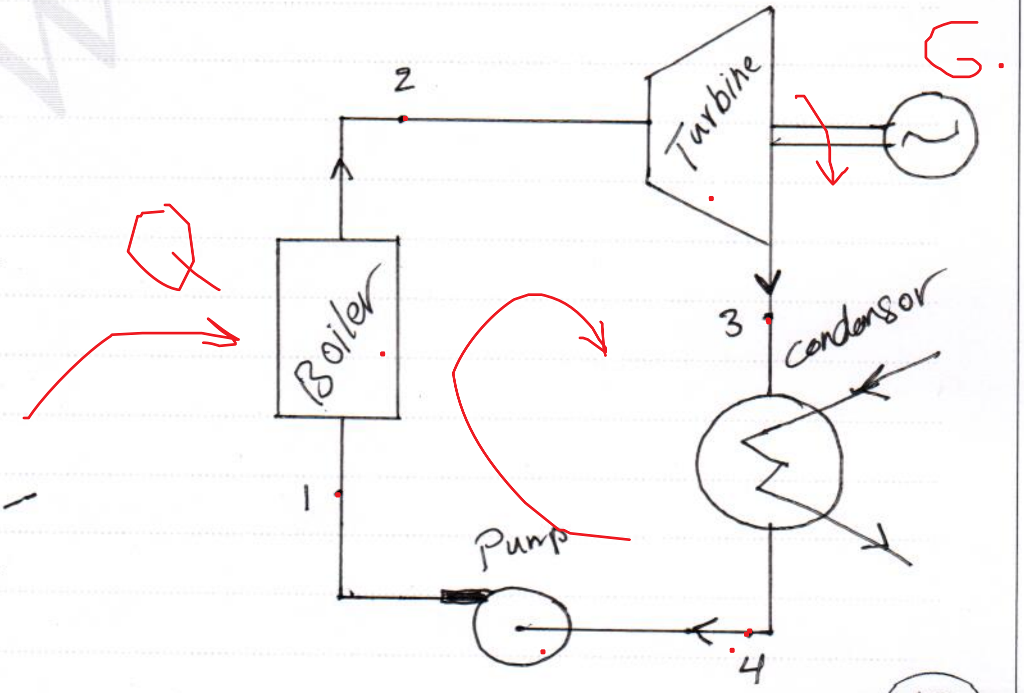
1-2 = Reversible isothermal heat addition in the boiler

2-3 = Reversible adiabatic expansion in steam turbine

3-4 = Reversible isothermal heat rjection in the condensor.

4-1 = Reversible adiabatic compression or Pumping in feed water pump.





Power Plants

Assuming steady-state flow processes in the cycle and neglecting changes in kinetic and potential energy:

$$\text{Thermal efficiency} = \frac{\text{Net work}}{\text{Head added}}$$

$$\text{Net work} = \text{Turbine work} - \text{Pumping work}$$

$$= \underline{(h_2 - h_3)} - \underline{(h_1 - h_4)}$$

$$\text{Head added} = h_2 - h_1$$

$$\eta_{carnot} = \frac{(h_2 - h_3) - (h_1 - h_4)}{(h_2 - h_1)}$$

$$= 1 - \frac{h_3 - h_4}{h_2 - h_1}$$

$$Q_{rejected} = h_3 - h_4$$

$$\eta_{carnot} = 1 - \frac{Q_{rej}}{Q_{add}}$$

Also, heat added and rejected may be given as function of temp. and entropy as follows :-

$$Q_{add} = T_1 * (S_2 - S_1)$$

$$Q_{rej} = T_3 * (S_3 - S_4)$$

$$S_1 = S_4 \quad , \quad S_2 = S_3$$

Therefore, Substituting values,

$$\boxed{\eta_{Carnot} = 1 - \frac{T_3}{T_1}}$$

$$T_1 = T_2 \quad , \quad T_3 = T_4$$

* Limitations of Carnot cycle

Although Carnot cycle is simple thermodynamically and has the highest thermal efficiency, it is difficult to operate in practice because of the following reasons :-

1. It is diffucult to compress a wet vapour isentropically to the saturated state as required by the process 4 – 1

2. It is difficult to control the quality of the condensate coming out of the condensor, so that the state (4) is hard to obtain.

3. It is difficult for a pump to handle wet mixture ~~steam~~ which undergoes simultanous change in ~~its~~ phase as its pressure increases

Ex/ In a steam power plant, the steam supply is at 15 bar and dry saturated. The condenser pressure is 0.4 bar. Calculate the Carnot efficiency

Solution:~

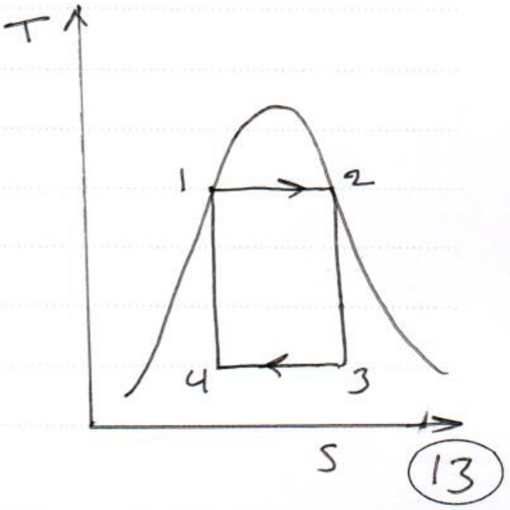
From Steam table:

At 15 bar: $t_s = 198.3\,^\circ C = T_1 = T_2$, $T_1 = 198.3 + 273 = 471.3\,K$

At 0.4 bar: $t_s = 75.9\,^\circ C = T_3 = T_4$, $T_3 = 75.9 + 273 = 348.9\,K$

$$\eta_{Carnot} = 1 - \frac{T_{min}}{T_{max}}$$

$$= 1 - \frac{348.9}{471.3} = 25.9\,\%$$



* Rankine Cycle

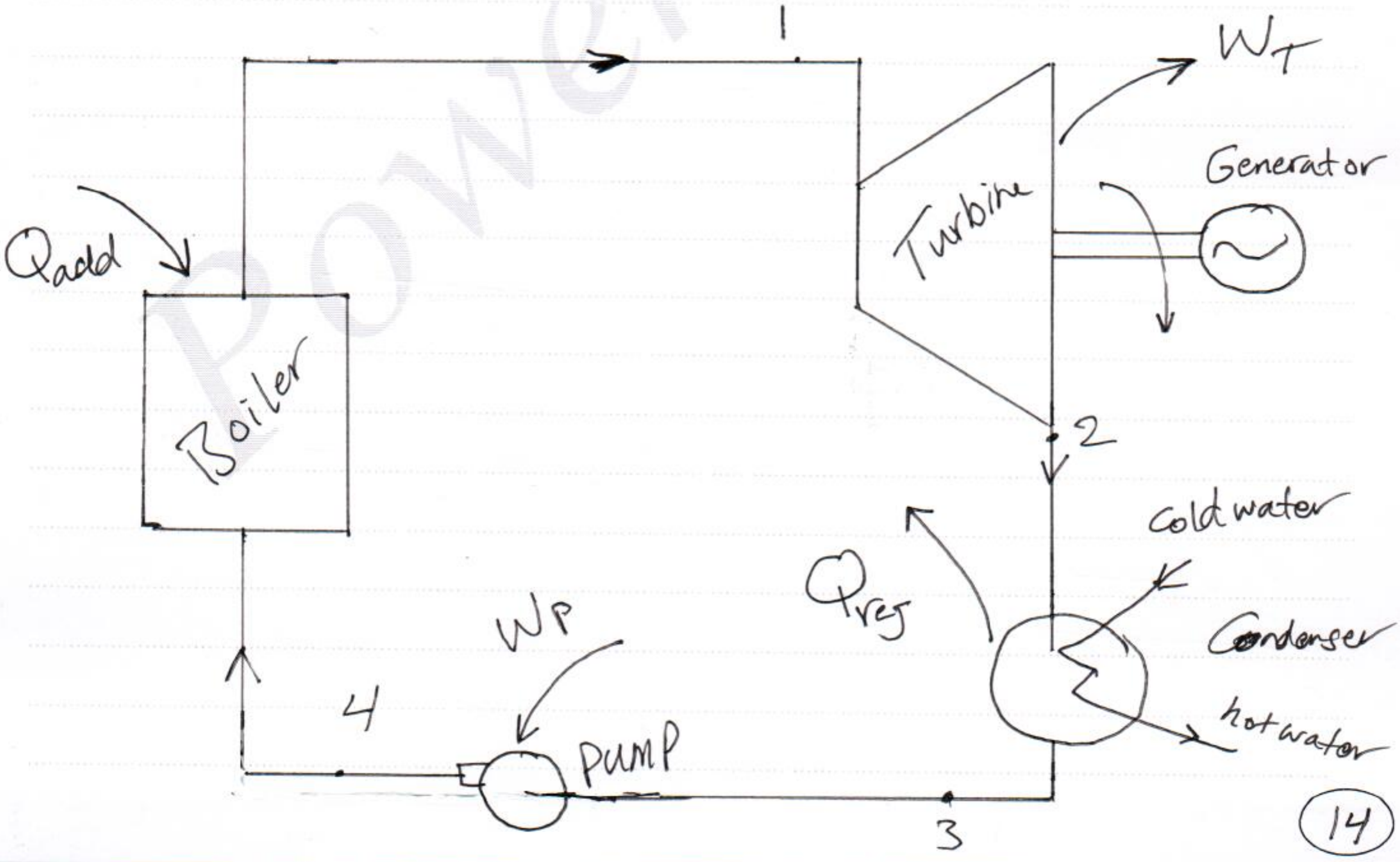
Rankine cycle is a thermodynamic cycle derived from Carnot vapour power cycle for overcoming its limitations. Rankine cycle has the following thermodynamic processes:

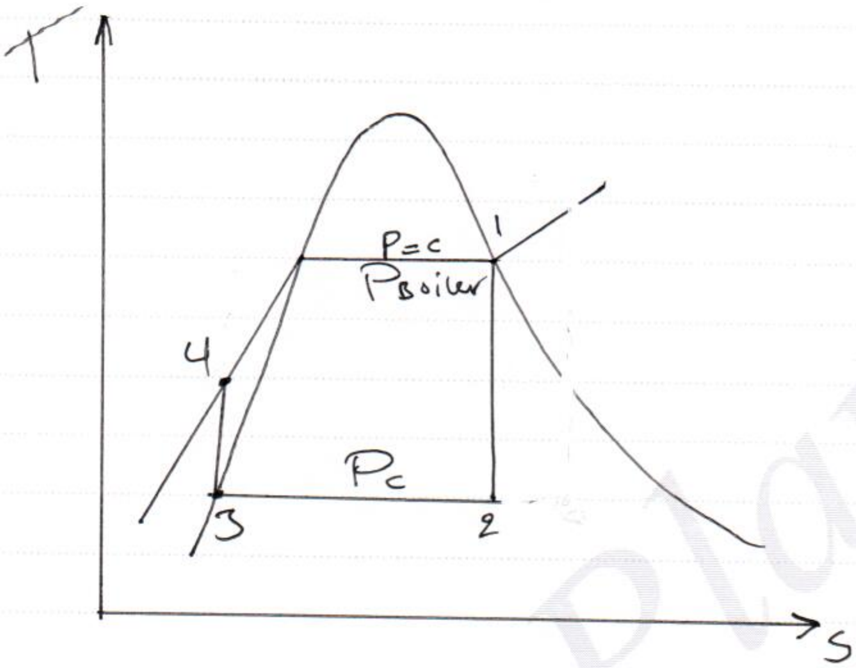
1-2 = Reversible adiabatic expansion in the turbine

2-3 = Constant-pressure transfer of heat in the Condenser.

3-4 = Reversible adiabatic pumping process in the feed Pump

4-1 = Constant-pressure transfer of heat in the boiler.





By applying steady flow energy equation to boiler, turbine, condenser and pump, we get:-

(i) For boiler

$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_o\left(h_o + \frac{V_o^2}{2} + gz_o\right)$$

Assumptions:-

* Steady state $\left(\frac{dE_{cv}}{dt} = 0\right)$

* No change in velocity $\left(\frac{V_i^2}{2} - \frac{V_o^2}{2} = 0\right)$

* No change in elevation $(gz_i - gz_o = 0)$

$\therefore$

$$0 = \dot{Q} - \dot{W} + \dot{m}_i h_i - \dot{m}_o h_o \quad , \quad \dot{m}_i = \dot{m}_o$$

$$\boxed{0 = q - w + h_i - h_o} \text{ ——— equ ①}$$

In boiler, there is no work added or rejected
$w = 0$

$$q_{add} = h_o - h_i$$

or $\boxed{q = h_1 - h_4}$ (for boiler Q_{add})

(ii) For turbine

Same steps are applied as we did above.

for turbine, there is heat added ~~or~~ rejected ($Q = 0$)

from equ ①

$$0 = -W + h_i - h_o$$

or

$$\boxed{W_{turbine} = h_1 - h_2}$$ (for turbine W_T)

(iii) For Condenser

In condenser, there is no work added or rejected ($W=0$)

So , from equation (1)

$0 = -q + h_i - h_o$ (the signal(-) is accounted fro heat rejection)

Or $\boxed{Q_{cond.} = h_2 - h_3}$ (for Condenser Q_{rej})

(iv) For feed pump

In pump, there is no heat added or rejected ($Q=0$)

so, from equ. (1)

$0 = +W + h_i - h_o$

the signal (-) was changed to (+) beacuse the pump work is input

So

$W_{pump} = h_o - h_i$

$\boxed{W_{pump} = h_4 - h_3}$ (for pump W_p)

Now, efficiency of Rankine cycle is given by :-

$$\eta_{Rankine} = \frac{W_{net}}{Q_{add}}$$

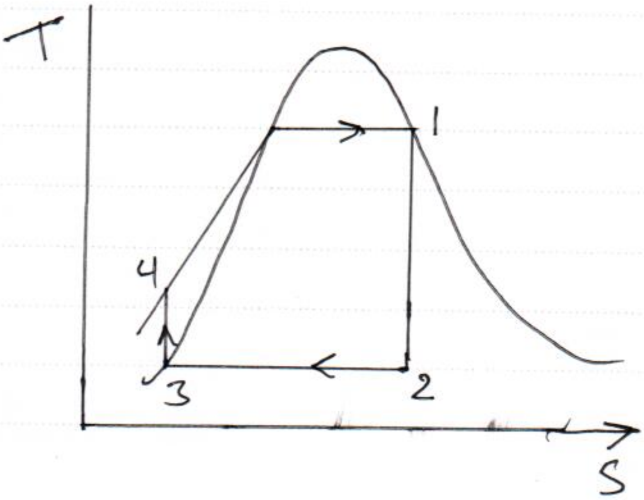
$$= \frac{W_T - W_P}{Q_{add}}$$

$$\boxed{\eta_{Rankine} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}}$$

$$W_{pump} = v\,(P_{Boiler} - P_{cond.}) = h_4 - h_3$$

Ex/ The same example above, Calculate Rankine efficiency cycle ?

Solution:-



From steam table

at 15 bar $h_1 = h_g = 2789.9$ KJ/Kg
$S_1 = S_g = 6.4406$ KJ/Kg K

at 0.4 bar $h_3 = h_f = 317.7$ KJ/Kg
$h_{fg} = 2319.2$ KJ/Kg
$S_f = 1.0261$ KJ/Kg K
$S_{fg} = 6.6448$ KJ/Kg K
$\nu = 0.001$ m^3/Kg

$S_1 = S_2$ (steam expands isentropically)

$S_2 = Sf_2 + X_2 S_{fg}$
$6.6406 = 1.0261 + X_2 * 6.6448$

$X_2 = 0.815$

$h_2 = h_f + X h_{fg}$
$= 317.7 + 0.815 * 2319.2$
$= 2207.8$ KJ/Kg

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$\nu (P_2 - P_1) = h_4 - h_3$ 1 bar = 100 KPa
$0.001(1500 - 40) = h_4 - 317.7$
$h_4 = 319.16$ KJ/Kg

$W_{done} = W_T - W_C = (h_1 - h_2) - (h_4 - h_3)$

$= (2789.9 - 2207.8) - (319.16 - 317.7)$

$W_{done} = 580.64$ KJ/Kg

$Q_{add} = h_1 - h_4$

$= (2789.9 - 319.16)$

$= 2470.74$ KJ/Kg

$$\eta_{Rankine} = \frac{W_{done}}{Q_{add}}$$

$$= \frac{580.64}{2470.74} = 23.5\ \%$$

Irreversibilities and losses in Rankine Cycle

In Rankine cycle, the major irreversibility is encountered during the expansion through turbine. Irreversibities in turbine significantly reduce the expansion work.

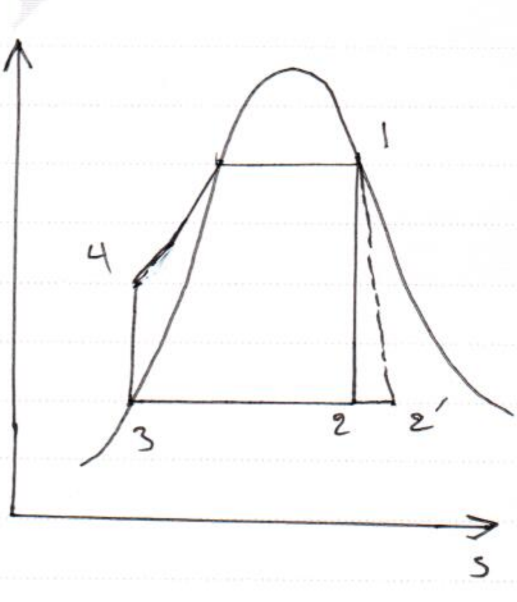
This deviation of expansion from ideal to actual process can be accounted for by isentropic turbine efficiency.

Ideal expansion in steam turbine is shown by 1-2 on T-s representation. Actual expansion process is shown by 1-2′

$$\eta_{isen,t} = \frac{W_{t,\,actual}}{W_{t,\,ideal}}$$

$$= \frac{W_{1-2'}}{W_{1-2}}$$

$$W_{1-2'} < W_{1-2}$$



$$\boxed{\eta_{isen.,t} = \frac{h_1 - h_2'}{h_1 - h_2}}$$

Ex/ A steam power plant operates between a boiler Pressure of 42 bar and a condenser pressure of 0.035 bar. Calculate for these limites the cycle efficiency

(i) for a Rankine cycle with dry saturated steam at entry to the turbine

(ii) for Rankine cycle of (i) when the expansion process has an isentropic efficiency of 80%

Solution :

(i) From steam table

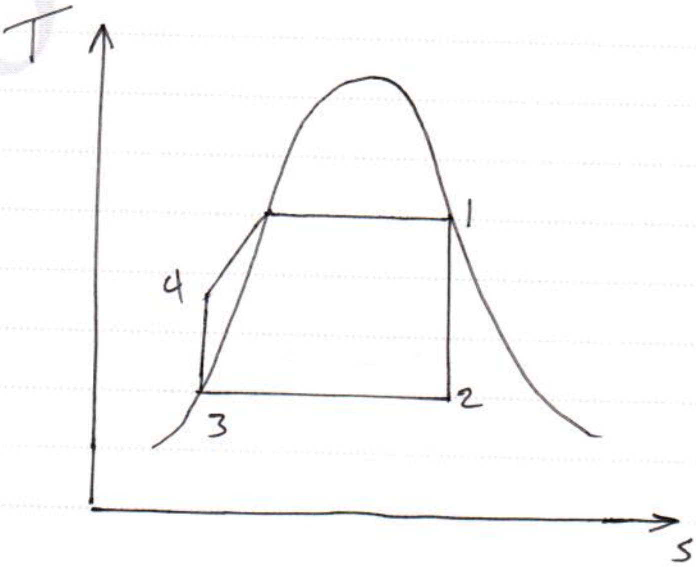
At 42 bar $T_{saturation} = 253.2\,^{\circ}C$

$h_{fg} = 1698$ KJ/Kg

$h_1 = h_g = 2800$ KJ/Kg

$S_1 = S_g = 6.049$ KJ/Kg K

$S_1 = S_2$



At 0.035 bar $\quad s_f = s_3 = 0.391$ KJ/KgK

$s_{fg} = 8.13$ KJ/KgK

$s_2 = 6.049 = s_f + X_2\, s_{fg}$

$6.049 = 0.391 + X_2 * 8.13$

$X_2 = 0.696$

$h_2 = h_f + X_2\, h_{fg}$

At 0.035 bar $\quad h_f = 112$ KJ/Kg $= h_3$

$h_{fg} = 2438$ KJ/Kg

$h_2 = 112 + 0.696 * 2438$.

$= 1808$ KJ/Kg

$v(P_2 - P_1) = h_4 - h_3$

$0.001\,(4200 - 3.5) = h_4 - 112$

$h_4 = 116.2$ KJ/Kg

$W_{net} = W_t - W_c$

$= (h_1 - h_2) - (h_4 - h_3)$

$= (2800 - 1808) - (116.2 - 112)$

$= 987.8$ KJ/Kg

$Q_{add} = h_1 - h_4$

$= 2800 - 116.2$

$= 2683.8$ kJ/kg

$$\eta_{Rankine, ideal} = \frac{W_{net}}{Q_{add}} = \frac{987.8}{2683.8} = 36.8\%$$

(ii) When turbine isen. efficiency is 80%

$$\eta_{isen,t} = \frac{h_1 - h_2'}{h_1 - h_2}$$

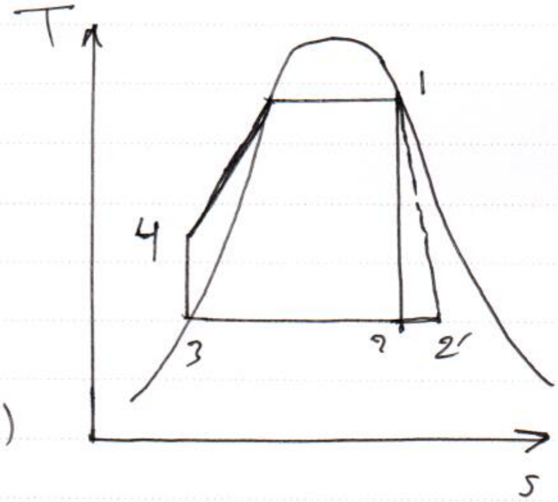
$$0.8 = \frac{2800 - h_2'}{2800 - 1808}$$

$h_2' = 2006.4$ kJ/kg

$W_{net} = (h_1 - h_2') - (h_4 - h_3)$

$= (2800 - 2006.4) - (116.2 - 112)$

$= 789.4$ kJ/kg

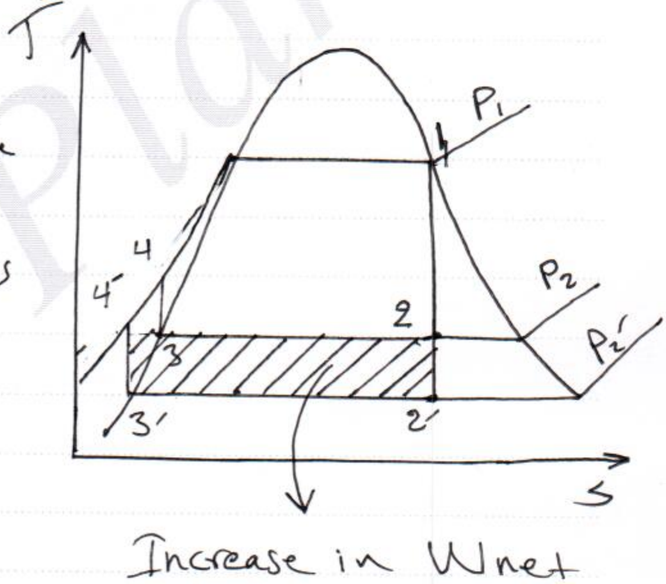


$$\eta_{Rankine, actual} = \frac{789.4}{2683.8} = 29.4\%$$

Increasing Rankine cycle efficiency

Steam power plants are used for the production of most of the electric power in the word, therefore, small increase in thermal efficiency can mean large saving of fuel requirment

1. Lowering the condenser pressure:



The dashed area in this daigram represents the increase in W_{net}.
The heat input also increases (4-4') but this increase is very small

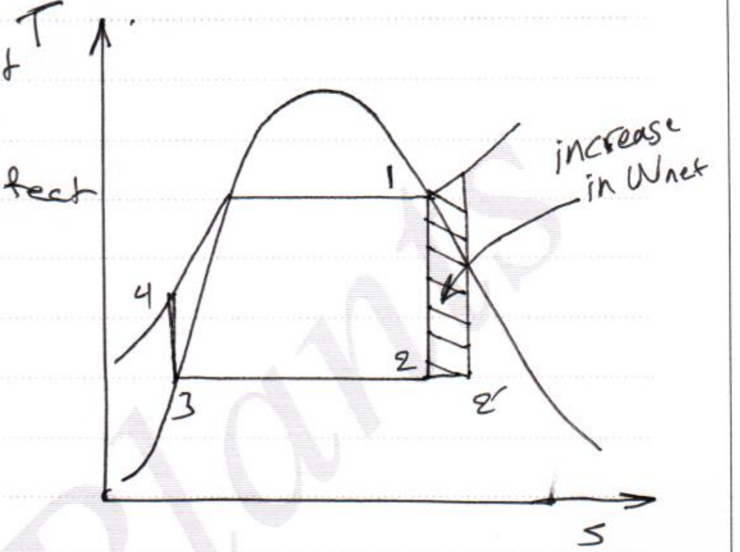
Dis advantage

- It increases the moisture content of the steam at the final stages of the turbine.

The large quantities of moisture are highly undesirable because it erodes the turbine blades

2. Superheating the steam to high temperature :

Both the W_{net} and heat input increase as a result of superheating. The overall effect is an increas in η

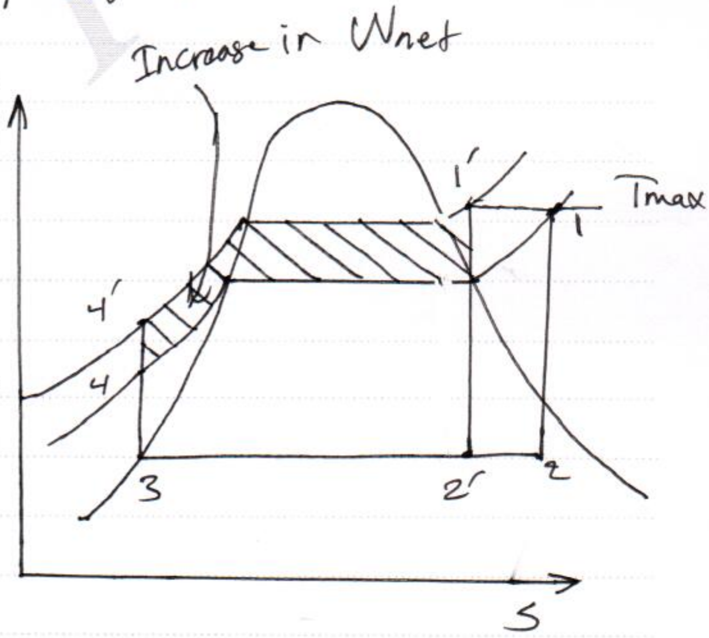


3. Increasing the boiler pressure

It raises the average temp at which heat is added to the steam and thus raises the η.

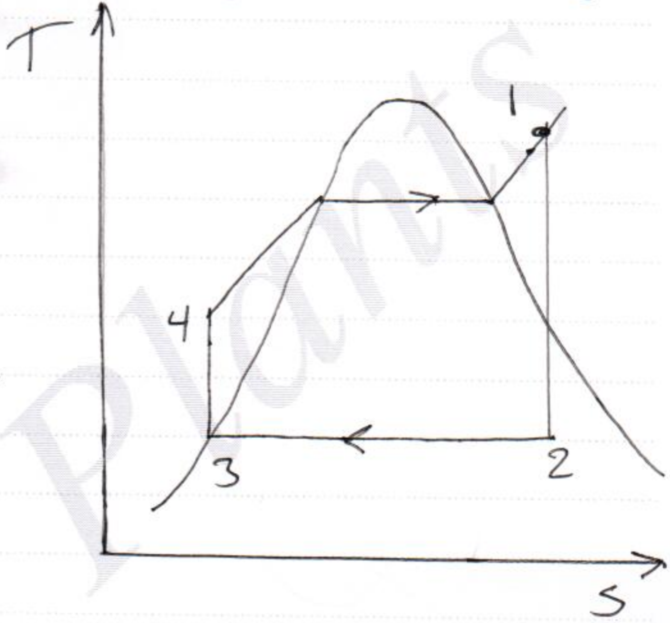
For a fixed turbine inlet temp., the cycle shifts to the left and moisture content of the steam at the turbine exit increases.

This side effect can be corrected by reheating the system



EX / In steam power plant, steam enters turbine at conditions of 42 bar, 500°C and exits at 0.035 bar. Calculate efficiency of the cycle?

Solution:~



From steam table
At 42 bar, 500°C
$h_1 = 3442.6$ KJ/Kg
$S_1 = 7.066$ Kg/Kg $= S_2$

At 0.03 bar
$h_f = 112$ KJ/Kg
$h_{fg} = 2438$ KJ/Kg
$S_f = 0.391$ KJ/KgK
$S_{fg} = 8.13$ KJ/KgK

$S_2 = S_f + X_2 S_{fg}$
$7.066 = 0.391 + X_2 \times 8.13$

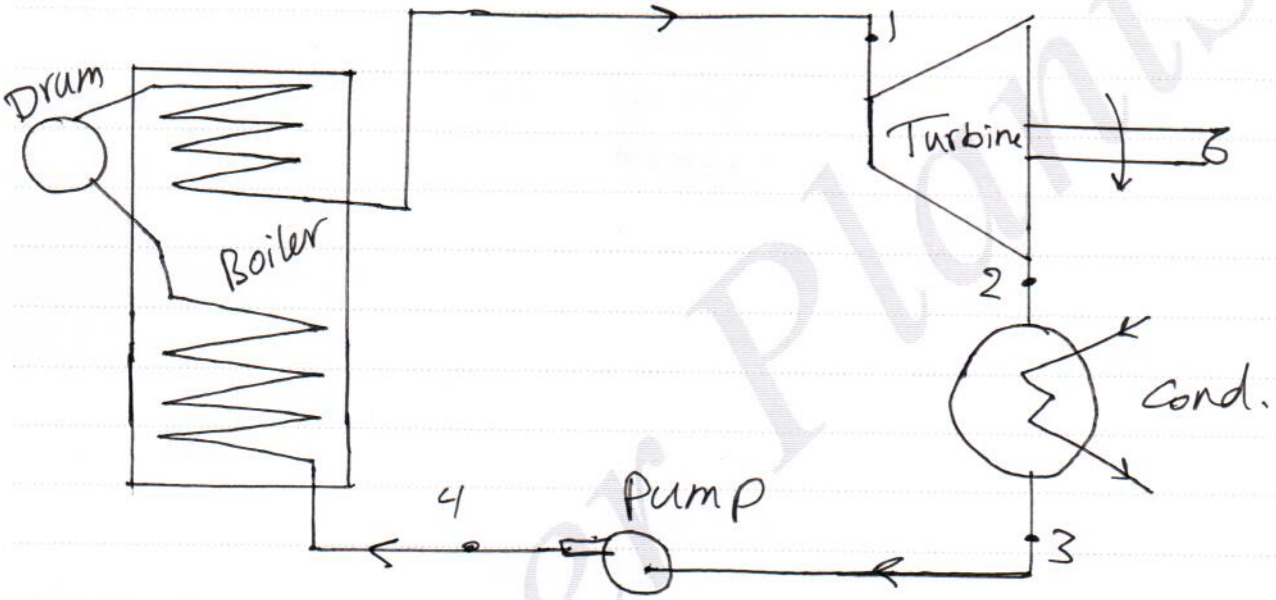
$X_2 = 0.821$

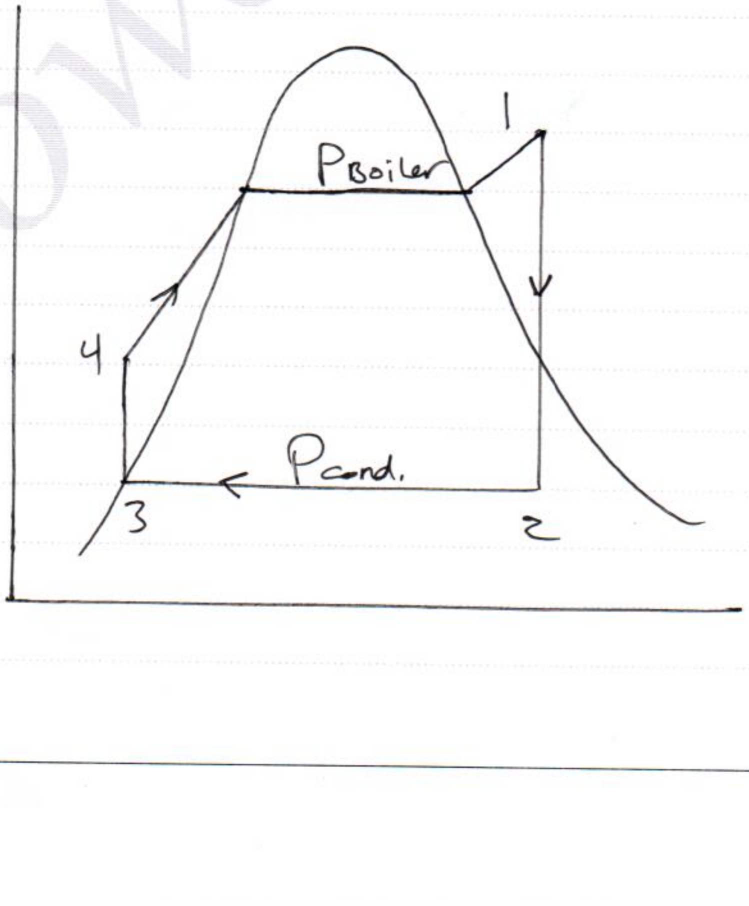
$h_2 = h_f + X_2 h_{fg}$
$= 112 + 0.821 * 2438$
$= 2113$ KJ/Kg

$h_3 = h_f = 112$ KJ/Kg

* Rankine Cycle with superheating

The dry saturated steam from the boiler drum is passed through a second bank of smaller bore tubes within the boiler.





$v(P_2 - P_1) = h_4 - h_3$

$0.001\,(4200 - 3.5) = h_4 - 112$

$h_4 = 116.2$

$$W_{net} = W_t - W_c$$
$$= (h_1 - h_2) - (h_4 - h_3)$$
$$= (3442.6 - 2113) - (116.2 - 112)$$
$$= 1325.4 \text{ KJ/Kg}$$

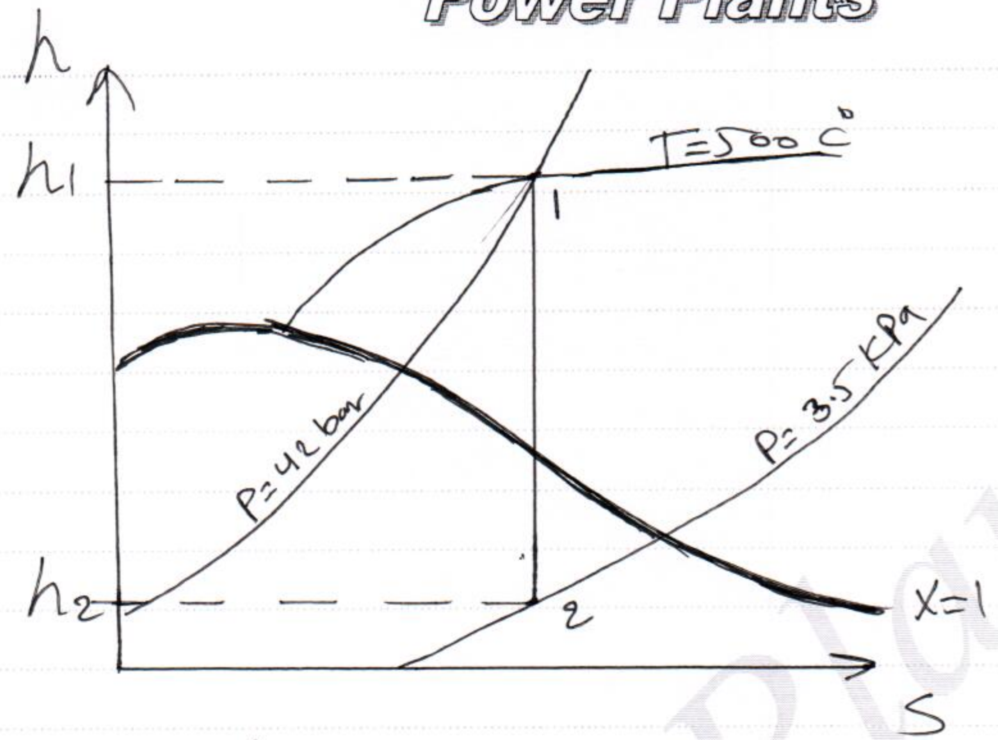
$$Q_{add} = h_1 - h_4$$
$$= 3442.6 - 116.2$$
$$= 3326.4 \text{ KJ/Kg}$$

$$\eta_{Rankine} = \frac{W_{net}}{Q_{add}}$$

$$= \frac{1325.4}{3326.4} = 39.8\ \%$$

Or,

If we use Mollier Chart to estimate the values of enthalpy instead of steam stable, the results will be as follows:-



Directly from the chart

$h_1 = 3450$ KJ/Kg
$h_2 = 2120$ KJ/Kg

$h_3 = 112$ from steam-table
$h_4 = 116.2$

$W_{net} = (3450 - 2120) - (116.2 - 112)$
$= 1325.8$ KJ/Kg

$Q_{add} = 3450 - 116.2$
$= 3333.8$

$$\eta = \frac{1325.8}{3333.8} = 39.7\%$$

you can notice that the diffrence between the two η are very small = 0.1 % which is acceptable

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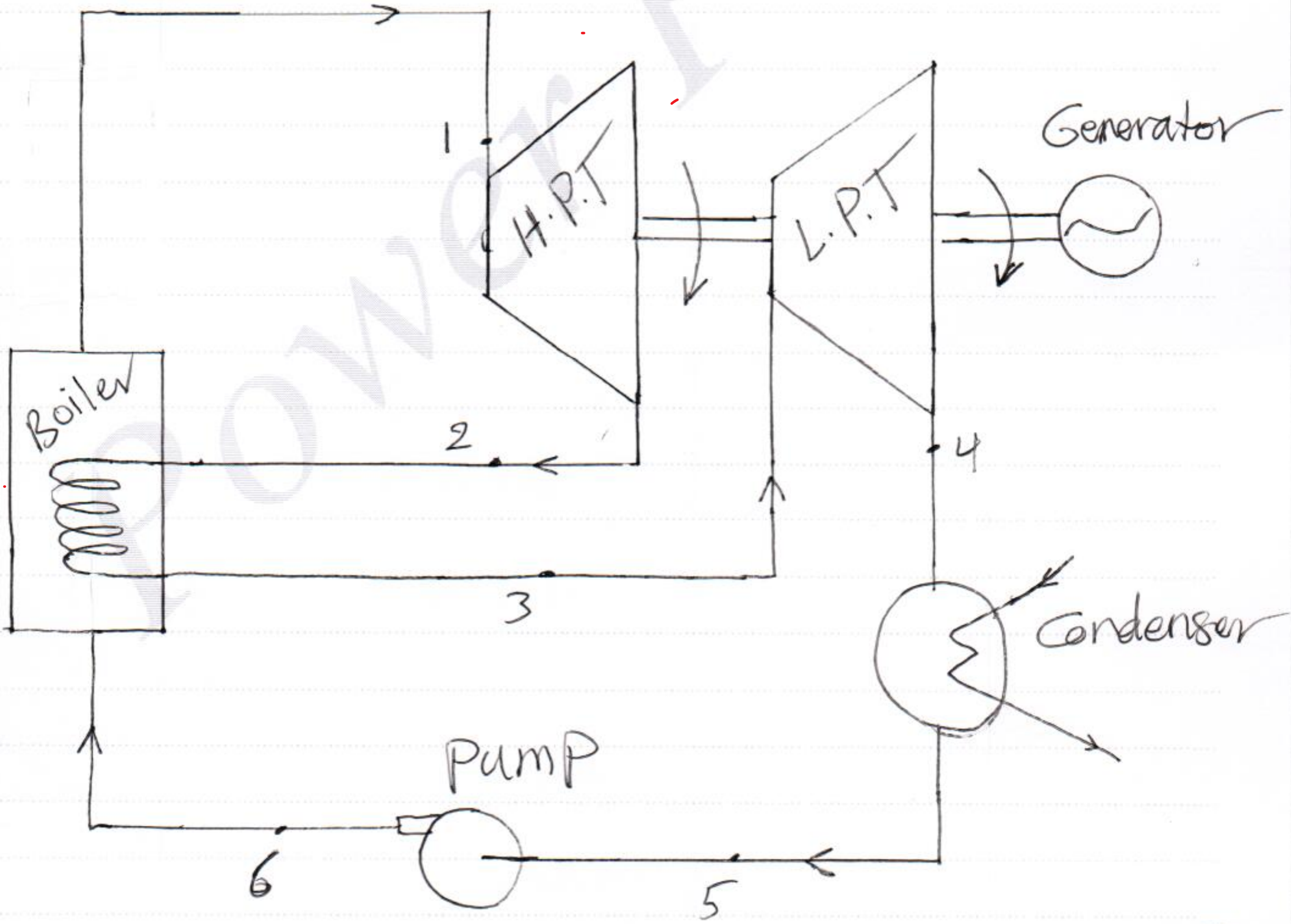
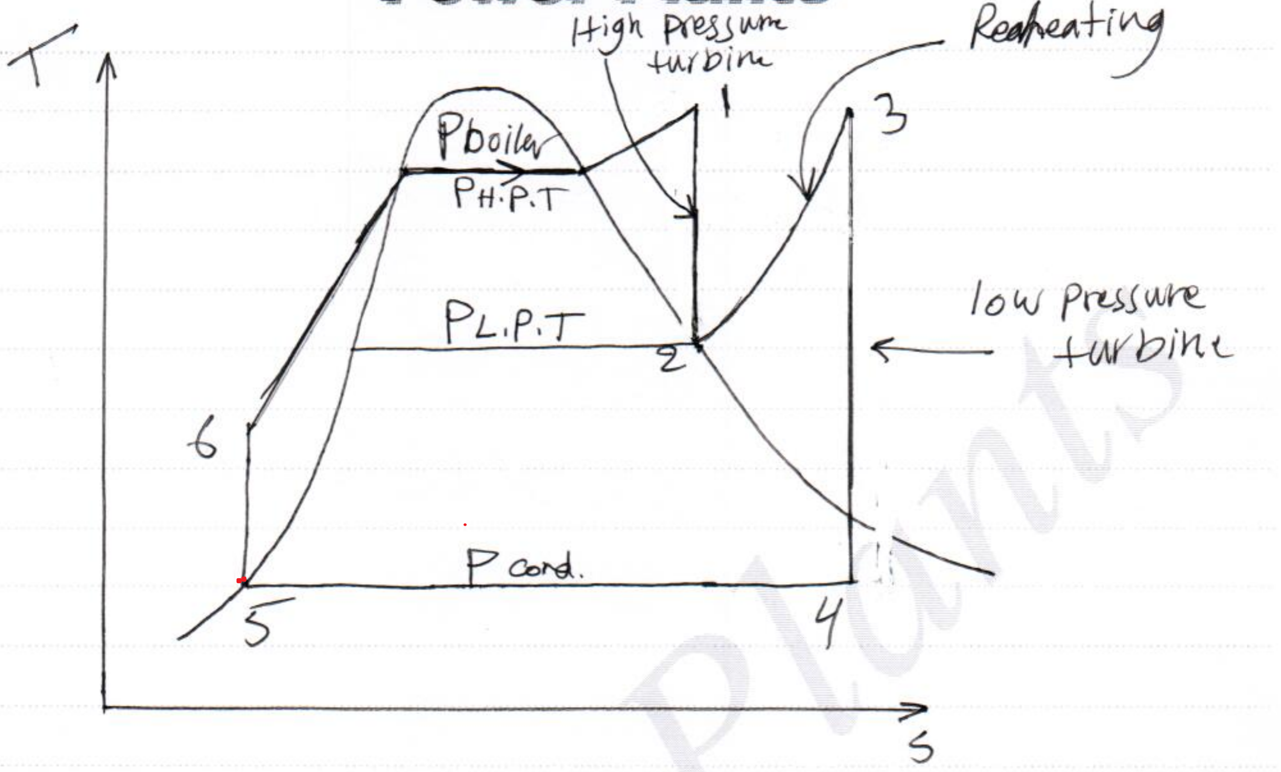
* Reheat Rankine Cycle

It is desirable to increase the tempreture at which heat is supplied to the Steam, and also to keep the steam as dry as possible in the lower stages of the turbine.

The ideal Rankine cycle differs from the simple ideal Rankine cycle in that the expansion process takes place in two stages.



Power Plants



(1-2): high-pressure turbine stage, Steam is expanded isentropically to an intermediate pressure

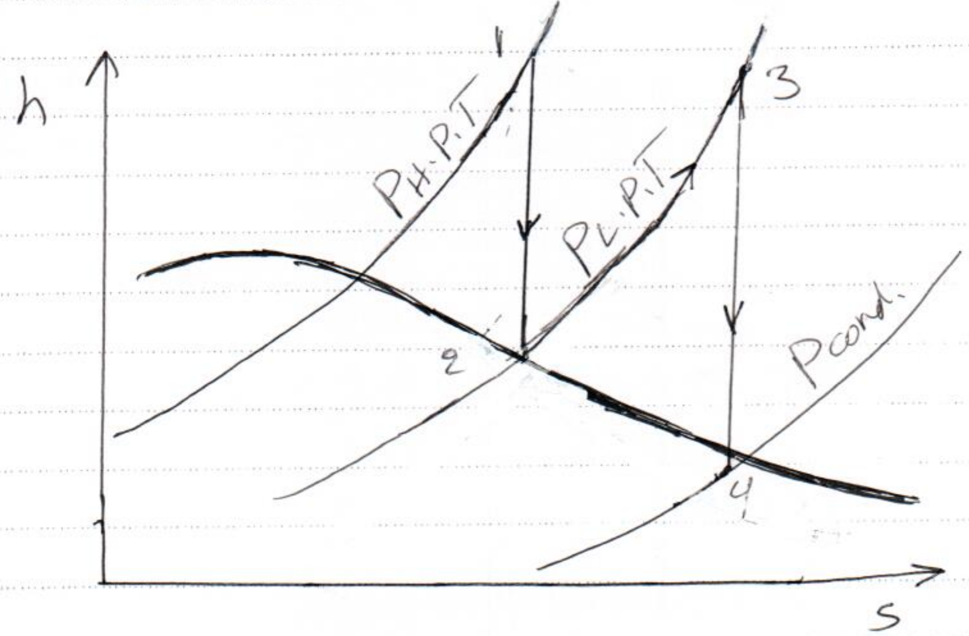
(2-3): Intermediate pressure, Steam is sent back to the boiler where it is reheated at Constant pressure

(3-4): Low-pressure turbine stage, Steam is expanded isentropically to the condenser pressure.

(4-5): Condenser Pressure, Steam is cooled down to saturated liquid

(5-6): Pump, water is pumped from condenser Pressure to boiler Pressure.

(6-1): Boiler pressure, heat is added to water and turnit to superheated steam.



Thermodynamic analysis of reheat cycle as shown on T-s and h-s representation are carried out as follows:-

$W_{H.P.T} = h_1 - h_2$

$W_{L.P.T} = h_3 - h_4$

$W_{pump} = h_6 - h_5$

$$W_{net} = (W_{H.P.T} + W_{L.P.T}) - W_{pump}$$

Power Plants

$$\boxed{W_{net} = (h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)}$$

$$Q_{add} = Q_{boiler} + Q_{reheating}$$

$$\boxed{Q_{add} = (h_1 - h_6) + (h_3 - h_2)}$$

$$\eta = \frac{W_{net}}{Q_{add}}$$

$$\boxed{\eta_{reheating} = \frac{(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)}{(h_1 - h_6) + (h_3 - h_2)}}$$

output power of the plant = $\dot{m}_s \cdot W_{net}$

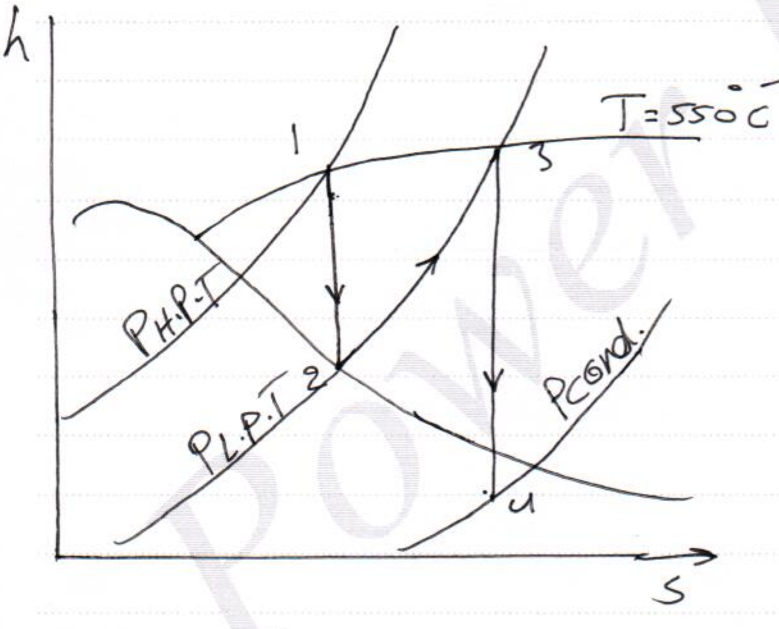
$\dot{m}_s$ = mass flow rate of the steam

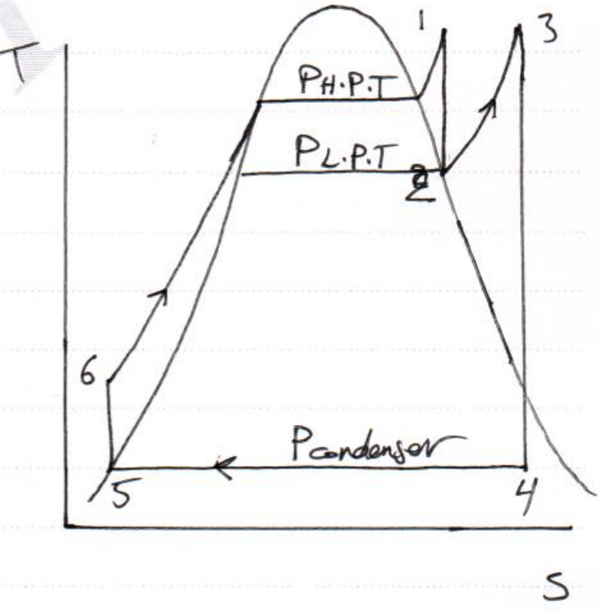
$$\boxed{P_{out} = \dot{m}_s \cdot W_{net}}$$

Ex/ In a steam power plant, steam enters HPT at 150 bar and 550°C and leaves as saturated vapor. the Condenser Pressure is 0.1 bar. Assume that the reheating occures up to the original tempressure Determine

a) Work done
b) heat added
c) output Power if the mass flow rate of steam is 50 kg/s
d) Thermal efficiency of the cycle

Solution:





From Mollier chart

At 150 bar and 550 °C

$h_1 = 3455$ KJ/Kg
$h_2 = 2785$ KJ/Kg

reheating pressure is 1.25 MPa

$h_3 = 3585$ KJ/Kg

$h_4 = 2465$ KJ/Kg

From Steam table

At 0.1 bar $h_5 = 191.83$ KJ/Kg

$$v(P_2 - P_1) = h_6 - h_5$$
$$0.001(15000 - 10) = h_6 - 191.83$$

$$h_6 = 206.82 \text{ KJ/Kg}$$

$$W_T = W_{H.P.T} + W_{L.P.T}$$

$$= (h_1 - h_2) + (h_3 - h_4)$$

$= (3455 - 2785) + (3585 - 2465)$

$= 1790$ KJ/Kg

$W_P = h_6 - h_5$
$= 206.82 - 191.83$
$= 15$ KJ/Kg

$W_{done} = W_T - W_P$
$= 1790 - 15$
$= 1775$ KJ/Kg

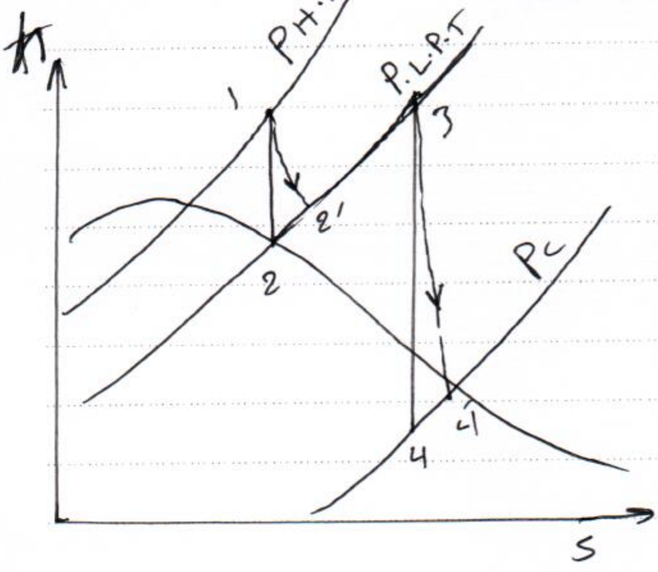
$Q_{add} = (h_1 - h_6) + (h_3 - h_2)$

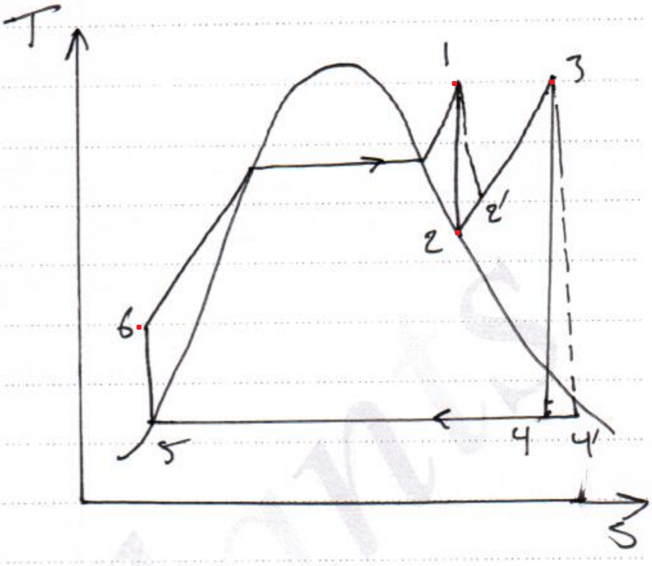
$= (3455 - 206.82) + (3585 - 2785)$
$= 4048.18$ KJ/Kg

$$\eta_{Ideal} = \frac{W_{done}}{Q_{add}} = \frac{1775}{4048.18} = 43.84\ \%$$

If the isentropic efficiency of the two turbines are 85 %, Find the new efficiency?

$P_{output} = \dot{m}_s . WD$
$= 50 * 1775 = 88.75$ MW





$$\eta_{ise.\,H.P.T} = \frac{h_1 - h_2'}{h_1 - h_2}$$

$$0.85 = \frac{3455 - h_2'}{3455 - 2785} \Longrightarrow h_2' = 2885.5 \text{ KJ/Kg}$$

$$\eta_{ise,\,L.P.T} = \frac{h_3 - h_4'}{h_3 - h_4}$$

$$0.85 = \frac{3585 - h_4'}{3585 - 2465} \Longrightarrow h_4' = 2633 \text{ KJ/Kg}$$

$$W_T = (h_1 - h_2') + (h_3 - h_4') - (h_6 - h_5)$$

$$= (3455 - 2885.5) + (3585 - 2633) - 15$$

$$= 1506.5 \text{ KJ/Kg}$$

$$Q_{add} = (h_1 - h_6) + (h_3 - h_2')$$

$$= (3455 - 266.82) + (3585 - 2885.5)$$

$$= 3947.7 \ KJ/kg$$

$$\eta_{actual} = \frac{W_{done}}{Q_{add}} = \frac{1506.5}{3947.7} = 38.16\%$$

$$\Delta\eta = \eta_{ideal} - \eta_{actual}$$

$$= 43.84\% - 38.16\%$$

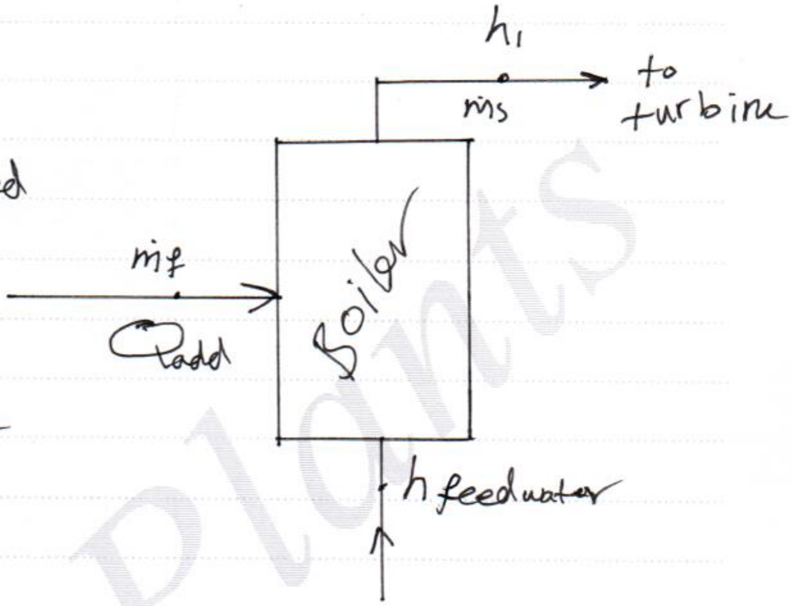
$$= 5.68\%$$

You can notice that the cycle efficiency has decreased 5.68% when taking into account isentropic efficiency of the H.PT and L.P.T.

* Efficiencies in steam Power plant

- Boiler efficiency

It is the heat supplied to the steam in the boiler expressed as a percentage of the chemical energy of the fuel which is available in the combustion.



ie,

$$\boxed{\eta_b = \frac{(h_1 - h_{F.W})\,\dot{m}_s}{\dot{m}_f * C.V}}$$

where, h_1 = Enthalpy of steam entering the turbine (KJ/Kg)

$h_{F.W}$ = Enthalpy of feed water (KJ/Kg)

$\dot{m}_s$ = steam mass flow rate (Kg/s)

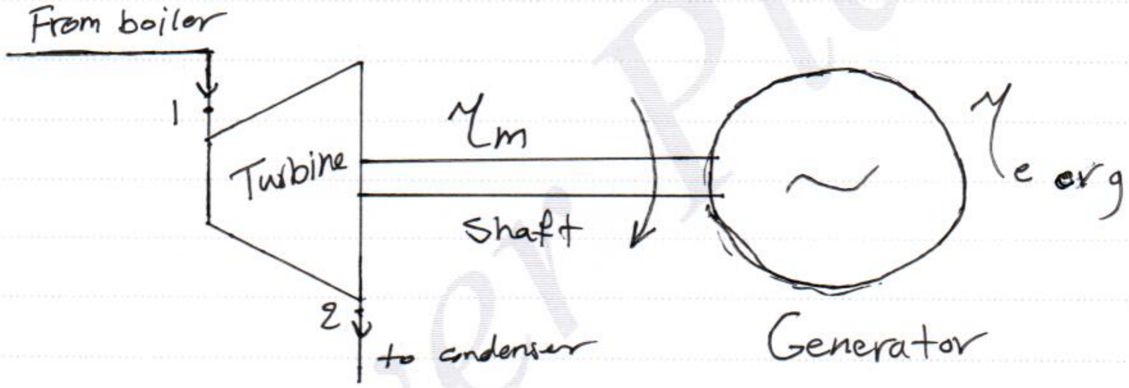
$\dot{m}_f$ = fuel mass flow rate (Kg/s)

C.V = Calorific value of the fuel (KJ/Kg)

- Mechanical and electrical (generator) efficiency

In steam plants, the work done by turbine is transferred to the generator to generate electricity by a shaft.

Due to friction losses in the shaft and iron losses in the generator, there are going to be two efficiencies mechanical efficiency and electrical efficiency



So, the output Power of plant in this case called "terminal Power"

$$\text{Terminal Power} = \dot{m}_s * W.D * \eta_g * \eta_m$$

- Cycle efficiency

Cycle efficiency which is explanied well previously takes into account equipment of the Clycle: turbine, Condenser, Pump and boiler

$$\eta_{cycle} = \frac{W.D}{Q_{add}}$$

- Specific Steam Consumption

When taking into account mechanical and electrical efficiency of the Shaft and the generator, S.S.C will be as follows,

$$S.S.C = \frac{3600}{W.D \ast \eta_g \ast \eta_m} \quad Kg_{fuel}/Kw.hr$$

- Plant efficiency

Plant efficiency includes cycle equipment and both mechanical and electrical efficiencies along with boiler efficiency :-

$$\eta_{Plant} = \eta_{cycle} \ast \eta_{boiler} + \eta_m \ast \eta_g$$

Power Plants

Ex/ Steam power plant has the following data:-

steam condition at turbine 6 MPa, 450°C

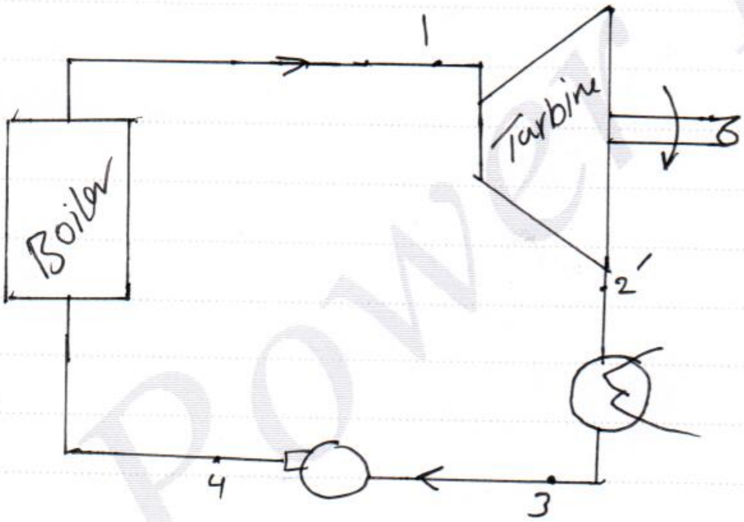
Condensor pressure 0.008 MPa

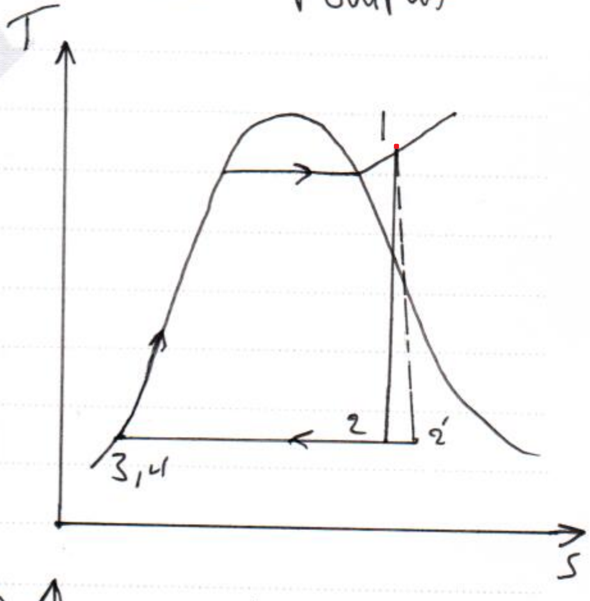
$\eta_{turbine} = 0.83$, $\eta_m = 0.92$, $\eta_g = 0.96$, $\dot{m}_s = 40$ kg/s

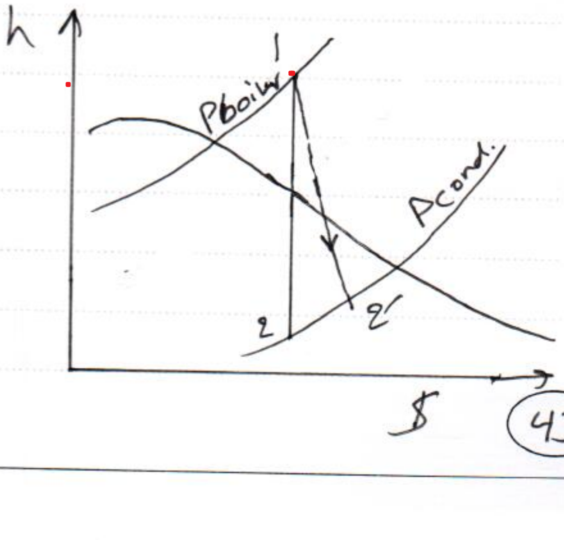
CV of fuel = 37000 KJ/kg, $\dot{m}_f = 4$ kg/s

Neglect pump work. Find

a) Work done
b) heat added
c) boiler efficiency
d) cycle efficiency
e) Plant efficiency
c) terminal Poutput







Solution:-

From Mollier chart:

$h_1 = 3305$ KJ/Kg
$h_2 = 2105$ KJ/Kg

$$\eta_t = \frac{h_1 - h_2'}{h_1 - h_2} \Longrightarrow 0.83 = \frac{3305 - h_2'}{3305 - 2105}$$

$h_2' = 2881.7$ KJ/Kg

From Steam table

at 0.008 MPa , $h_3 = h_4 = h_f = 173.7$ KJ/Kg

$$W.D = h_1 - h_2'$$
$$= 3305 - 2105$$
$$= 1200 \text{ KJ/Kg}$$

$$Q_{add} = h_1 - h_4$$
$$= 3305 - 173.7$$
$$= 3131.3 \text{ KJ/Kg}$$

$$\eta_b = \frac{(h_1 - h_4)\dot{m}_s}{\dot{m}_f\ CV}$$

$$= \frac{(3305 - 173.7) * 40}{4 * 37000} = 84.6\ \%$$

Cycle efficiency $= \frac{W.D}{Q_{add}}$

$= \frac{1200}{3131.3} = 38.3\%$

$\eta_{Plant} = \eta_{cycle} + \eta_b * \eta_m + \eta_e$

$= 0.383 * 0.846 + 0.92 + 0.96$

$= 28.6\ \%$

You can notice that $\eta_{Plant} < \eta_{cycle}$

Terminal $P_{output} = \dot{m}_s * W.D + \eta_g + \eta_m$

$= 40 * 1200 + 0.92 + 0.96$
$= 42.4$ MW

Steam Generator

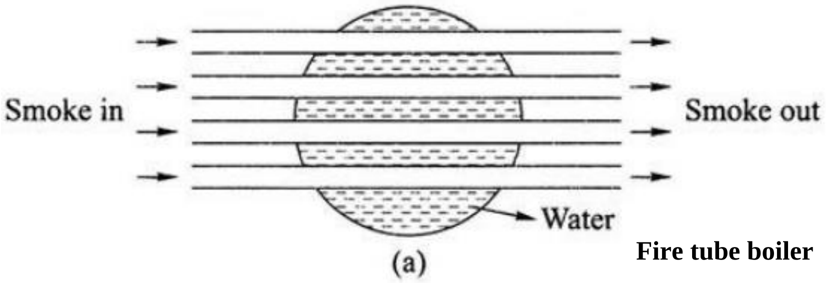
Steam generator is a closed vessel that is used to generate steam at constant pressure as per the process requirement. The steam generated may be wet, dry saturated or superheated in state. In modern power plants, it is very common to use one boiler (single unit) per turbine, which leads to simpler piping systems and relatively easier boiler and turbine control. These boilers are usually designed to operate either at critical pressure (221.2 bar) or above or below the critical pressure.

In a steam generator or boiler, constant pressure is maintained by balancing the rate of steam generated with the rate of steam consumed. In a thermal power station, coal is the main source of combustion. The heat generated by burning coal is utilized to generate steam, which in turn runs the turbo-generator.

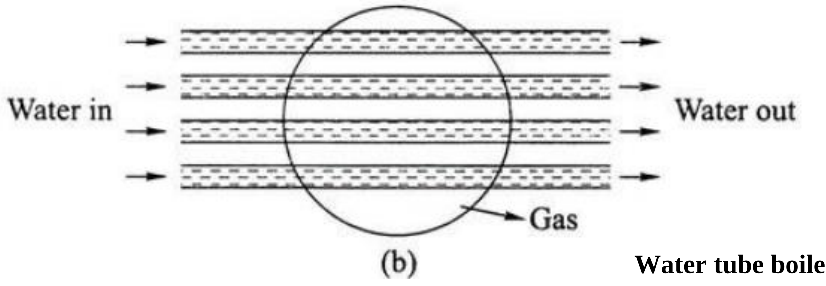
Classification of Boilers

- **Fire tube and water tube boilers**

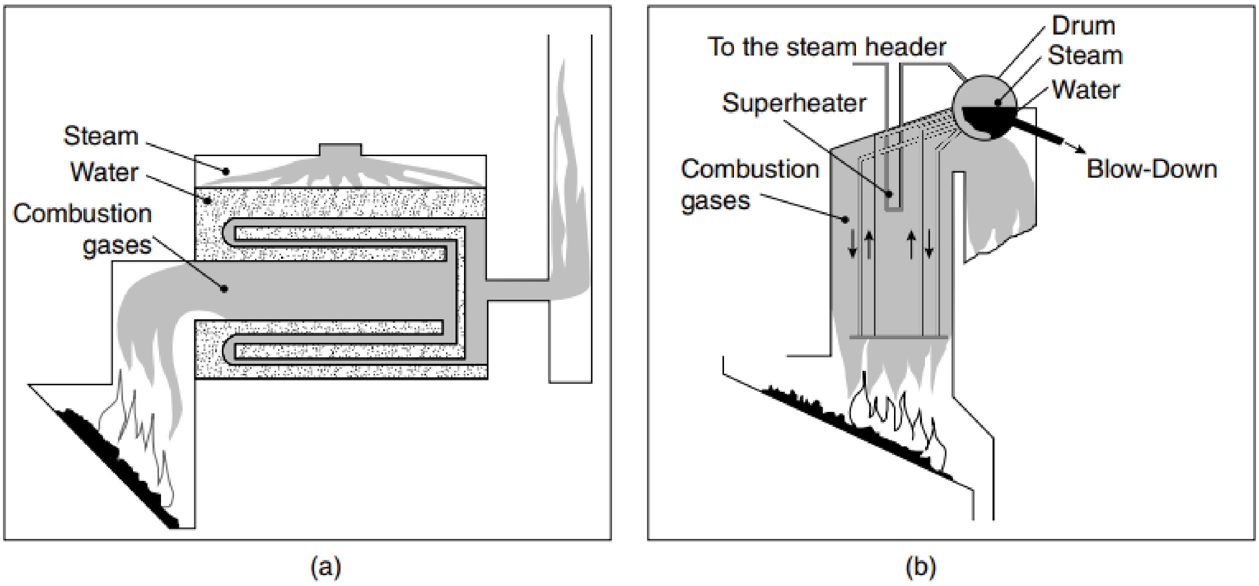
In the fire tube boilers, the hot gases produced after the combustion of fuel pass through the tubes and the water surrounds these tubes. In the water tube boilers, water flows inside tubes and gas remains outside these tubes.



Fire tube boiler



Water tube boiler

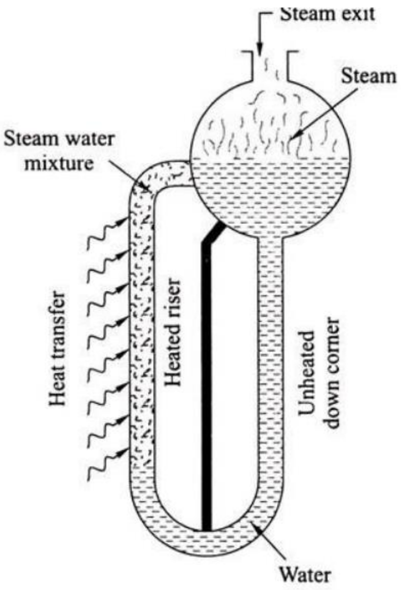


Fire tube boiler **Water tube boiler**

➢ Natural and Forced Circulation Boiler:

All conventional boilers in which the circulation of water is done by thermo-symphonic method, are known as natural circulation boilers. In natural circulation boiler, the circulation of water takes place due to natural convection current and density variation of fluid by the application of heat, i.e., thermo-siphon.

This is based on the principle that the density of water is more than steam and as such requires a boiler drum. The method is effective only up to a pressure less than 20 bar. After this pressure, the difference in density of water and steam becomes less and so this system fails to work.



In forced circulation type boilers, the circulation of water inside the tube is done by a forced circulating pump. Water is forced inside the tube by mechanical means. This method is applicable in high-capacity water tube boilers.

- **Based on Heat Sources**

Boilers may be classified based on the fuel used for combustion or heat generation source. Various heat sources used may be the following:
(i) Heat generated by the combustion of fuel in solid, liquid or gaseous forms
(ii) Heat generated by hot waste gases as byproducts of other chemical processes
(iii) Heat generated by nuclear energy

- **Stationary and Mobile Boilers**

If the boilers are used at one place only they are termed stationary boilers. These boilers are used either for process heating in industries or for power generation in steam power plants.

Mobile boilers are portable and are used in locomotives and ships.
Examples: Locomotive boiler and marine boiler

Essentials of a Good Steam Boiler

A good boiler must possess the following features:

i. The boiler should be capable of producing large quantity of steam of the required quality.
ii. The steam must be generated at minimum cost.
iii. The rate of steam generation must match with the requirement.
iv. It must occupy less floor area.
v. It must be started quickly.
vi. Construction should be so simple and well-designed that the repair and inspection can be done easily.

Accessories of Steam Boiler:

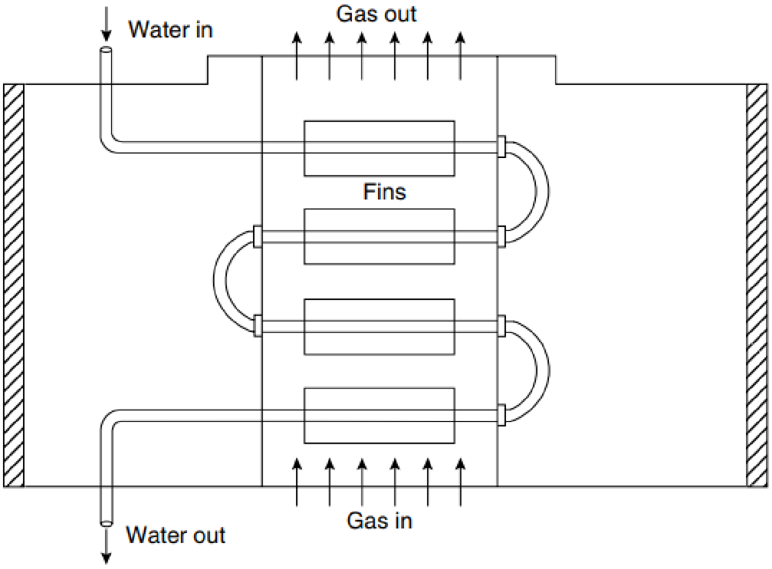
Boiler accessories are auxiliary systems in boiler installation for the proper functioning and increase of the thermal efficiency of the boiler.

The essential boiler accessories are as follows:

➢ Economizer

The purpose of economizer is to heat the feed water by the direct use of the heat of flue gas discharged to the atmosphere through chimney. The economizer reduces the temperature of flue gas. The feed water temperature is increased substantially.

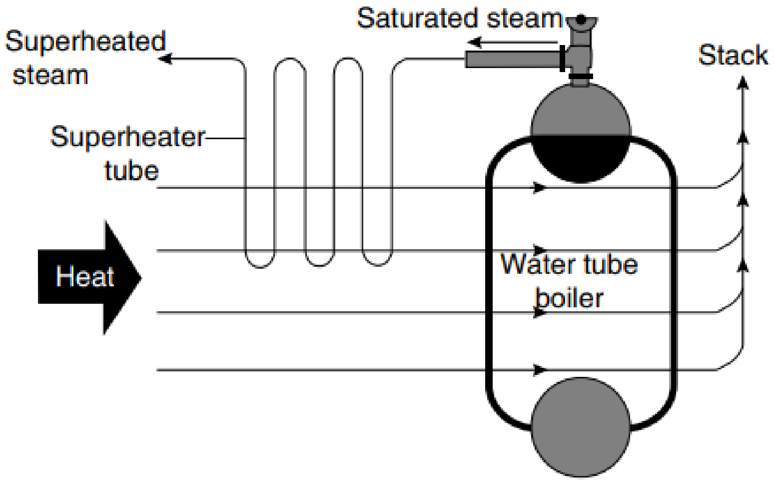
Thus, there is a saving in heat. The boiler efficiency is increased substantially. The economizer is placed in the path of the exit gas nearer to the boiler.



➢ Superheaters

The functions of the superheater are to remove the last traces of moisture from the saturated steam coming out of boiler and to increase its temperature above saturation temperature. Superheating increases overall cycle efficiency as well as avoids too much condensation in the last stages of the turbine, which avoids the blade corrosion.

Superheater is made of coils of tubes forming parallel tube circuits connected between heaters. The superheater tubes are made of high-temperature strength special alloy steels. The coils are heated by the heat of combustion gas during their passage from the furnaces to the chimney.



- **Steam separator**

The function of the steam separator is to separate the water particles in suspension that are carried by the steam coming from the boiler. If suspended water particles enter the turbine or engine, they cause erosion and corrosion of blades and other parts. It is always installed as close to the engine or turbine as possible on the main pipeline.

Steam Turbines

A Steam Turbine is an engine that converts heat energy from pressurized steam into mechanical energy where the steam is expanded in the turbine in multiple stages to generate the required work. Steam turbine engines are used to produce electricity.

Types of Steam Turbines

- **Impulse Steam Turbine**

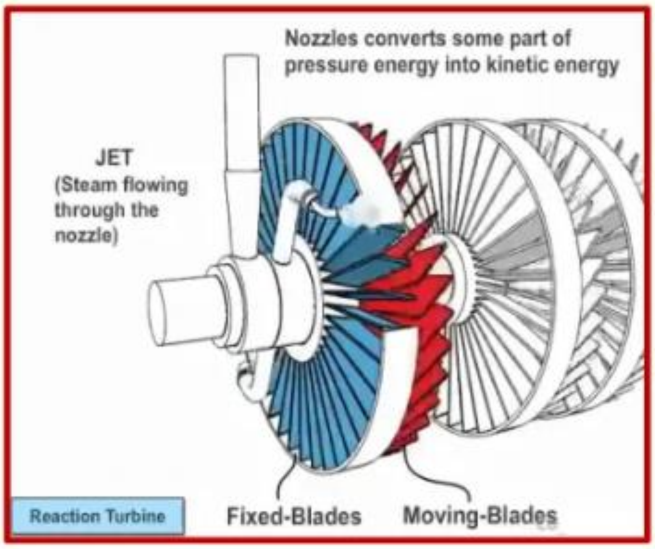
The basic idea of an impulse steam turbine is that a jet of steam from a fixed nozzle pushes against the rotor blades and impels them forward. So the impulse force of high-velocity steam exerts a force on the blade to turn the rotor. The kinetic energy of the steam is transferred to the rotating wheel by momentum transfer within the blades. Pelton Wheel, Banki Turbine, etc are typical examples of Impulse turbine.

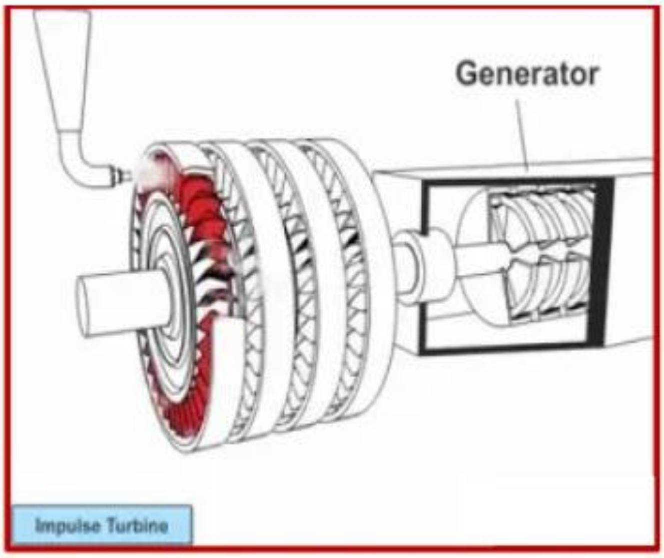
- **Reaction Steam Turbine**

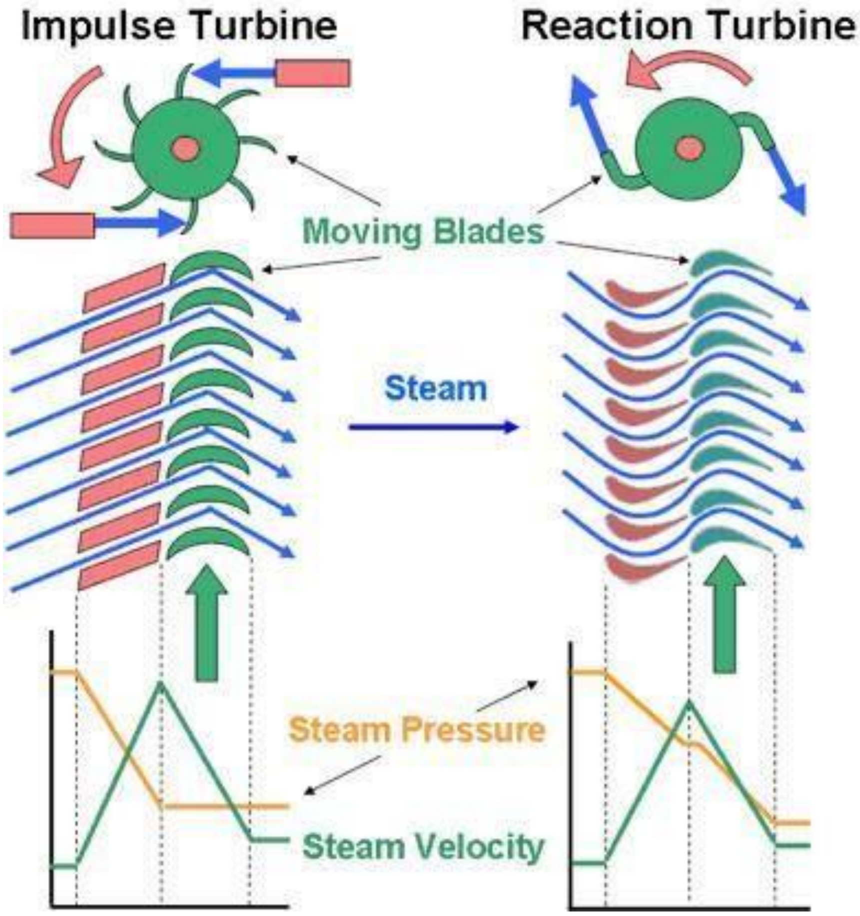
In the reaction steam turbine, a jet of steam flows from a nozzle on the rotor (the moving blades) by fixed blades designed to expand the steam. The rotor gets its rotational force from the steam as it leaves the blades. Roughly 50% of the output power is generated by the impact force and the other 50% from the reaction force by the steam expansion. Francis Turbine, Kaplan Propeller turbine, Deriaz turbine, etc are examples of reaction turbine.

The main difference between impulse and reaction turbine lies in the way in which steam is expanded while it moves through them such that:

- In the impulse type steam turbine, the steam expands in the nozzle and its pressure doesn’t change as it moves over the blades.
- In the reaction type, the steam expands continuously as it passes over the blades and thus there is a gradual fall in pressure during expansion.


Nozzles converts some part of pressure energy into kinetic energy
JET (Steam flowing through the nozzle)
Fixed-Blades
Moving-Blades
Reaction Turbine


Generator
Impulse Turbine


Impulse Turbine
Reaction Turbine
Moving Blades
Steam
Steam Pressure
Steam Velocity

LOSSES IN STEAM TURBINE

Losses are all-time very important for manufacturing any machine. That's why Manufacturer takes special attention for manufacturing any machine. We know an ideal machine which has 100% gross efficiency will do the equivalent work to the isentropic enthalpy. It means turbine uses every single bit of heat drop produced by steam.

But practically turbine's work done is much less than isentropic heat drop of the steam used. Because some internal losses occurred at the time of its operation. These losses are directly affected by the turbines output as well as its efficiency

Though there are several losses in a turbine, but here we will discuss some important internal losses in the turbine.

- **Nozzle Friction Loss :-**

It is a very important loss for Impulse Turbine. When steam passes through the nozzles, friction loss occurs and the formation of eddies. Friction occurs in the nozzle due to the factor of nozzle efficiency and it is the ratio of actual enthalpy drop to isentropic enthalpy drop.

- **Blade Friction Loss :-**

This loss is important for both Impulse and Reaction turbine . Blade friction loss is due to the steam's gliding over the blades and friction of the surface of the blades

- **Wheel Friction Loss :-**

When steam passes through the rotating turbine wheel, it produces some resistance on the turbine wheel. As a result, it rotates in lower speed from its original speed. It is the loss in both Impulse and Reaction turbine. The total frictional loss is about 10% of total turbine loss.

- **Losses due to mechanical friction :-**

This loss is for turbine's bearing. Mechanical friction loss is due to the friction between the shaft and wheel bearing and also the regulating valve of the turbine. This loss may be reduced by proper lubrication of the moving parts of the turbine. This loss occurs both Impulse and Reaction turbine.

Steam Condensers

Steam condensers are devices in which the exhaust steam from the steam turbine is condensed by means of cooling water. Condensation can be done by removing heat from exhaust steam using circulating cooling water. During condensation, the working substance (steam) changes its phase from vapour to liquid and rejects latent heat.

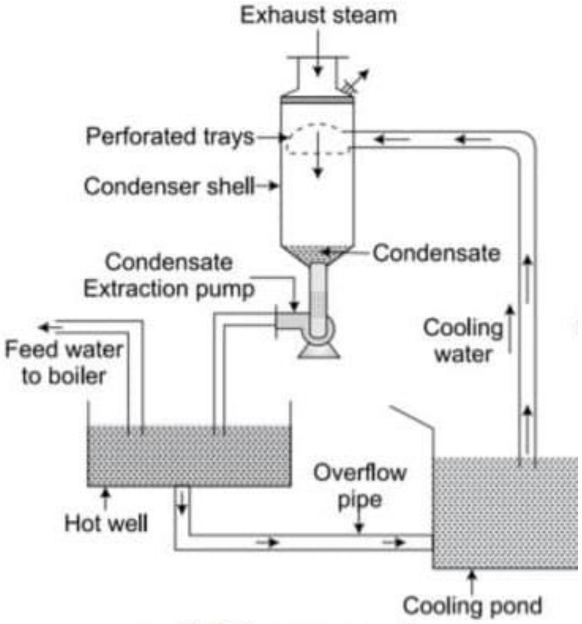
The main advantages of a steam condenser in a steam power plant are as follows:

- It increases the efficiency of the power plant due to increased enthalpy drop.
- It reduces temperature of the exhaust steam which also results in more work output.
- The condensed steam can be reused as feed water for boiler which reduces the cost of power generation.

Types of condensers

Mixing type condensers (Parallel flow jet condenser)

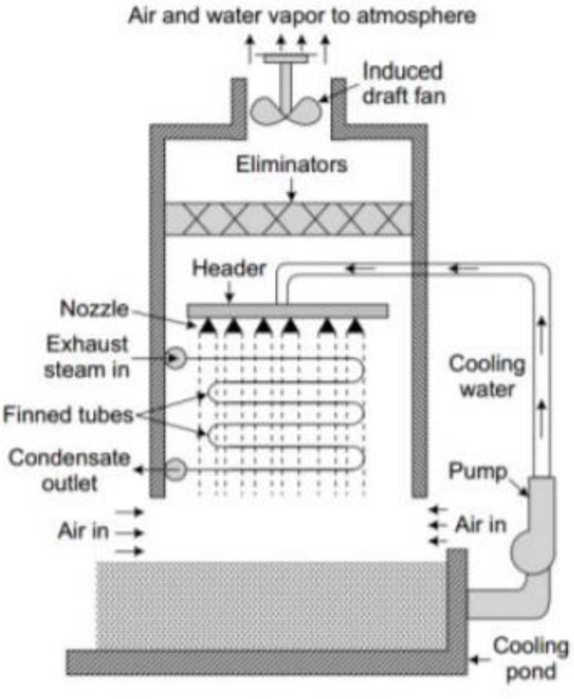
In parallel flow jet condenser both the steam and the water enters from the top and flows in the same direction. The exhaust steam is condensed when it mixes up with water. The condensate and the cooling water are delivered to the hot well from where surplus water flows to the cooling pond through an overflow pipe. Sometimes a single pump know as wet air pump is used to remove both air and the condensate but generally separate air pump is used to remove air as it gives a great vacuum.



Parallel Flow Jet Condenser

Non-mixing type condensers (Evaporative condenser)

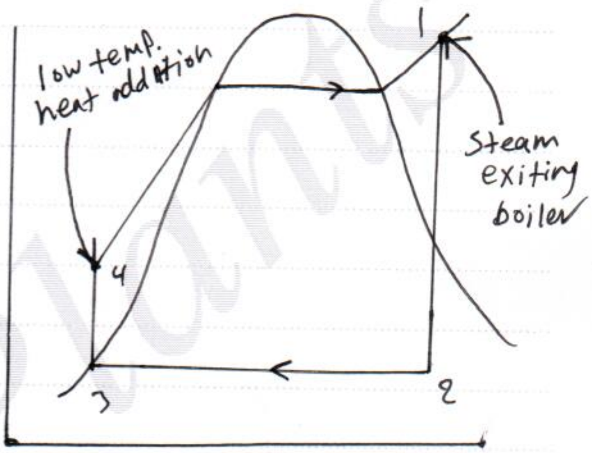
In evaporative condenser the steam flows enters the gilled pipes and flows backwards and forwards in a vertical plane. The water pump sprays water on the pipes which condenses the steam. The quantity of cooling water needed to condense the steam can be reduced by causing the circulating water to evaporate which decrease the temperature. The remaining water is collected in the cooling pond.



Evaporative Condenser

* Regenerative Cycle

In simple Rankine cycle, the heat is added to the working fluid at relatively low temprture. at which heat is added and thus lowers the cycle efficiency as seen in the figure.



The Rankine efficiency can be improved by bleeding off some of the steam at an intermediat pressure during the expansion, and mixing this steam with feed water which has been pumped to the same pressure.

The purpose of this is to increase the mean temprature at which heat is added, so heat added in the boiler is reduced thus efficiency iss increased.

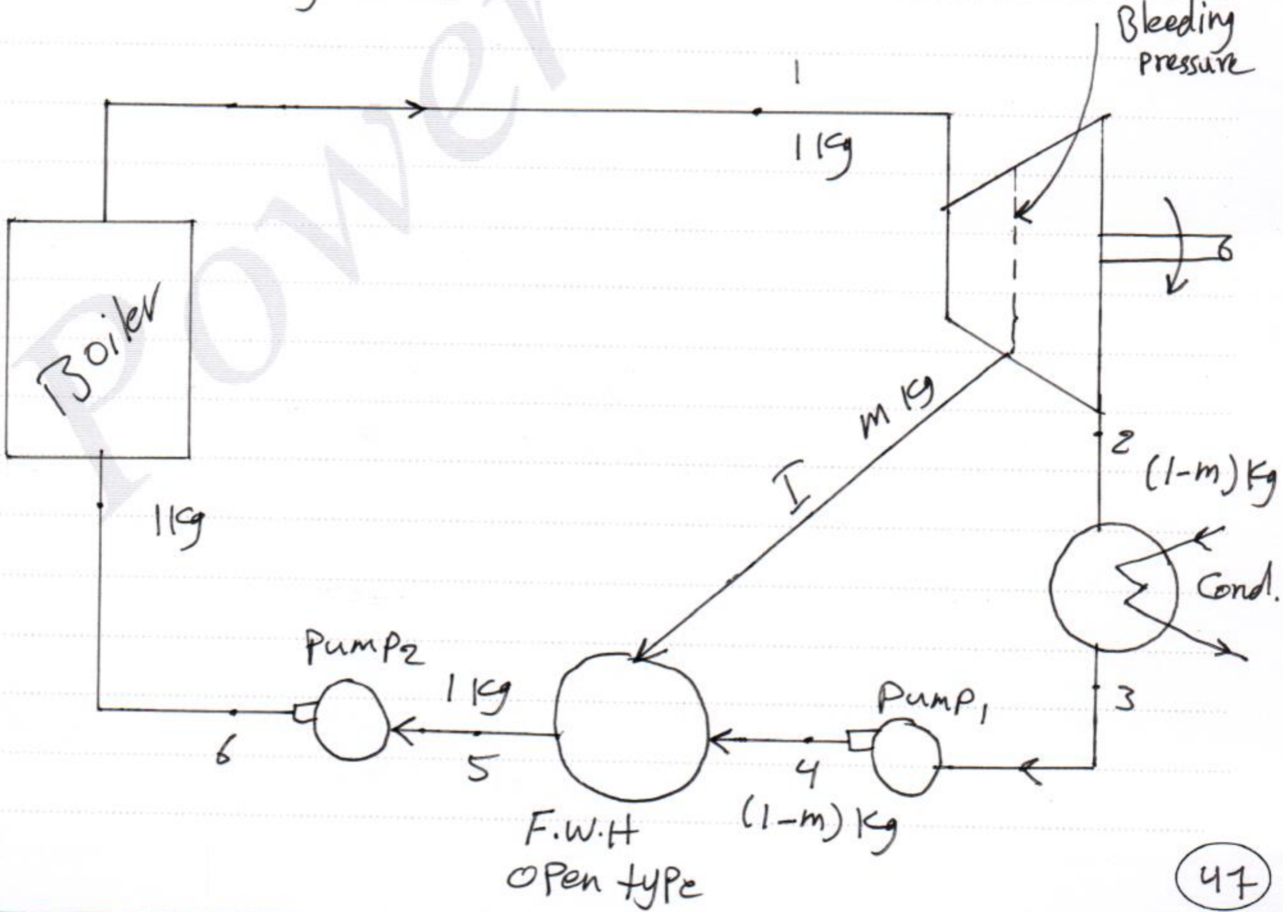
Mohanad Alheety

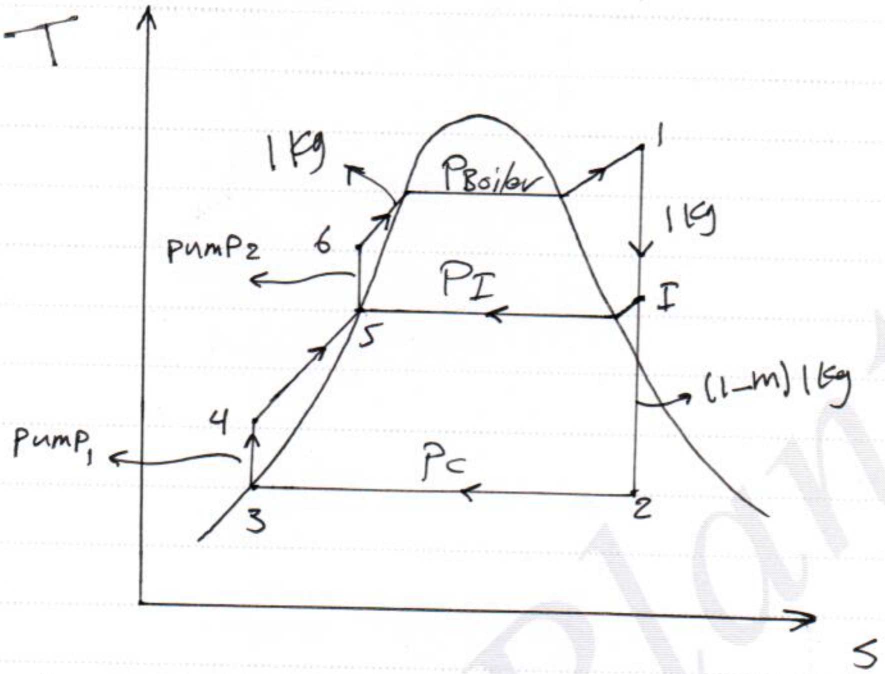
* Feed water heaters

A feed water heater is basically a heat exchanger where heat is transffered from the steam to the feed water either by the two fluid stream (open feed waterheater) or without mixing (closed feed water heater).

- Open feed-water heater

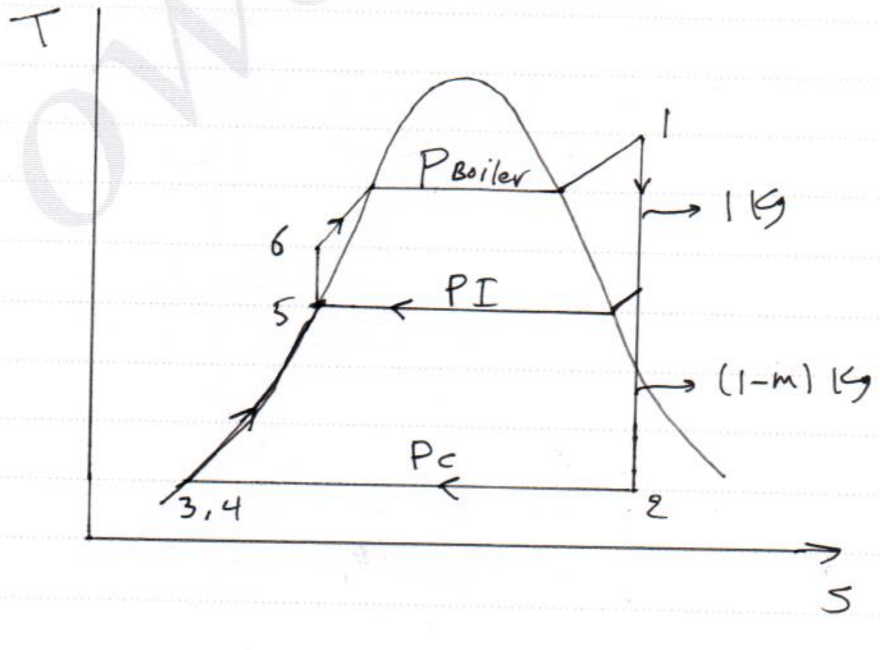
An open feed water heater is basically a mixing chamber where steam extracted from the turbine and mixed with the feed water exiting the pump.

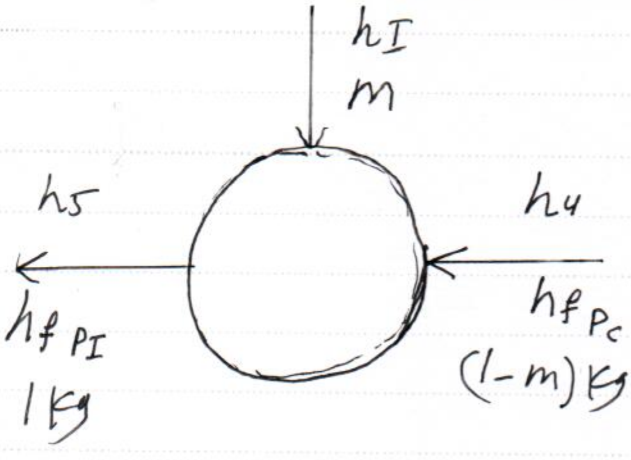


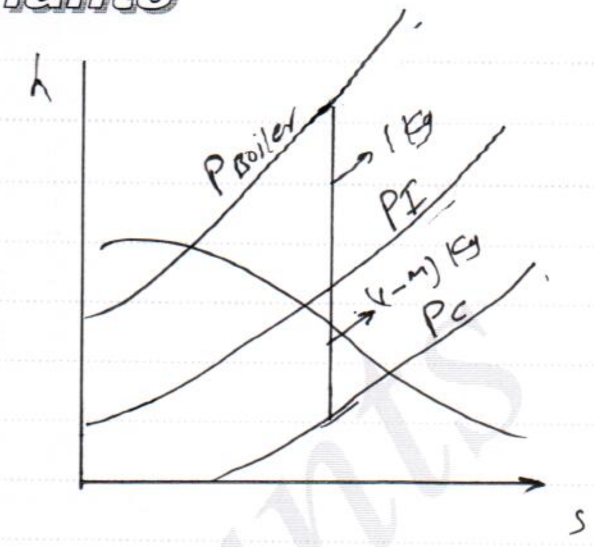


In order to make the Calculations eaiser, We neglect Work of PumP1, so that:-

$h_4 = h_3$







Heat balance of the heater

Energy input = Energy output

$$m h_I + (1-m) h_4 = 1kg * h_5$$
$$m h_I + (1-m) h_{fP_c} = 1kg + h_{fP_I}$$

$$\therefore \quad m = \frac{h_{fP_I} - (1-m) h_{fP_c}}{h_I}$$

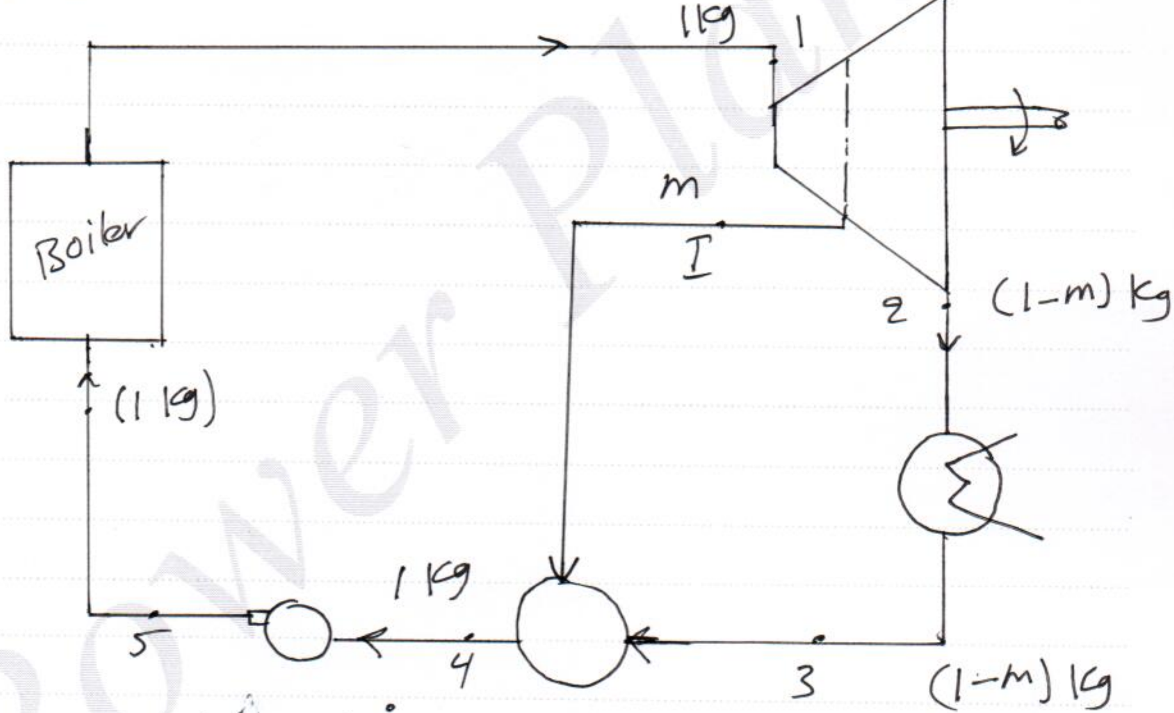
$$W.D = W_{1-I} + W_{I-2} - W_{6-5}$$
$$= 1kg (h_1 - h_I) + (1-m)(h_I - h_2) - (h_6 - h_5)$$

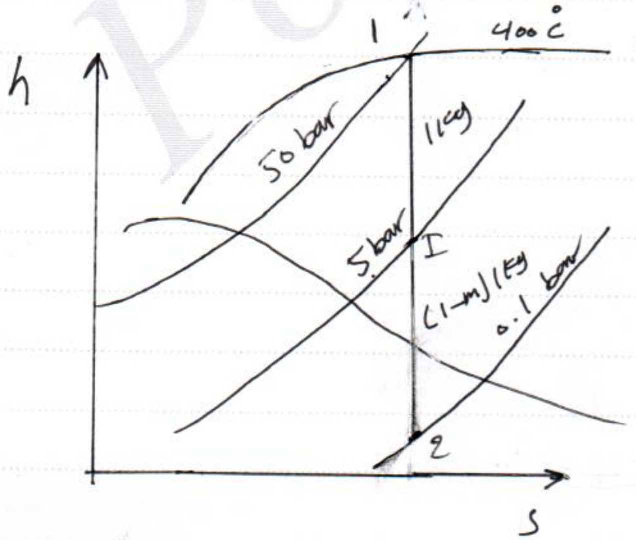
$$Q_{add} = (h_1 - h_6) * 1kg$$

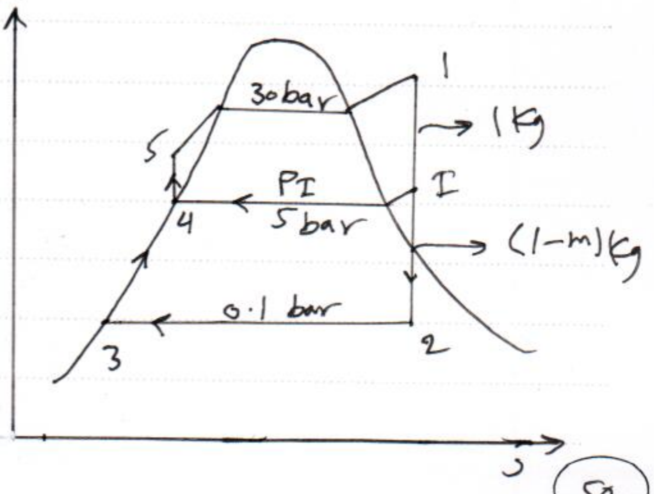
$$\eta_{cycle} = \frac{W.D}{Q_{add}}$$

EX/ In a single-heater regenerative cycle, the steam enters the turbine at 30 bar, 400°C and the exhust pressure is 0.1 bar. The feed water heater is a direct contact type which operate at 5 bar. Find

a) Amount of mass used for bleeding
b) Efficiency of the cycle
c) S.S.C







Solutions:-

From Mollier chart

At 30 bar, 400°C $h_1 = 3230$ KJ/Kg

$h_I = 2790$ KJ/Kg

$h_2 = 2190$ KJ/Kg

From steam table

At 0.1 bar $h_3 = h_{f P_c} = 191.8$ KJ/Kg

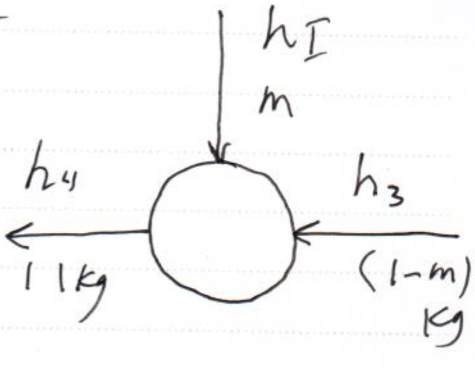
At 5 bar $h_4 = h_{f P_I} = 640.1$ KJ/Kg

$v(P_{Boiler} - P_I) = h_5 - h_4$

$0.001(3000 - 500) = h_5 - 640.1$

$h_5 = 642.6$ KJ/Kg

Heat balance for the heater



$m h_I + (1-m) h_3 = h_4 * 1$

$m * 2790 + (1-m) * 191.8 = 640.1$

$2598.2\, m = 448.3$

$m = 0.1725$ Kg

$$W.D = 1Kg(h_1 - h_I) + (1-m)(h_I - h_2) - (h_5 - h_4)$$

$$= (3230 - 2790) + (1 - 0.1725)(2790 - 2190) - (640.6 - 640.1)$$

$$= 936 \text{ KJ/Kg}$$

$$Q_{add} = (h_1 - h_5) * 1Kg$$

$$= (3230 - 642.6) * 1$$

$$= 2587.4 \text{ KJ/Kg}$$

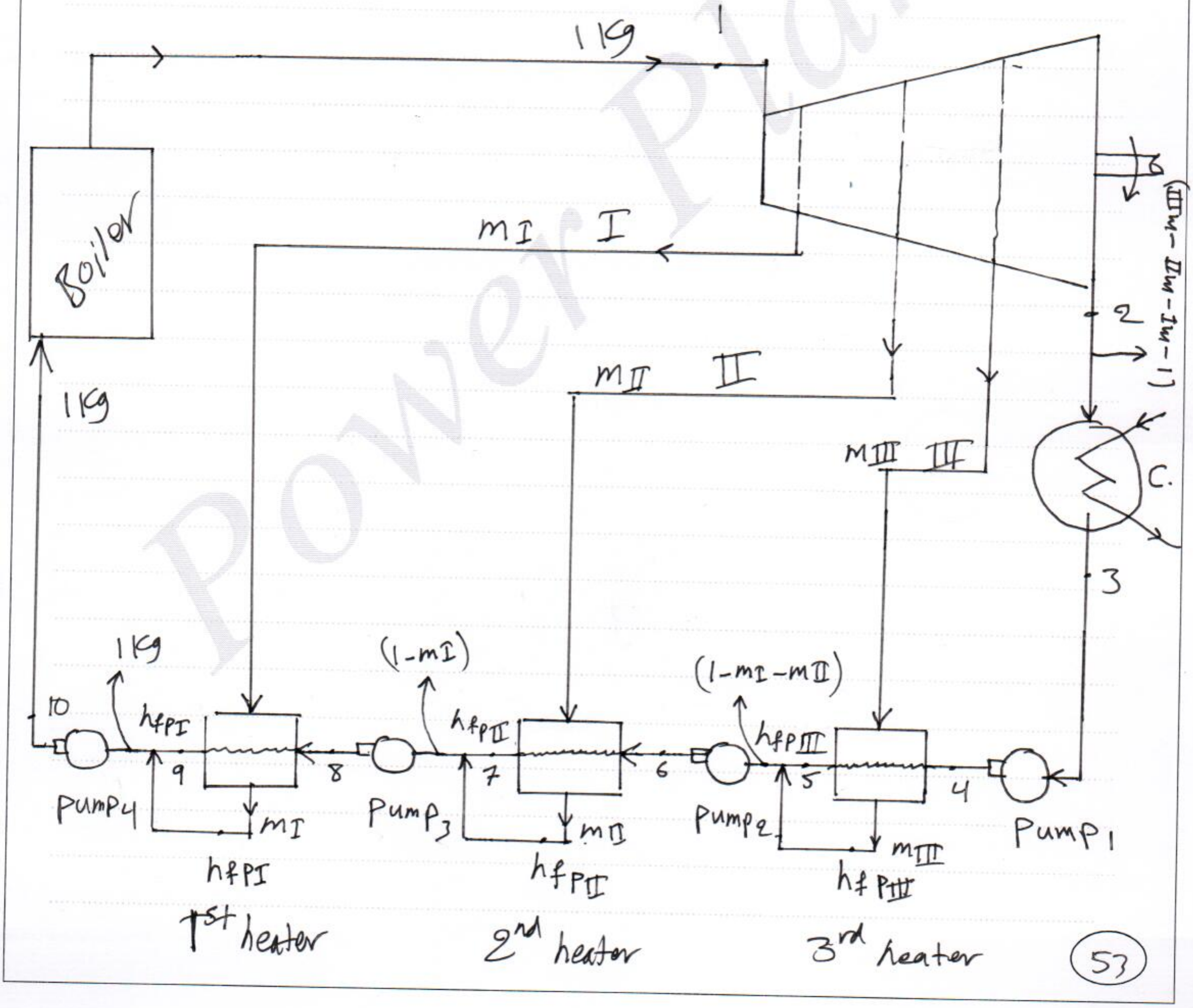
$$\eta_{cycle} = \frac{W.D}{Q_{add}} = \frac{936}{2587.4} = 36.18\%$$

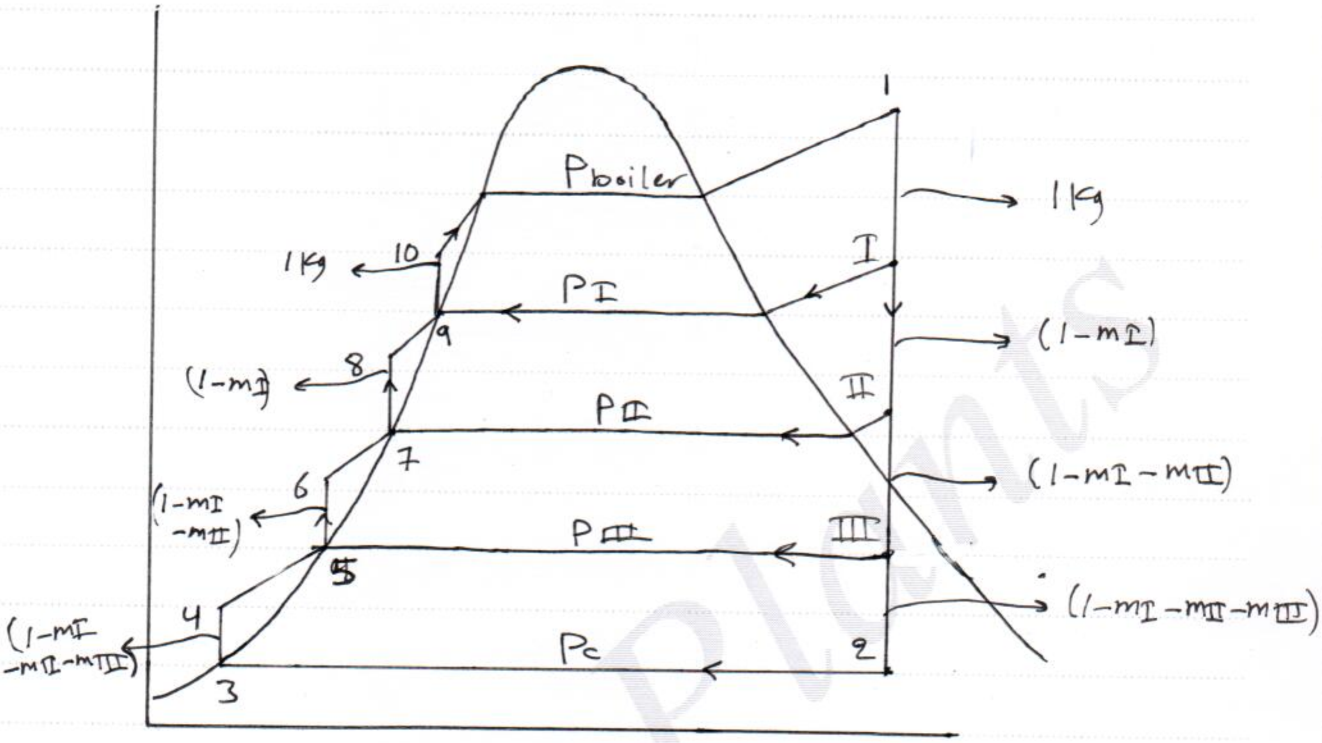
$$S.S.C = \frac{3600}{W.D} = \frac{3600}{936} = 3.846 \text{ Kg}_{fuel}/\text{Kw.h}$$

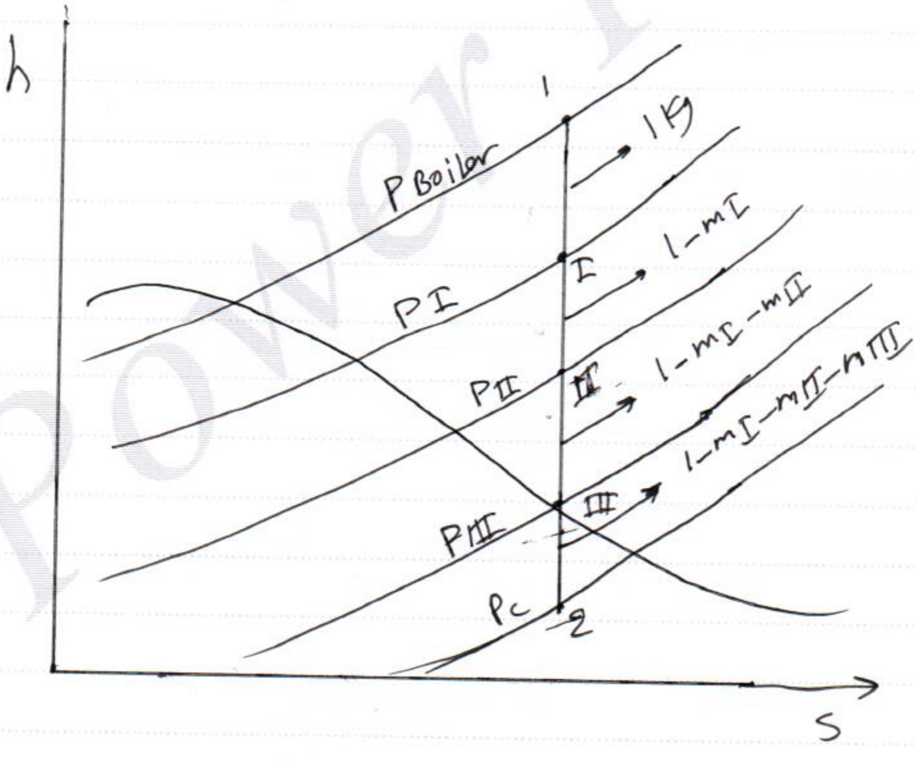
- Closed feed water heaters

In this type, the heat is transferred from the extracted (bleeded) steam to the feed water without mixing taking place. The two streams can be at diffrent pressure since they donot mix

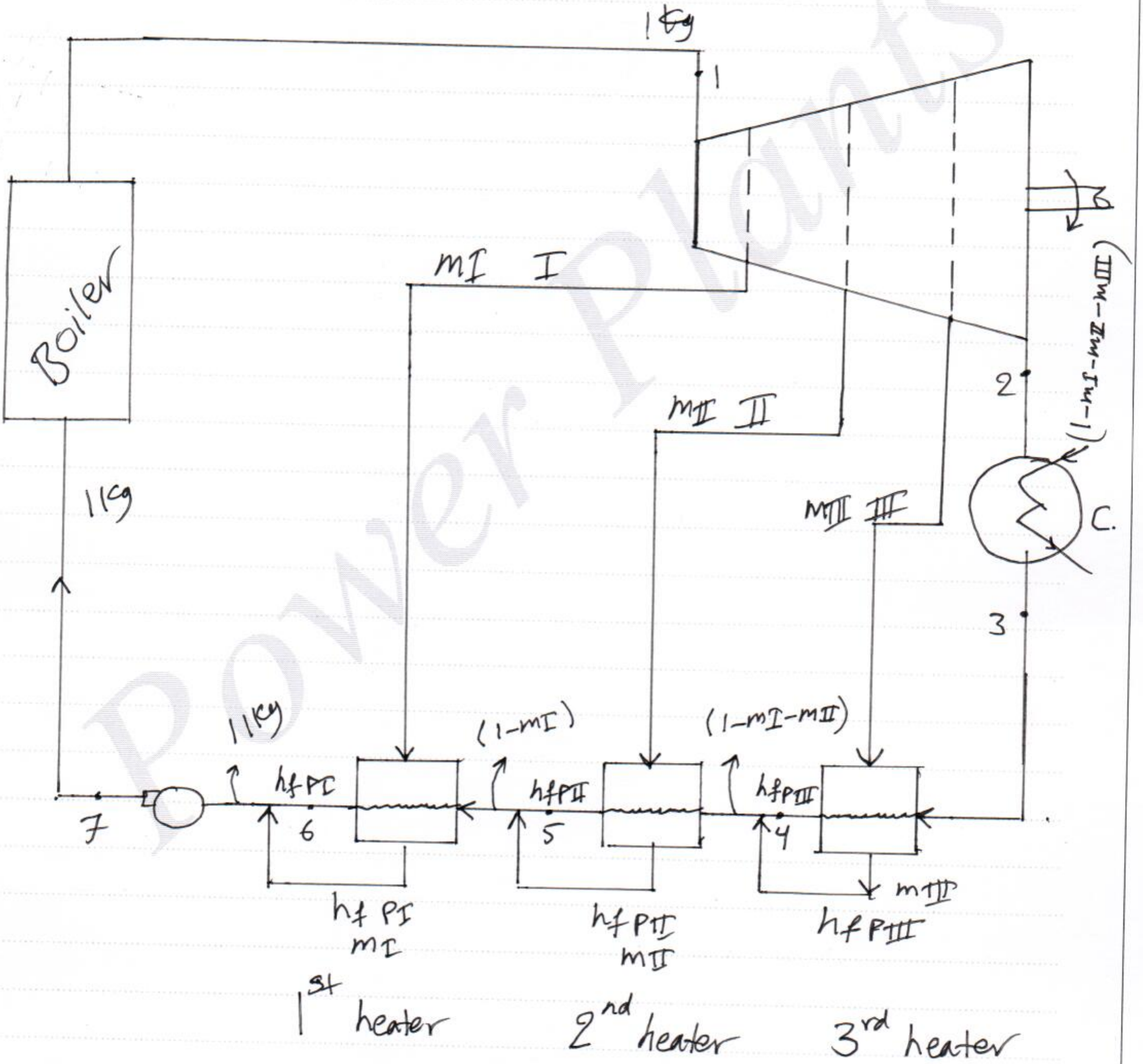
- Forward flow heaters :-

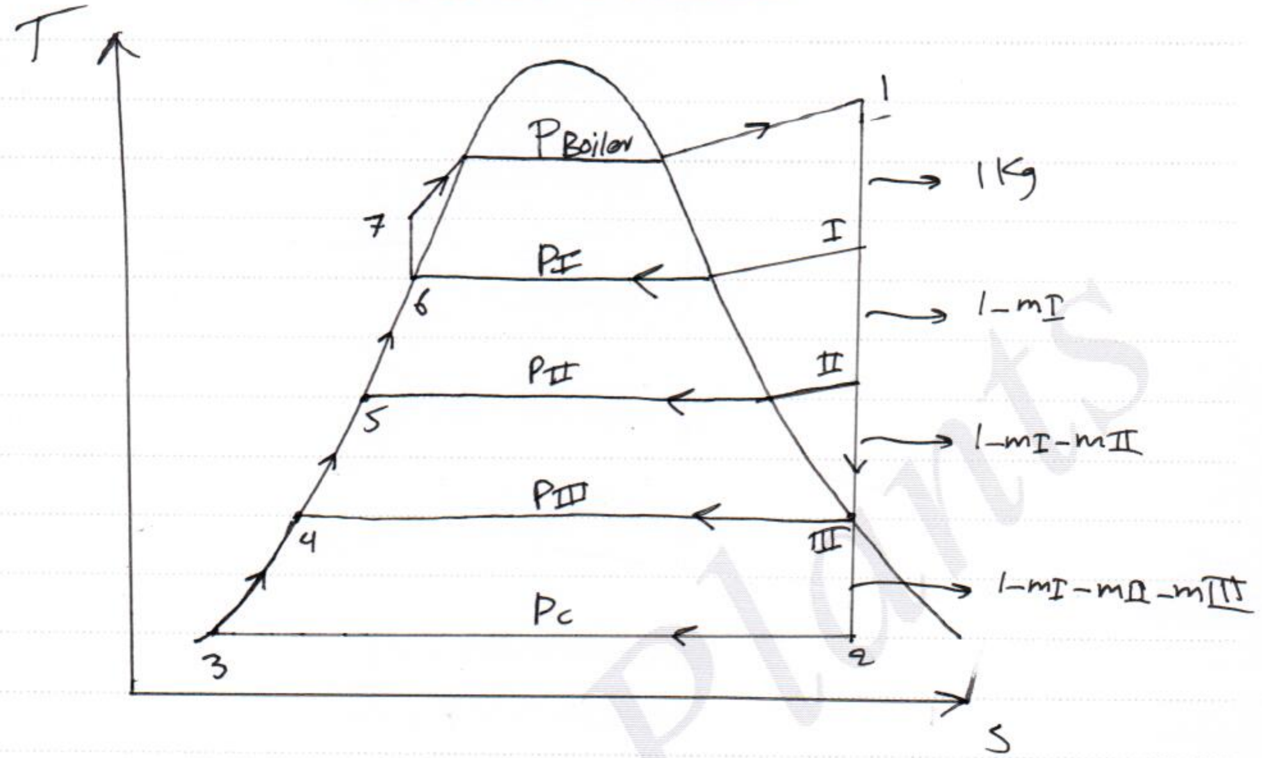



1
Pboiler
1Kg
10
1Kg
I
PI
9
(1-mI)
8
(1-mI)
II
PII
7
(1-mI-mII)
6
(1-mI
-mII)
PIII
III
5
(1-mI-mII-mIII)
4
(1-mI
-mII-mIII)
Pc
2
3


h
1
PBoiler
1Kg
PI
I
1-mI
PII
II
1-mI-mII
1-mI-mII-mIII
PIII
III
Pc
2
S

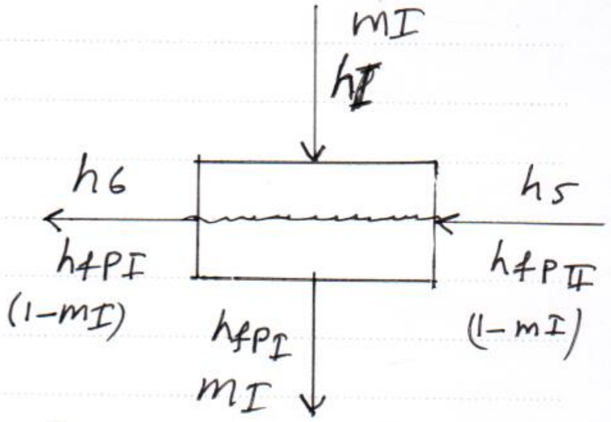
In order to make the Calculations eaiser, we can neglect work of pump1, pump 2, pump$_3$, so the new cycle is as follows:-





* Calculations :-

\- 1st heater



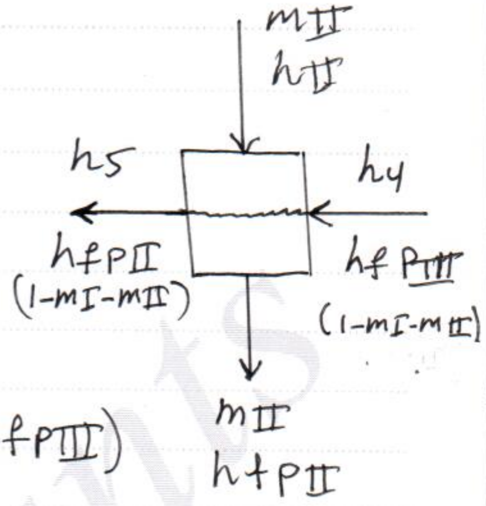
Heat rejected = heat gained

$m_I\,(h_I - h_{fP_I}) = (1-m_I) * (h_6 - h_5)$

$m_I\,(h_I - h_{fP_I}) = (1-m_I)\,(h_{fP_I} - h_{fP_{II}})$

Then, m_I is calculated from the equation above

- 2nd heater



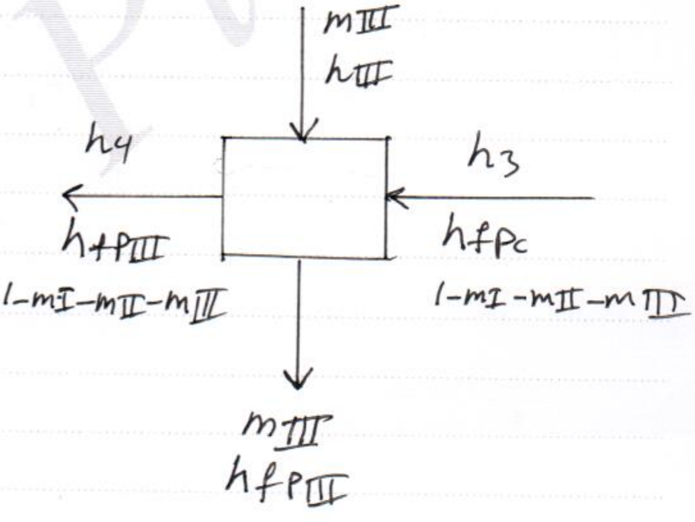
Heat rejected = Heat gained

$$m_{II}(h_{II} - h_{fPII}) = (1 - m_I - m_{II})(h_5 - h_4)$$

$$m_{II}(h_{II} - h_{fPII}) = (1 - m_I - m_{II})(h_{fPII} - h_{fPIII})$$

Then, m_{II} is calculated from equation above.

- 3rd heater



Heat rejected = heat gained

$$m_{III}(h_{III} - h_{fPIII}) = (1 - m_I - m_{II} - m_{III})(h_4 - h_3)$$

$$m_{III}(h_{III} - h_{fPIII}) = (1 - m_I - m_{II} - m_{III})(h_{fPIII} - h_{fPc})$$

m_{III} is also calculated from equation above.

Now, after all extracted masses are evaluated, we can calculate the cycle efficiency:-

$$W.D = W_{1-I} + W_{I-II} + W_{II-III} + W_{III-2} - W_{7-6}$$

$$= (h_1 - h_I) * 1\,kg + (h_I - h_{II}) * (1 - m_I) + (h_{II} - h_{III}) * (1 - m_I - m_{II}) + (h_{III} - h_2) * (1 - m_I - m_{II} - m_{III})$$

$$Q_{add} = (h_1 - h_7) * 1\,kg$$

Now, $\eta_{cycle} = \frac{W.D}{Q_{add}}$

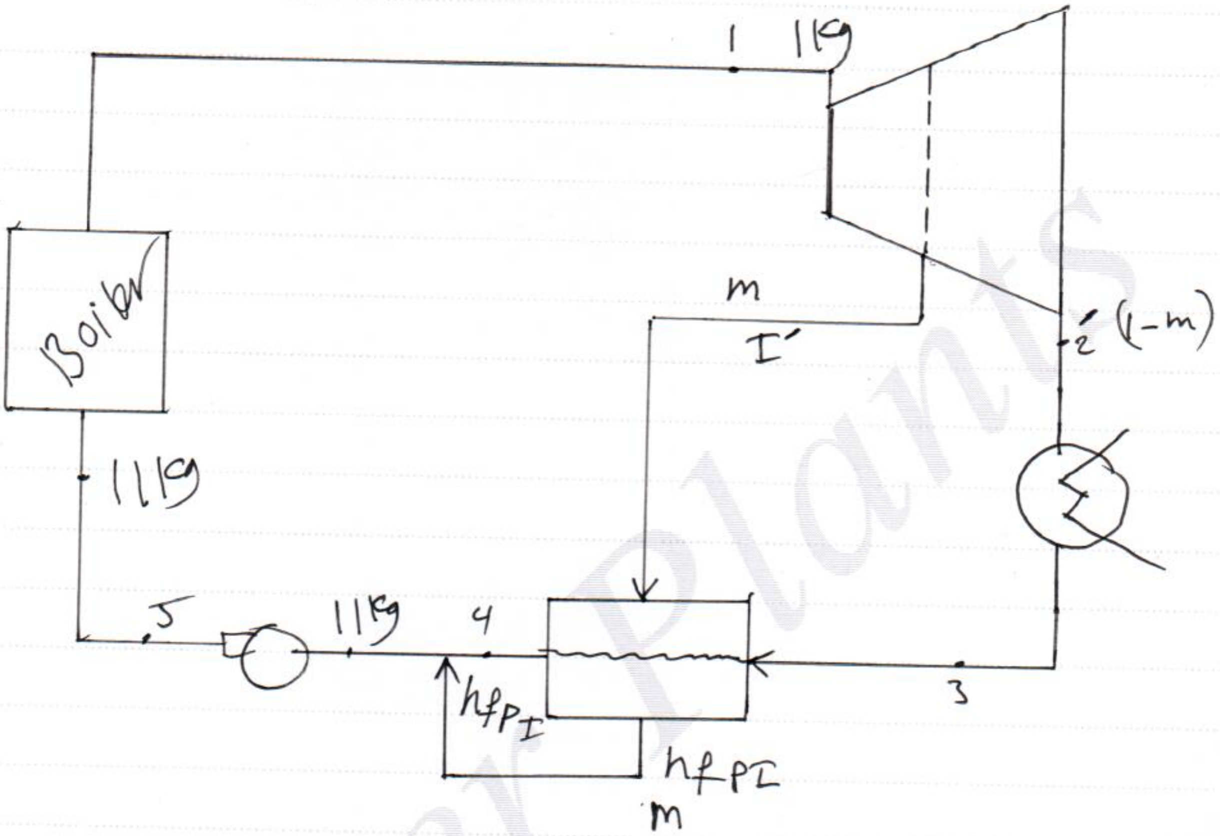
Ex/ For example on page 50, Use the same conditions. The feed water heater is closed type (forward). Calculate

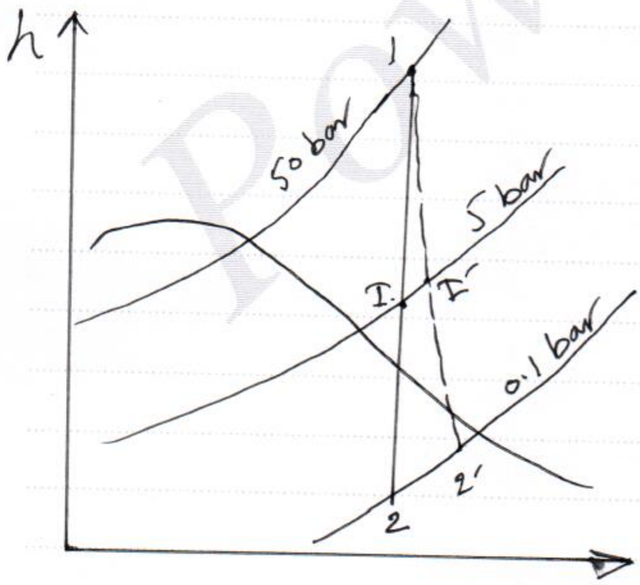
a) amount of mass used for bleeding

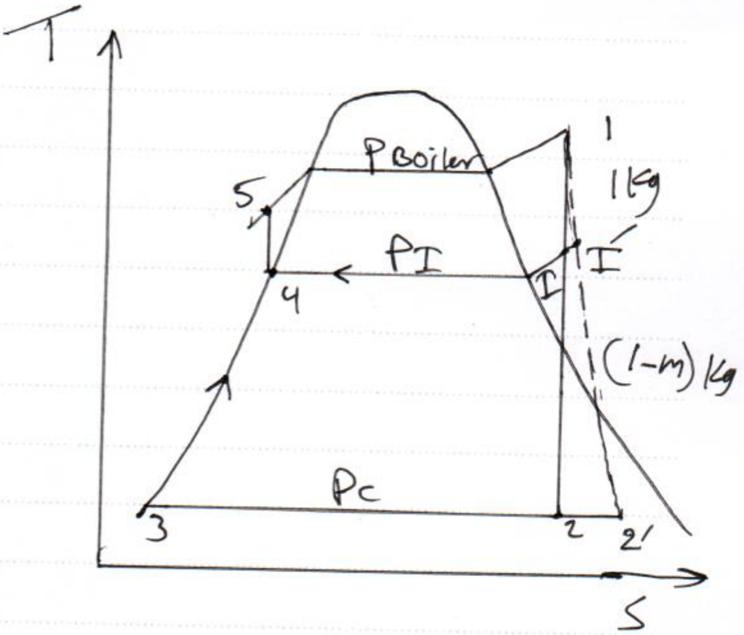
b) η_c

turbine efficiency is 85 %

Solutions.


1
1 kg
Boiler
m
I'
2' (1-m)
1 kg
5
1 kg
4
3
hf PI
hf PI
m


h
1
50 bar
5 bar
0.1 bar
I.
I'
2'
2
s


T
1
P Boiler
1 kg
5
PI
I'
4
I
(1-m) kg
Pc
3
2
2'
s

From chart : $h_1 = 3230$ KJ/Kg
$h_I = 2790$ KJ/Kg
$h_2 = 2190$ KJ/Kg

From steam table : $h_3 = h_f = 191.8$ KJ/Kg
$h_4 = h_{fP_I} = 640.1$ KJ/Kg

$$\eta_t = \frac{h_1 - h_2'}{h_1 - h_2} \Rightarrow 0.85 = \frac{3230 - h_2'}{3230 - 2190}$$

$h_2' = 2346$ KJ/Kg

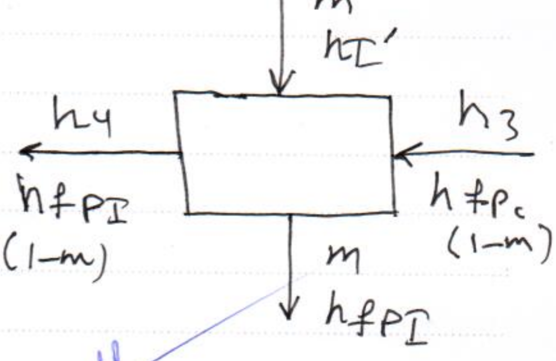
$$0.85 = \frac{h_1 - h_I'}{h_1 - h_I} \Rightarrow 0.85 = \frac{3230 - h_I'}{3230 - 2790}$$

$h_I' = 2856$ KJ/Kg

$h_5 = 642.6$ KJ/Kg , $v(P_b - P_I) = h_5 - h_4$

Heat balance for heater

$m(h_I' - h_{fP_I}) = (1-m)(h_4 - h_3)$



$m(2856 - 640.1) = (1-m)(640.1 - 191.8)$

$\therefore 2664.2\,m = 448.3$

$m = 0.1682$ Kg

Moh
Mohand Alheety

$$W.D = 1Kg\,(h_1 - h_I') + (h_I' - h_2')(1-m) - (h_5 - h_4)$$

$$= 1*(3230 - 2856) + (2856 - 2346)(1 - 0.1682) - (642.6 - 640.1)$$

$$= 795.7 \ KJ/Kg$$

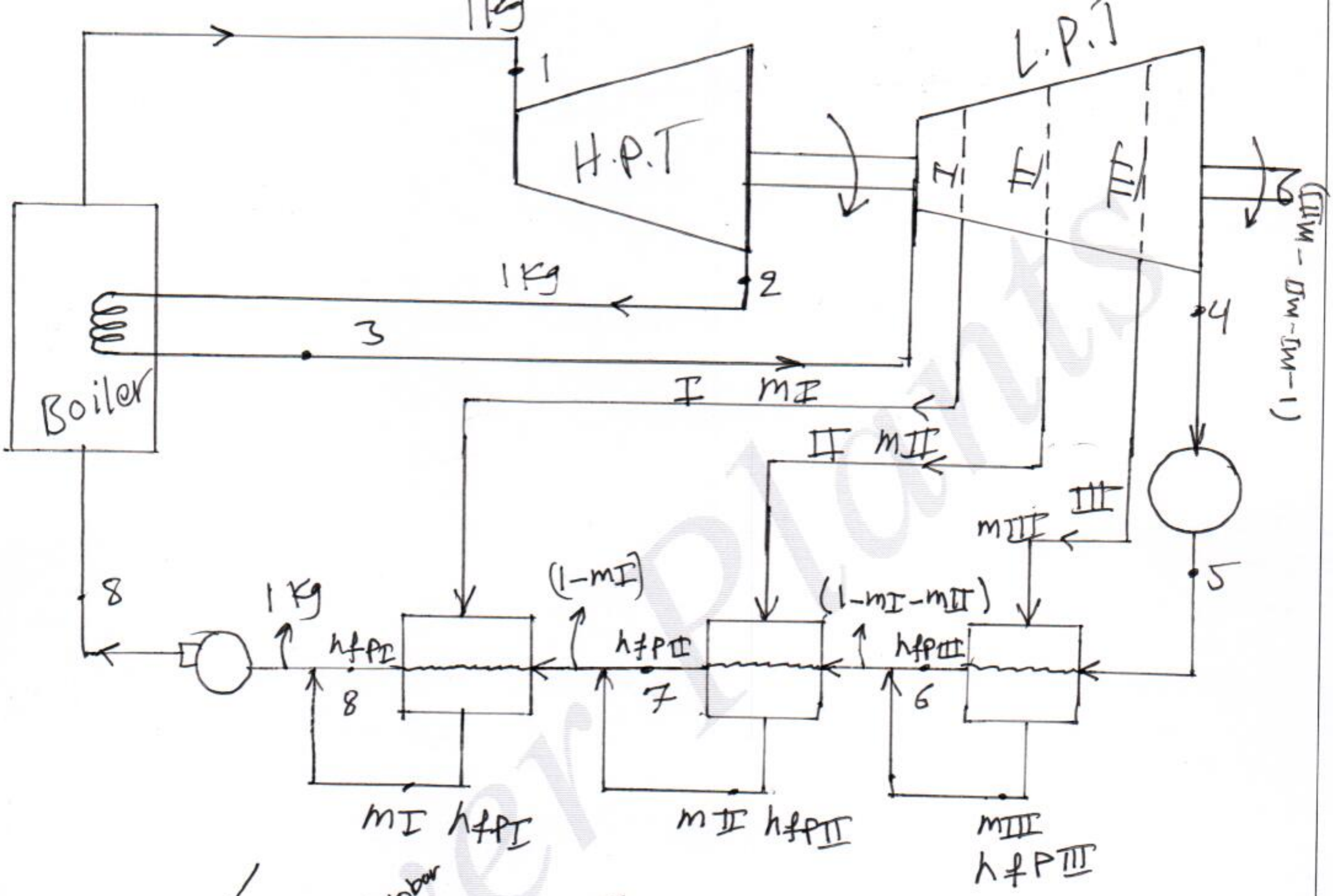
$$Q_{add} = (h_1 - h_5)/Kg$$
$$= (3230 - 642.6)*1$$
$$= 2587.4 \ KJ/Kg$$

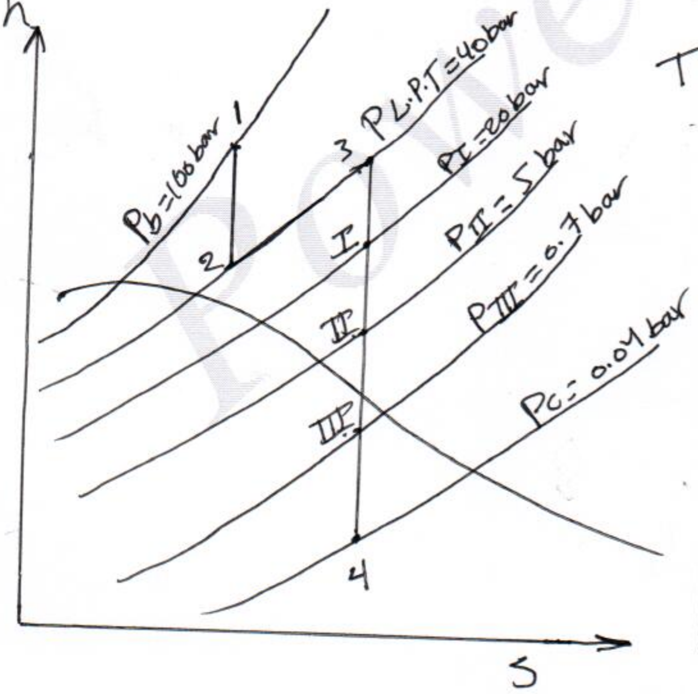
$$\eta_{cycle} = \frac{795.7}{2587.4} = 30.75\ \%$$

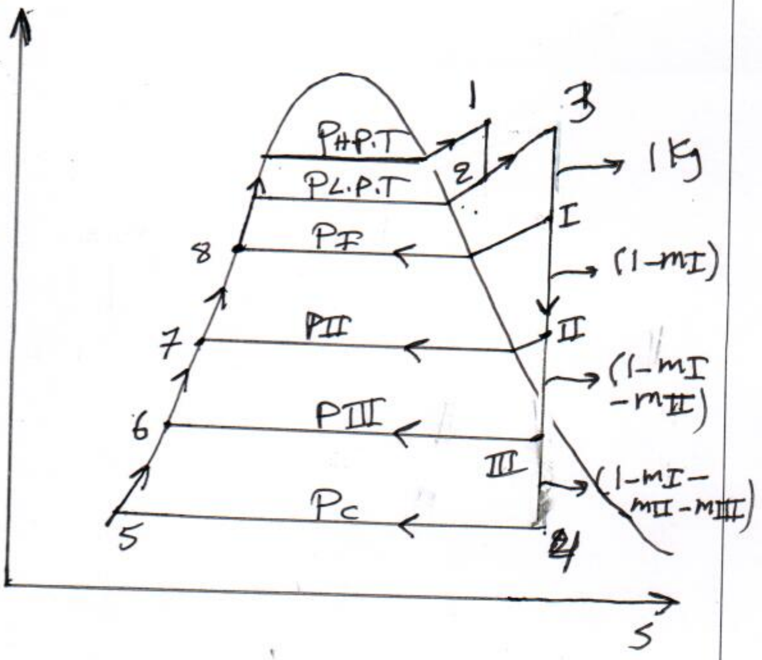
Ex/ The output Power of a steam plant is 100 MW. The turbine consists of high and low pressure cylinders with a reheating between them using boiler fuel gases. There are three forward flow feed water heaters (Closed type) located in the cycle and use bleed steam from the low pressure turbine.
Bleedings occure at 20 bar, 5 bar, 0.7 bar
Boiler steam pressure and temprature are 100 bar, 550°C
high pressure turbine exhausts at 40 bar.
steam admitted to low pressure turbine at 40 bar, 510C
Steam exhuasts from low pressure turbine at 0.04 bar
Find: a) amounts $\overset{\text{of steam}}{\uparrow}$ used for bleeding
b) mass flow rate of steam
c) Cycle efficiency

Neglect all pumps Work.

Solution:-


1Kg
1
H.P.T
2
1Kg
3
L.P.T
I
II
III
(1-mI-mII-mIII)
4
Boiler
I mI
II mII
III mIII
5
8
1Kg
(1-mI)
(1-mI-mII)
hfPI
hfPII
hfPIII
8
7
6
mI hfPI
mII hfPII
mIII hfPIII


h
Pb=100 bar
1
2
3 PL.P.T=40 bar
PI=20 bar
PII=5 bar
PIII=0.7 bar
Pc=0.04 bar
I
II
III
4
S


T
1
3
1Kg
PHP.T
PL.P.T
2
PI
I
(1-mI)
8
PII
II
7
(1-mI-mII)
PIII
6
III
(1-mI-mII-mIII)
Pc
5
4
S

From h-s Chart:

$h_1 = 3500$ KJ/Kg

$h_2 = 3200$ KJ/Kg

$h_3 = 3470$ KJ/Kg

$h_I = 3250$ KJ/Kg

$h_{II} = 2880$ KJ/Kg

$h_{III} = 2527$ KJ/Kg

$h_4 = 2135$ KJ/Kg

From steam table:

$h_5 = h_{fP_c} = 121.4$ KJ/Kg

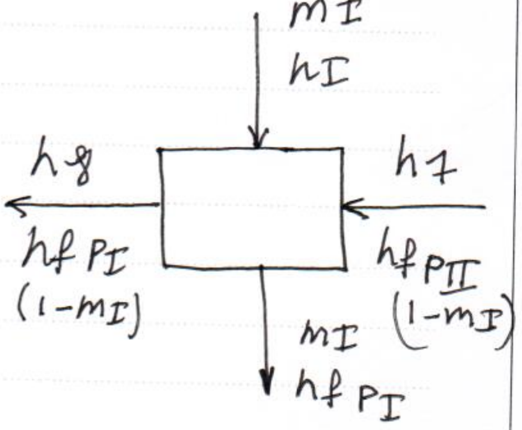
$h_6 = h_{fP_{III}} = 376.8$ KJ/Kg

$h_7 = h_{fP_{II}} = 640.1$ KJ/Kg

$h_8 = h_{fP_I} = 908.6$ KJ/Kg

Heat balance

- 1st heater



$$m_I(h_I - h_{fP_I}) = (1-m_I)(h_8 - h_7)$$

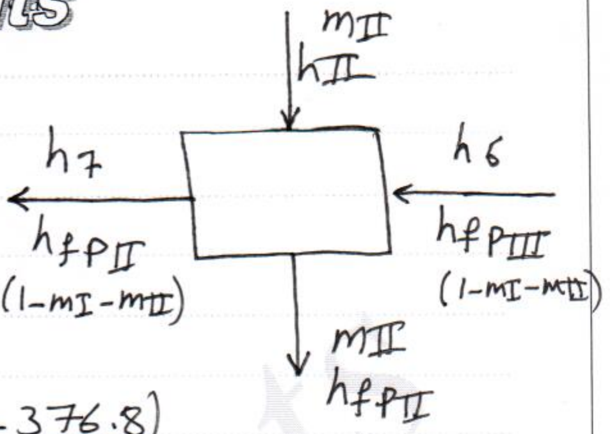
$$m_I(3250 - 968.6) = (1-m_I)(968.6 - 640.1)$$

$$2341.4\, m_I = (1-m_I) * 268.5$$

$$2609.9\, m_I = 268.5$$

$$m_I = 0.1028 \text{ Kg}$$

- 2nd heater

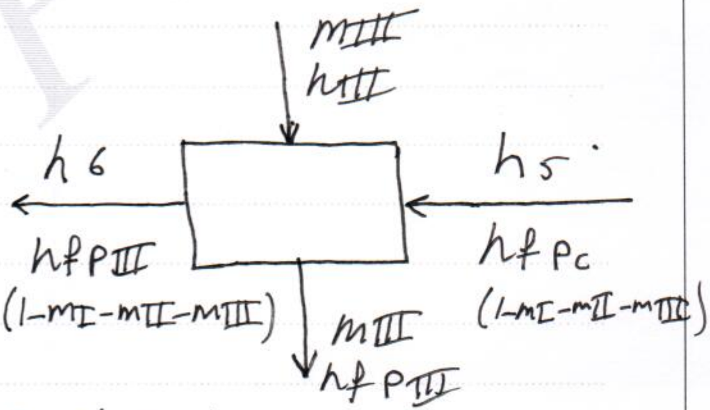


$$m_{II}(h_{II}-h_{fP_{II}}) = (1-m_I-m_{II}) * (h_7-h_6)$$

$$m_{II}(2880-640.1) = (1-0.1028-m_{II}) * (640.1-376.8)$$
$$2239.9\, m_{II} = (0.8972-m_{II}) * 263.3$$
$$2503.2\, m_{II} = 236.237$$

$$m_{II} = 0.0943 \text{ Kg}$$

- 3rd heater



$$m_{III}(h_{III}-h_{fP_{III}}) = (1-m_I-m_{II}-m_{III})(h_6-h_5)$$

$$m_{III}(2527-376.8) = (1-0.1028-0.0943-m_{III})(376.8-121.4)$$
$$2150.2\, m_{III} = (0.8029-m_{III}) * 255.4$$
$$m_{III} * 2405.6 = 205.06$$

$$m_{III} = 0.0852 \text{ Kg}$$

$W.D = W_{H.P.T} + W_{L.P.T}$

$= W_{H.P.T} + W_{3-I} + W_{I-II} + W_{II-III} + W_{III-4}$

$= 1kg(h_1-h_2) + 1kg(h_3-h_I) + (1-m_I)(h_I-h_{II}) + (1-m_I-m_{II})(h_{II}-h_{III}) + (1-m_I-m_{II}-m_{III})(h_{III}-h_4)$

$= (3500-3200) + (3470-3250) + (1-0.1028)(3250-2880)$

$+(1-0.1028-0.0943)(2880-2527) + (1-0.1028-0.0943-0.0852) * (2527-2135)$

$= 1416.7 \; KJ/Kg$

$Q_{add} = 1kg(h_1-h_8) + 1kg(h_3-h_2)$

$= (3500-908.6) + (3470-3200)$

$= 2861.4 \; KJ/kg$

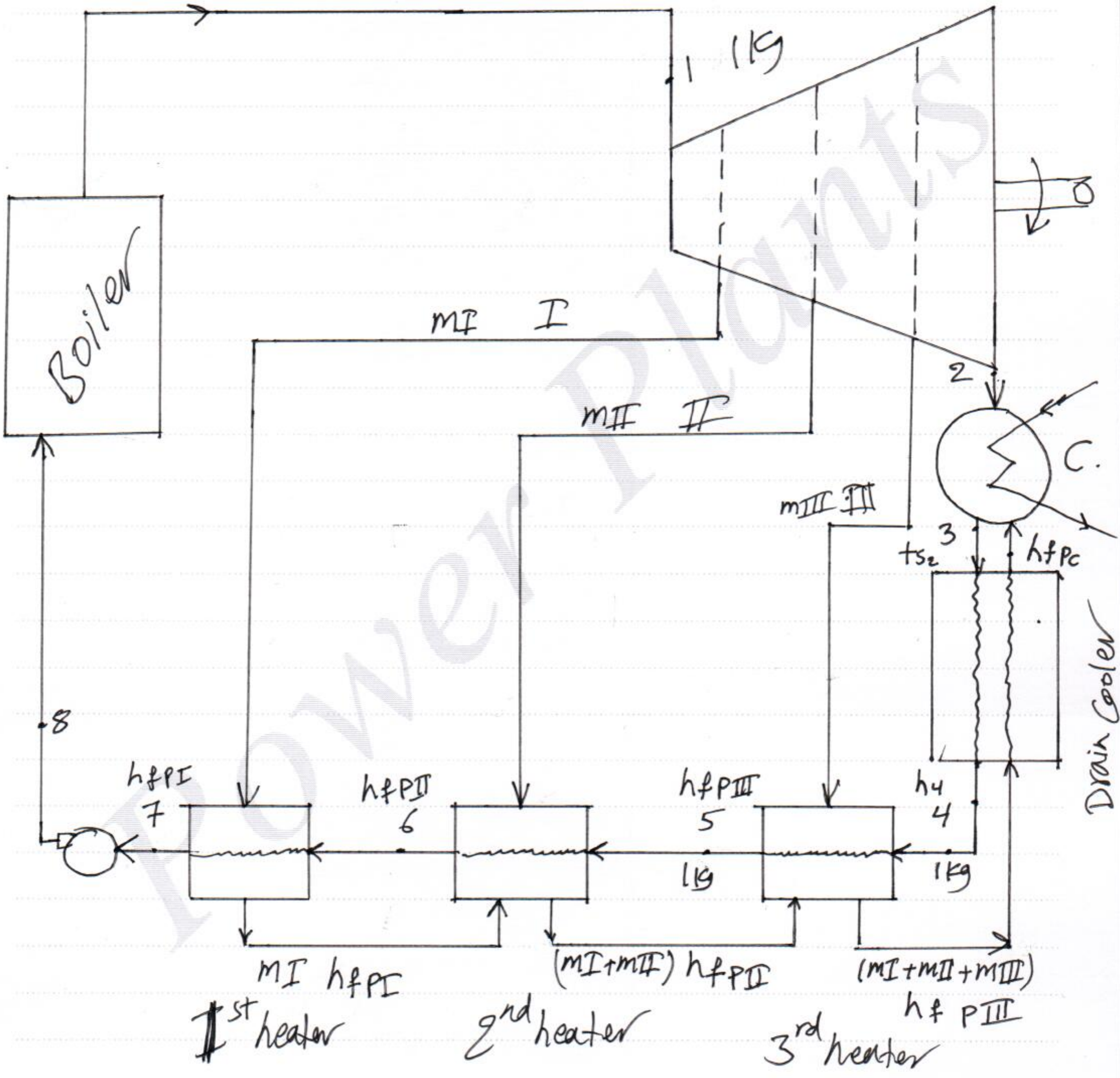
$P_{output} = \dot{m}_s * W.D$

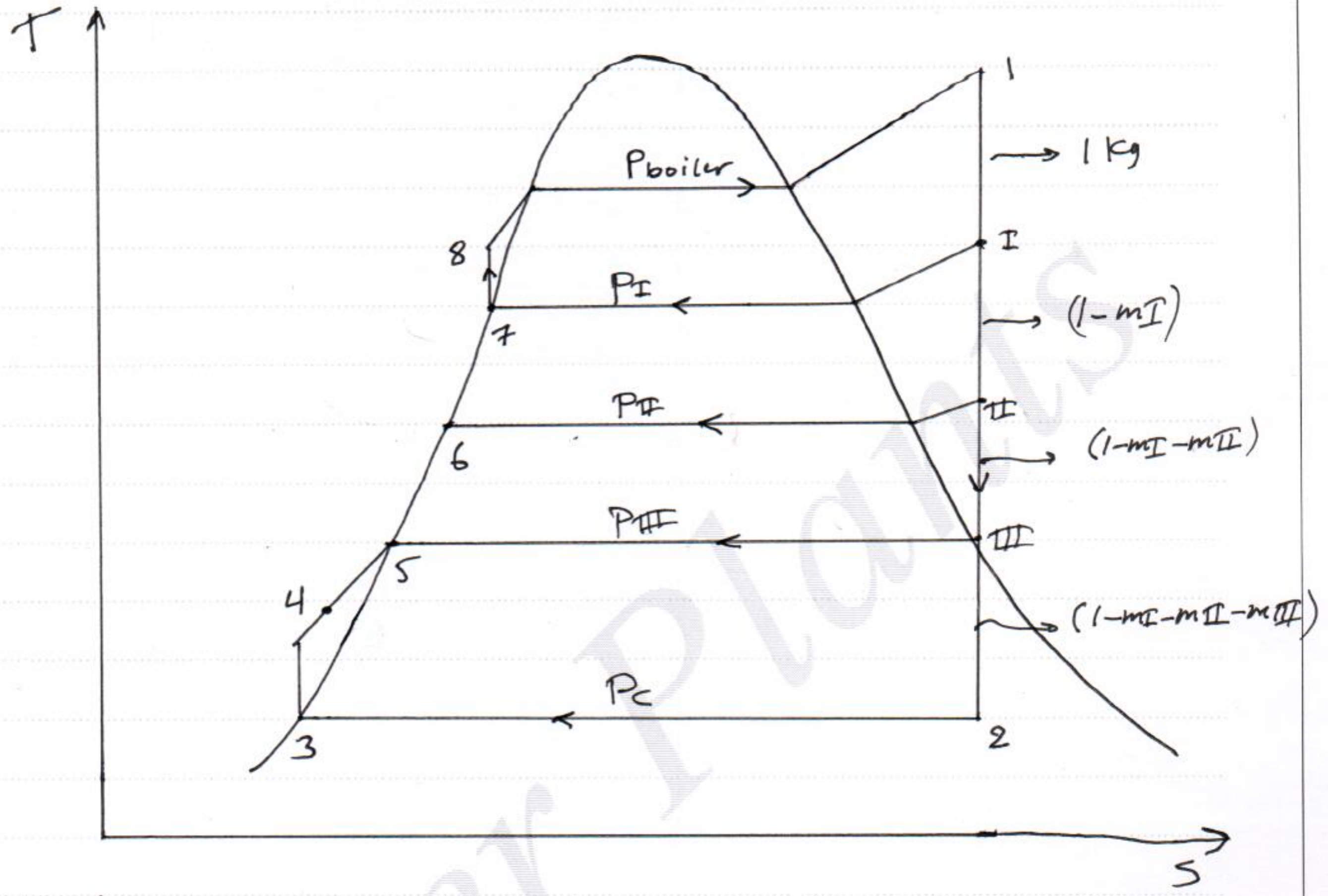
$100\,000 = \dot{m}_s * 1416.7$

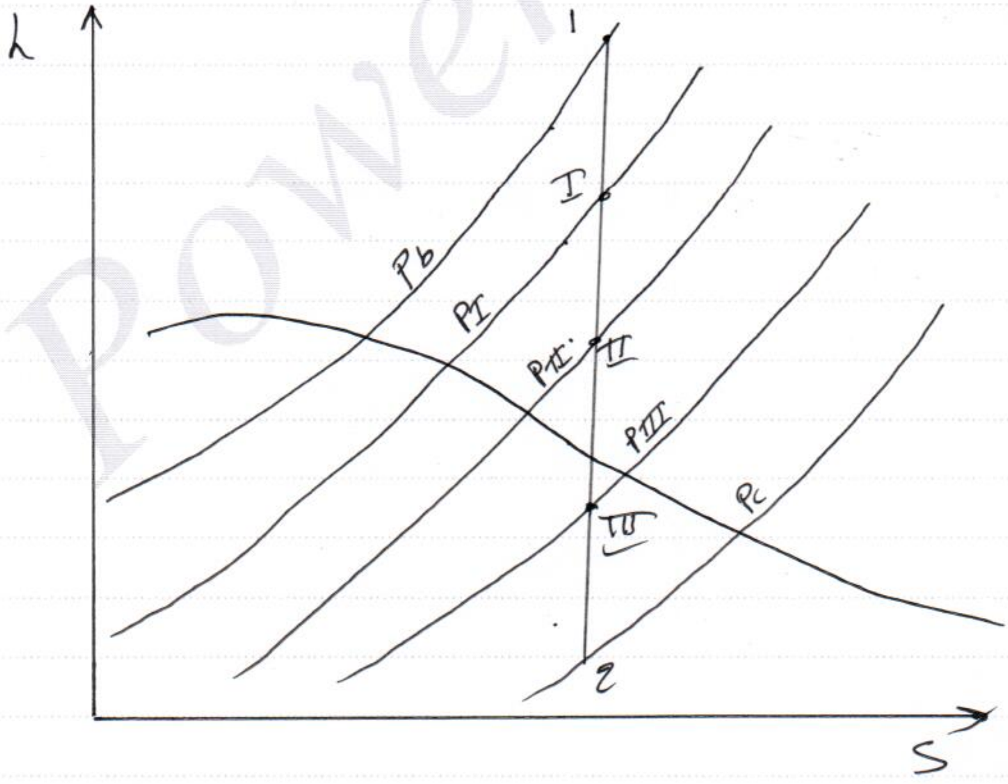
$\dot{m}_s = 70.58 \; Kg/s$

$\eta_{cycle} = \frac{1416.7}{2861.4} = 49.5\ \%$

- Backward flow heaters (Cascaded)

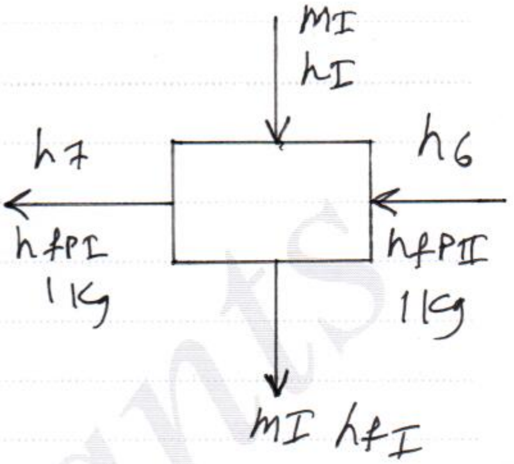



T
1
→ 1 Kg
Pboiler
I
8
PI
→ (1 - mI)
7
PII
II
6
→ (1-mI-mII)
PIII
III
5
4
→ (1-mI-mII-mIII)
Pc
3
2
S


h
1
I
Pb
PI
PII
II
PIII
III
Pc
2
S

Heat balance for heaters

- 1st heater

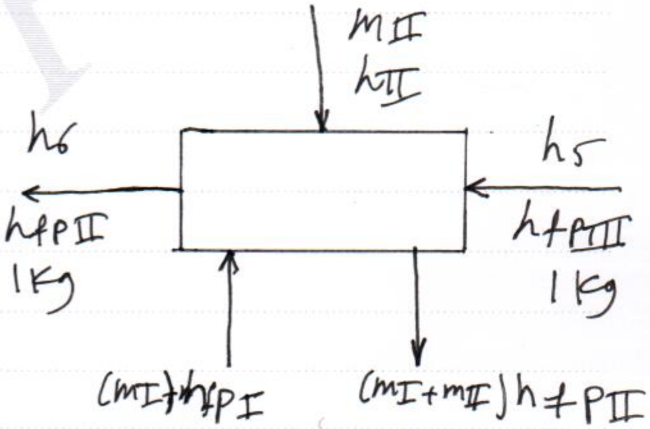


$$1kg\,(h_7 - h_6) = m_I\,(h_I - h_{fI})$$

$$1kg\,(h_{fpI} - h_{fpII}) = m_I\,(h_I - h_{fI})$$

$$m_I = \frac{h_{fpI} - h_{fpII}}{h_I - h_{fpI}}$$

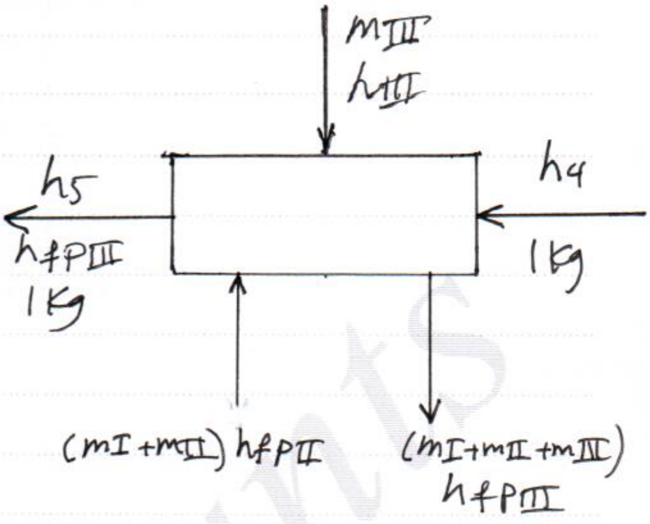
- 2nd heater



$$h_5 * 1kg + m_{II} h_{II} + m_I h_{fpI} = h_6 * 1kg + (m_I + m_{II})\, h_{fpII}$$

We already evaluated m_I

So, m_{II} can be calculated.



$$h_4 \times 1\,Kg + m_{III}\,h_{III} + (m_I+m_{II})\,h_{fpII} = h_5 \times 1\,Kg + (m_I+m_{II}+m_{III})\,h_{fpIII} \quad ①$$

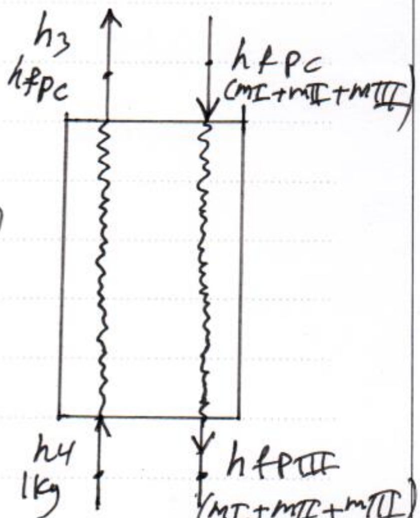
m_I, m_{II} are evaluated previously
In order to calculate m_{III}, we need to estimat (h_4), so we can make heat balance on the drain cooler

- Drain Cooler

$$1\,Kg\,(h_4 - h_3) = (m_I+m_{II}+m_{III})(h_{fpIII} - h_{fpc})$$

$$1\,Kg\,(h_4 - h_{fpc}) = (m_I+m_{II}+m_{III})(h_{fpIII} - h_{fpc})$$

$$h_4 = (m_I+m_{II}+m_{III})(h_{fpIII} - h_{fpc}) + h_{fpc} \quad ②$$



by subistituting equ ② in equ ①

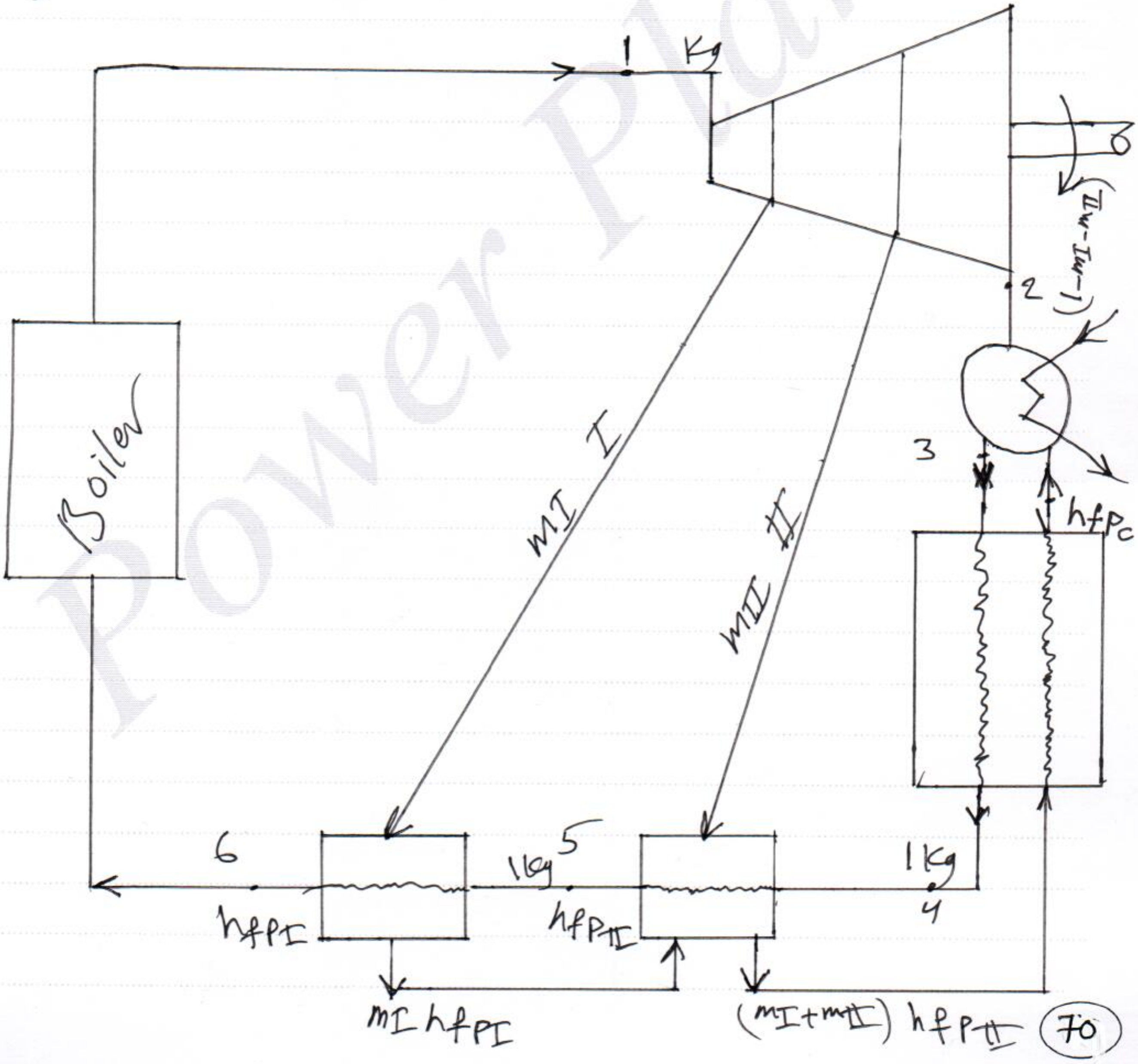
We can find m_{III}.

Ex/ Steam is supplied to a turbine at 30 bar and 350°C. The turbine exhaust pressure is 0.08 bar. The main Condensate is heated in two stages of backward closed feed water heaters. The steam bled from the turbine at 5 bar and 1 bar. Calculate:

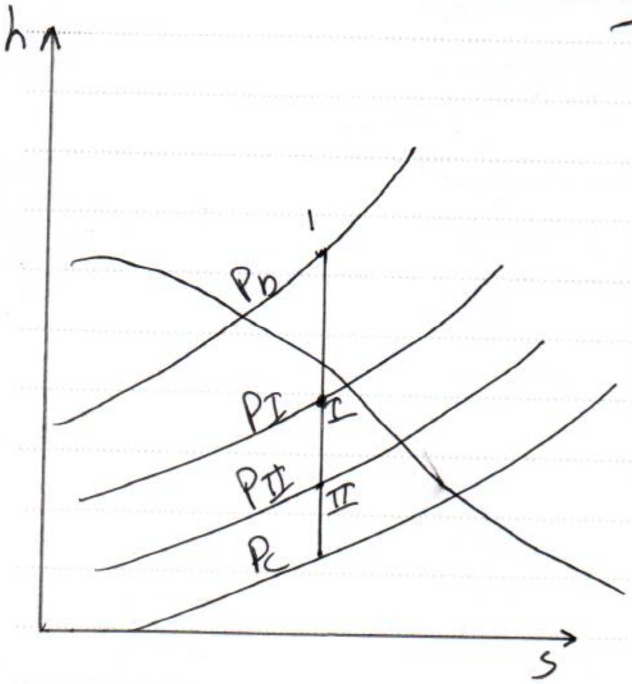
a) masses of bled steam of each heater.

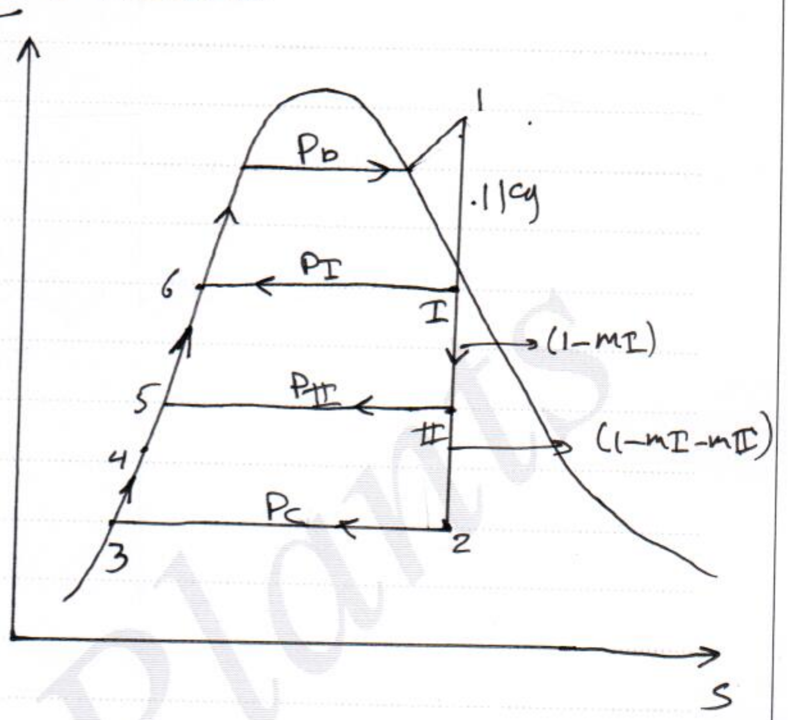
b) Thermal efficiency of the cycle.

Neglect all pumps work.



Power Plants





From Mollier chart

At 30bar, 350 C

$h_1 = 3115$ KJ/Kg

$h_I = 2720$ KJ/Kg

$h_{II} = 2450$ KJ/Kg

$h_2 = 2120$ KJ/Kg

From steam table

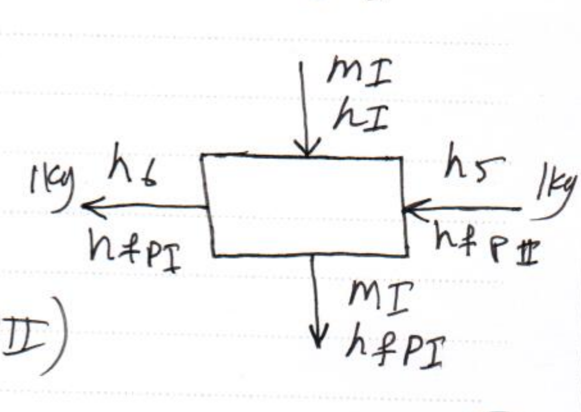
$h_3 = h_{fP_C} = 173.9$ KJ/Kg

$h_5 = h_{fP_{II}} = 417.5$ KJ/Kg

$h_6 = h_{fP_I} = 640.1$ KJ/Kg

Heat balance

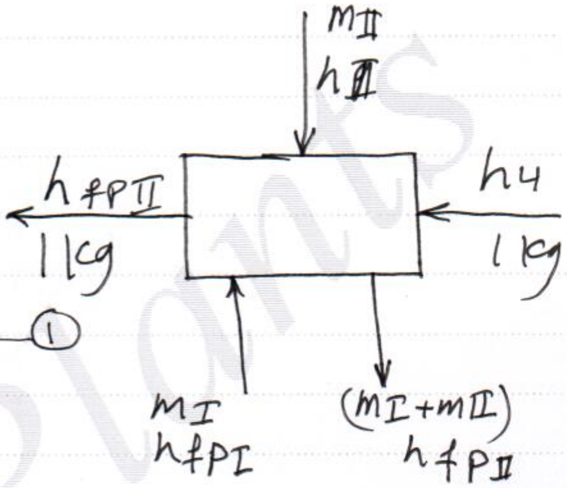
1st heater



$$m_I(h_I - h_{PfI}) = 1Kg\,(h_{fPI} - h_{fPII})$$

$$m_I = \frac{640.1 - 417.5}{2720 - 640.1} = 0.107 \text{ kg}$$

- 2^{nd} heater



$$h_{II} m_{II} + m_I h_{fpI} + h_4 * 1\text{kg} = h_{fpII} * 1\text{kg} + (m_I + m_{II}) h_{fpII} \quad \text{——} ①$$

- Drain Cooler

$$1\text{kg}(h_4 - h_3) = (m_I + m_{II})(h_{fpII} - h_{fpc})$$

$$h_4 = (m_I + m_{II})(h_{fpII} - h_{fpc}) + h_3 \quad \text{——} ②$$

Inserting the value of h_4
in equ ① :-

$$m_{II} h_{II} + m_I h_{fpI} + (m_I + m_{II})(h_{fpII} - h_{fpc}) + h_3 = (m_I + m_{II}) h_{fpII} + h_{fpII}$$

$$2456\, m_{II} + 0.107 * 640.1 + (0.107 + m_{II})(417.5 - 173.9) + 173.9 = (0.167 + m_{II}) * 417.5 + 417.5$$

$$2450\,m_{II} + 68.4967 + 243.6\,m_{II} + 26.06 + 173.9 =$$
$$417.5\,m_{II} + 44.673 + 417.5$$

$$2276.1\,m_{II} = 193.72$$

$$m_{II} = 0.085 \text{ Kg}$$

$$W.D = 1\text{Kg}\,(h_1 - h_I) + (1 - m_I)(h_I - h_{II}) + (1 - m_I - m_{II})(h_{II} - h_2)$$

$$= (3115 - 2720) + (1 - 0.107)(2720 - 2450) + (1 - 0.107 - 0.085)(2450 - 2120)$$

$$= 903 \text{ KJ/Kg}$$

$$Q_{add} = (h_1 - h_6) \times 1\text{Kg}$$

$$= (3115 - 640.1) = 2475.2 \text{ KJ/Kg}$$

$$\eta_{cycle} = \frac{W.D}{Q_{add}}$$

$$= \frac{903}{2475.2} = 36.48\ \%$$

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Ex/ In a steam power plant, steam enters a H.P.T at 100 bar and 500°C and exits at 25 bar. steam is re-heated to 490°C. Then, it enters intermediate pressure turbine and expands to 3 bar. Then, it is reheated again to 311°C, and it enters the L.P.T and expand to the condenser pressure of 0.05 bar. A closed feed water heater is located in the feed cycle and uses bleed steam from the H.P.T at 40 bar. The net output power is 100 MW.

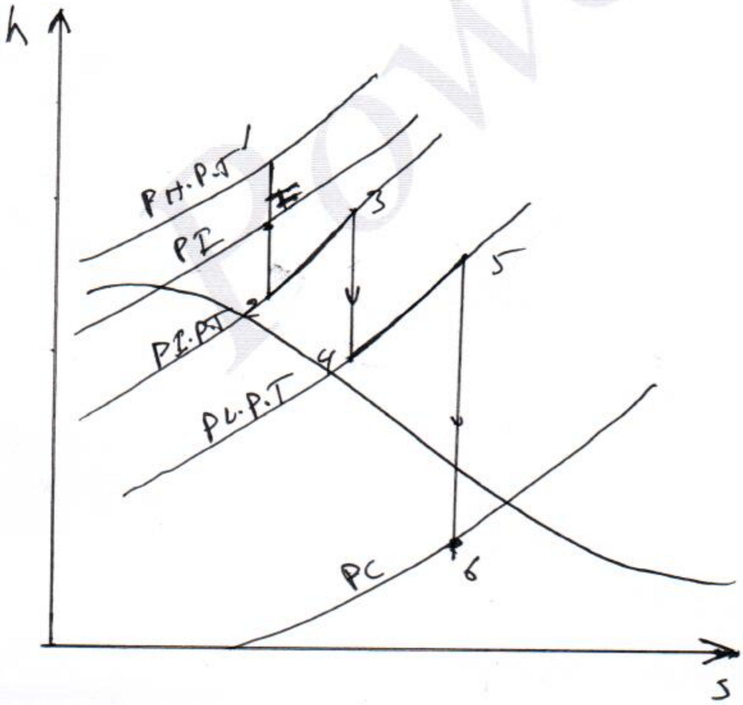
Determine :-

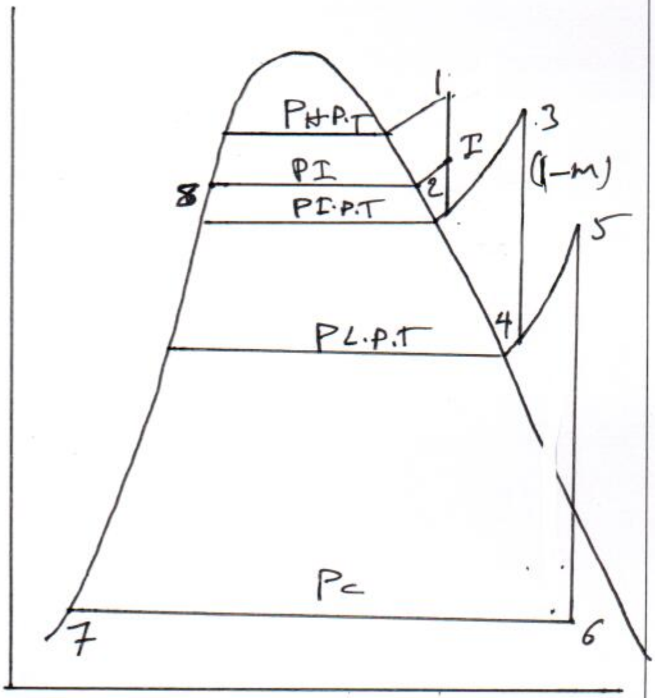
a) amount of steam used for bleeding.

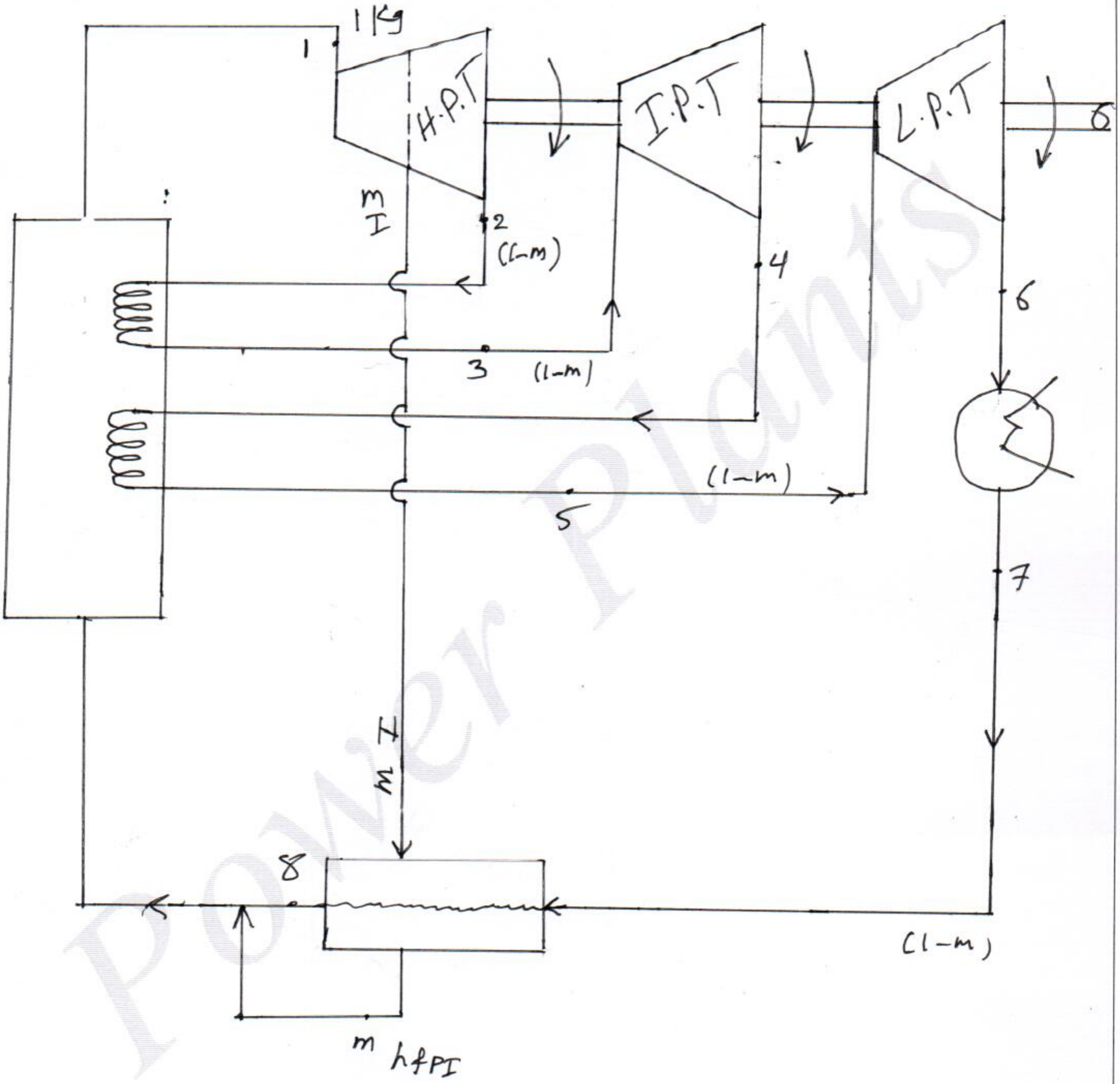
b) mass flow rate of the steam

c) Work done

d) Cycle efficiency.






1 Kg
1
H.P.T
I.P.T
L.P.T
G
m
I
2
(1-m)
3
(1-m)
4
6
(1-m)
5
7
m I
8
(1-m)
m hfPI

From Mollier Chart $h_1 = 3375$ KJ/Kg

$h_2 = 2985$ KJ/Kg

$h_I = 3095$ KJ/Kg

$h_3 = 3440$ KJ/Kg

$h_4 = 2860$ KJ/Kg

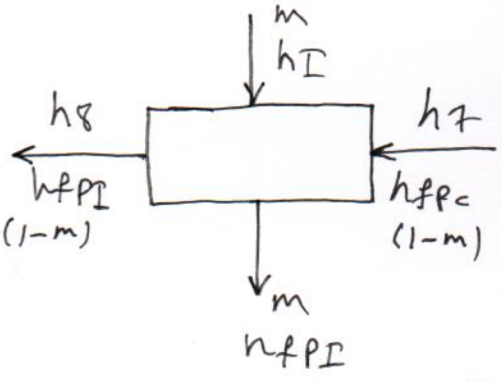
$h_5 = 3090$ KJ/Kg

$h_6 = 2360$ KJ/Kg

From Steam table $h_7 = h_{fPc} = 137.82$ KJ/Kg

$h_8 = h_{fPI} = 1087.3$ KJ/Kg

Heat balance for heater



$$m(h_I - h_{fPI}) = (1-m)(h_{fPI} - h_{fPc})$$

$$m(3095 - 1087.3) = (1-m)(1087.3 - 137.82)$$

$$2007.7\,m = 949.48 - 949.48\,m$$

$$m = 0.321 \text{ Kg}$$

$$W.D = (h_1 - h_I)\,\text{Kg} + (1-m)\left[(h_I - h_2) + (h_3 - h_4) + (h_5 - h_6)\right]$$

$$= (3375 - 3095) + (1 - 0.321)\left[(3375 - 2985) + (3440 - 2860) + (3090 - 2360)\right]$$

$$= 1434.3 \text{ KJ/Kg}$$

$Q_{add} = (h_1 - h_8) 1kg + (1-m)[(h_3 - h_2) + (h_5 - h_4)]$

$= (3375 - 1087.3) + (1 - 0.321)[(3440 - 2985) + (3090 - 2860)]$

$= 2752.8$ KJ/kg

$P_{output} = \dot{m}_s * W.D$

$\dot{m}_s = \frac{100\,000}{1434.3} = 69.7$ kg/s

$\eta_{cycle} = \frac{1434.3}{2752.8} = 52.1\,\%$

Power Plants

Sheet 1

Q1/ Steam is supplied to a two-stage at 40 bar and 350°C. It expands in the first turbine until it is just dry saturated, then it is reheated to 350°C and expanded through the second turbine. The condenser pressure is 0.035 bar. Calculate S.S.C and η_{cycle}

[2.79 Kg/Kw.hr, 38.4%]

Q2/ A steam power plant operates on ideal regenerative cycle with one open feed water heater. Steam enters the turbine at 15 MPa and 600°C. Some steam leaves the turbine at a pressure of 1.2 MPa and enters the open heater. Determine the fraction of steam extraction from the turbine and thermal efficiency of the cycle

[0.227 Kg, 46.3%]

Q3/ In a regenerative steam cycle employing three closed feed water heaters, the steam is supplied to the turbine at 42 bar and 500°C and is exhusted to the condenser at 0.035 bar. The bleed steam for feed heating is taken at pressures of 15, 4 and 0.5 bar. Neglect work of the pumps, Calculate :

a) masses of bled steam
b) Work done
c) Cycle efficiency

[0.0952, 0.0969, 0.0902, 1183.6 KJ/Kg, 43.6%]

Q4/ A steam power plant operates on an ideal reheat-regenerative cycle and has a net ~~work~~ power output of 120 MW. Steam enters the high-pressure turbine at 10 MPa and 550 °C and leaves at 0.8 MPa. Some steam is extracted at this pressure to heat the feed water in an open feedwater heater. The rest is reheated to 500 °C and expanded in the low pressure turbine to the condenser pressure of 10 KPa. Determine

a) masses of bleed steam

b) cycle efficiency [81.9 kg/s, 44.4%]

Q5/ In a steam power plant, the steam mass flow rate is 80 ton/hr, the steam enter the turbine at 6 MPa and 480 °C. Condenser pressure is 0.06 MPa Mechanical and electrical efficiencies are 0.96 and 0.95. Find

a) S.S.C

b) Output power

c) Cycle efficiency

University of Anbar

College of Engineering

Mechanical Eng. Department

Power Plants

Chapter two

Gas Turbine

Tutor

Mohanad A. Alheety

Gas Turbine

A gas turbine, also called a combustion turbine, is atype of internal combusion engine. It has an opstream rotating compressor coupled to an downstream turbine, and a combusion chamber in between.

The basic operation of the gas turbine is similer to that of the steam power plant expcept that ~~the~~ air is used instead of water.

Applications :-

- Aircraft field
- Electrical Power generation
- Marine propulsion

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Advantages :-

- Very high power-to-weight ratio
- Smaller than most reciprocating engines of the same power rating.
- Fewer moving parts than reciporocating engines.
- Very low toxic emissions

Disadvantages :-

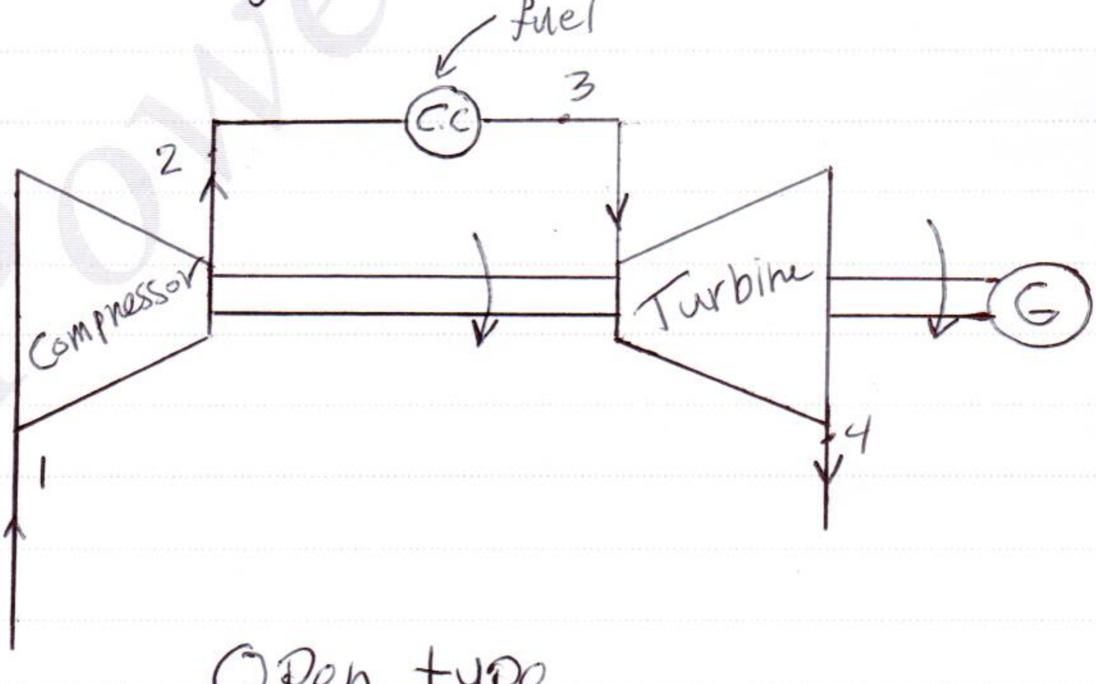
- Cost is very high
- Less efficient than reciprocating engines at idle speed.
- Very sensitive to changes of the components.

Bryton Cycle

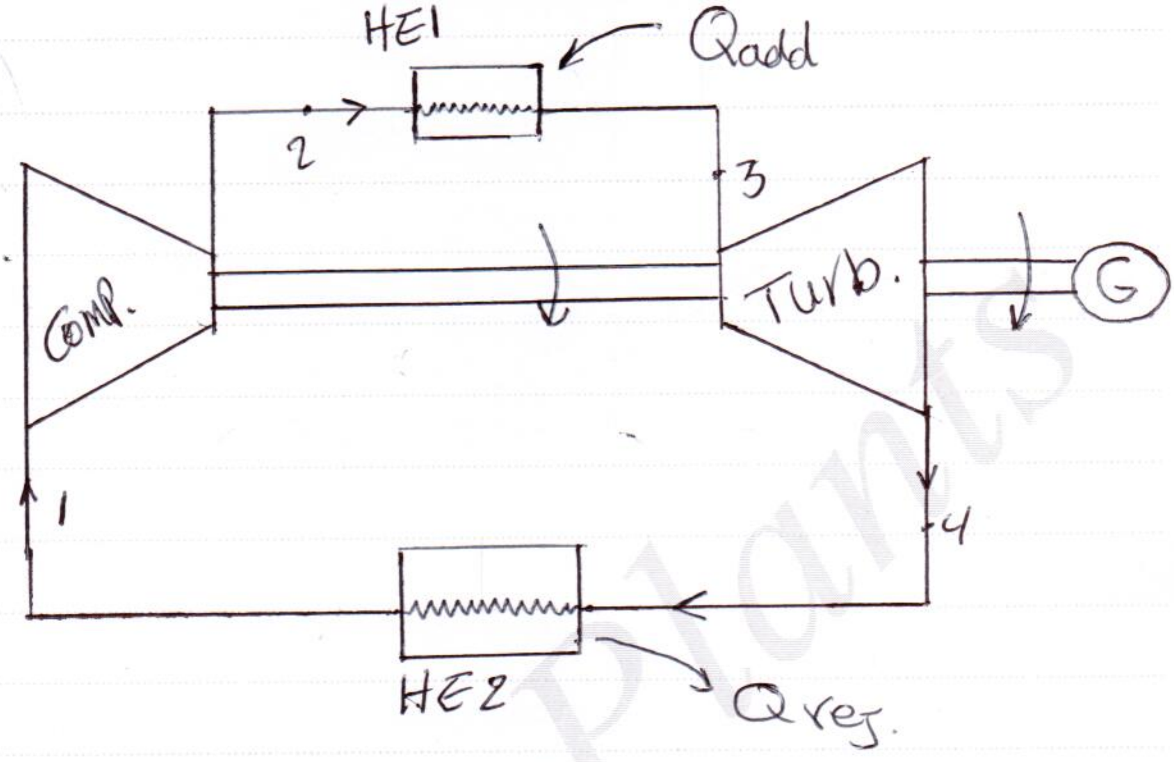
Brayton Cycle popularly used for gas turbine plants. It comprises of adiabatic compression process, Constant pressure heat addition adiabatic expansion process and constant pressure heat release process.

There are two types of gas turbine power plants:-

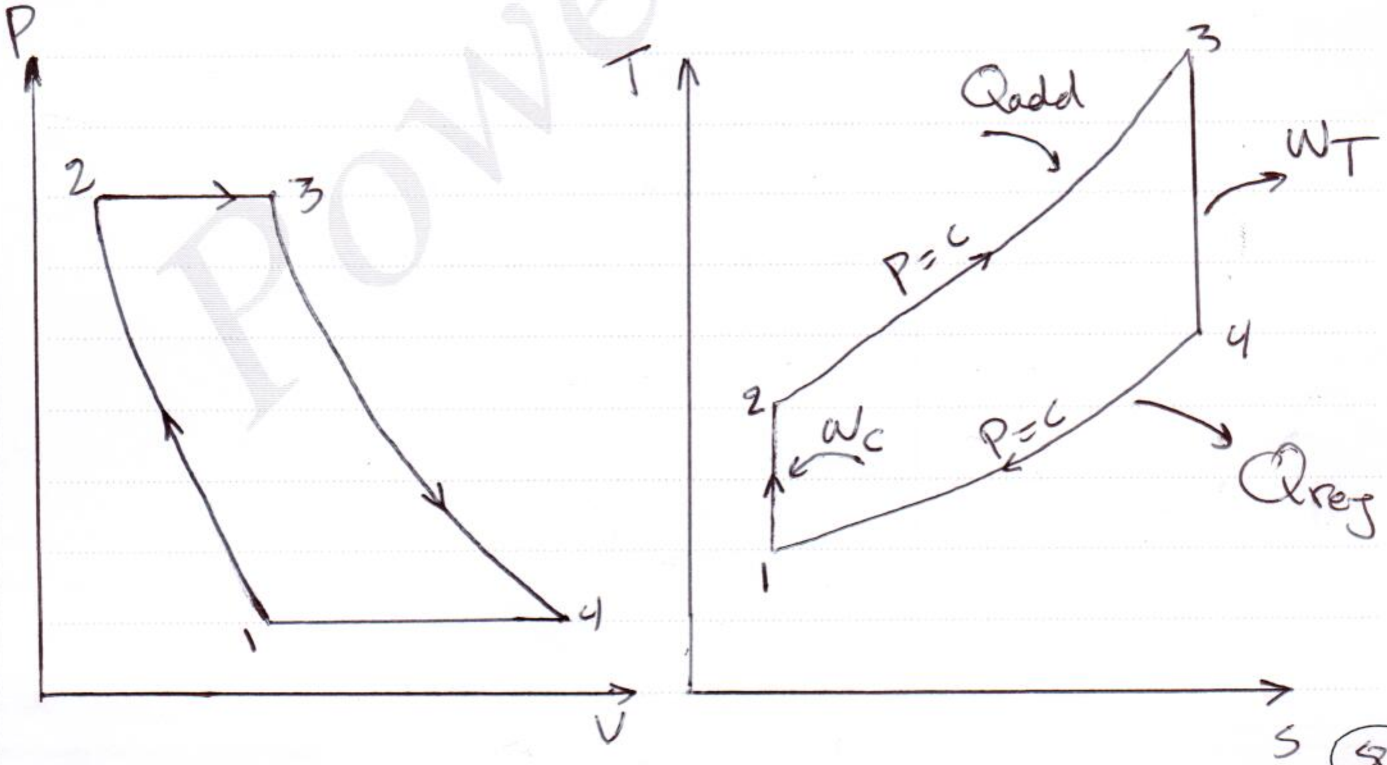
- Open type.
- Closed type.



Open type


HE1
Qadd
2
3
COMP.
Turb.
G
1
4
HE2
Q rej.

Closed type


P
2
3
1
4
V
T
3
Qadd
W_T
P=C
4
2
W_c
P=C
Q_{rej}
1
S

Power Plants

Thermodynamic cycle shows following Processes:

1-2 : Adiabatic compression, involving (-ve) work, W_C in compressor.

2-3 : Constant pressure heat addition, involving heat addition Q_{add} in combustion chamber of heat exchanger.

3-4 : Adiabatic expansion, involving (+ve) Work, W_T in turbine

4-1 : Constant Pressure heat rejection, involving heat Q_{rej} in atmosphere or heat exchanger.

It will be assumed that kinetic energy is zero. After applying the flow equation to each part of the plant, we get :—

For compressor :

$$W_c = Cp_a (T_2 - T_1) \quad \frac{KJ}{Kg}$$

For the Combusion chamber :

$$Q_{add} = Cp_g (T_3 - T_2)$$

For the turbine :

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

Then,

$$W_{net} = W_t - W_c$$
$$= Cp_g (T_3 - T_4) - Cp_a (T_2 - T_1)$$

$$\text{Thermal eff. } \eta = \frac{\text{net work output}}{\text{heat supplied}}$$

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

For a perfect gas law, in terms of pressure ratio across the turbine (r_{PT}) given by:

$$r_{PT} = \frac{P_3}{P_4}$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma_g-1}{\gamma_g}} \Rightarrow \frac{T_3}{T_4} = \left(r_{PT}\right)^{\frac{\gamma_g-1}{\gamma_g}}$$

Where γ is the ratio of specific heat at constant pressure and constant volume

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

The same thing is applied across the compressor,

$$rp_c = \frac{P_2}{P_1}$$

$$\frac{T_2}{T_1} = (rp_c)^{\frac{\gamma_a - 1}{\gamma_a}}$$

$$P_{output} = \dot{m} * W_{net}$$

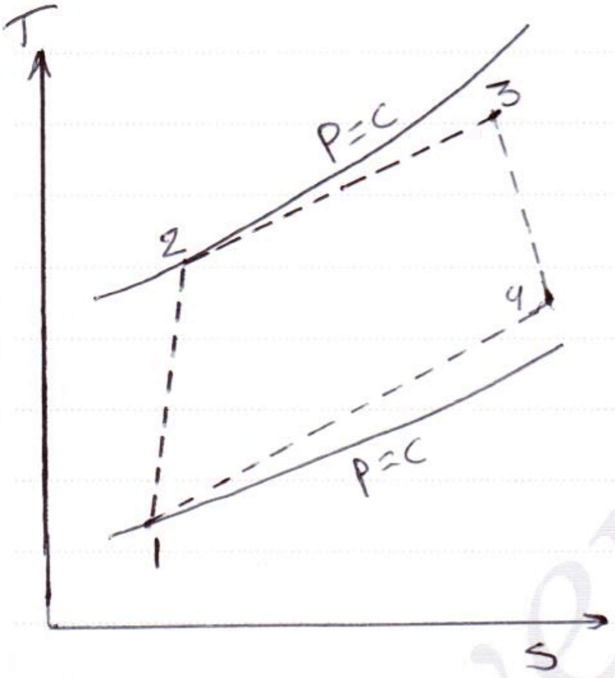
Where, $\dot{m}$ = mass flow rate of air (kg/s)

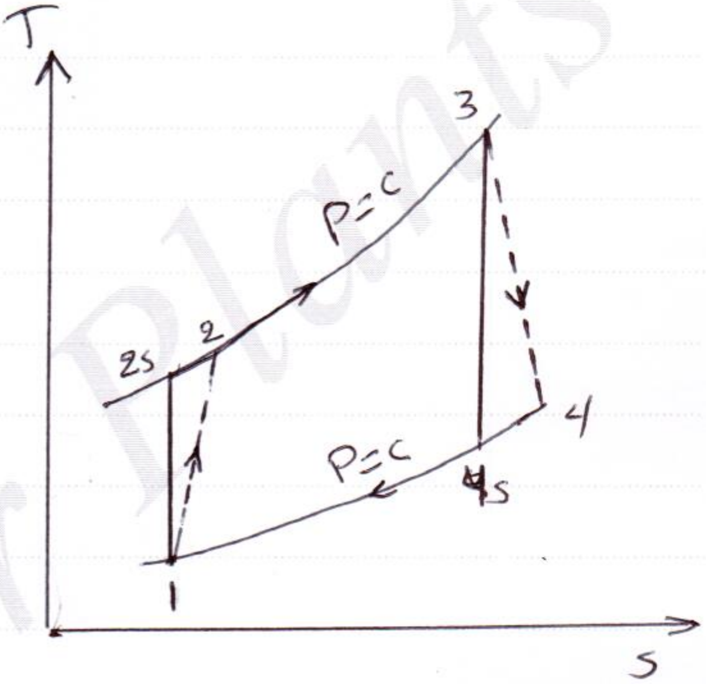
Gas turbine irreversibilites and losses:-

Because of frictional effects within the Compressor and turbine, the working fluid would experience increases in specific entropy across these components.

Owing to friction, there also would be pressure drops as the working fluid passes through the heat exchangers.

However, because frictional pressure drops are less significant sources of irreversibility, we ignore them and for simplicity show the flow through the heat exchangers as occuring at constant pressure.



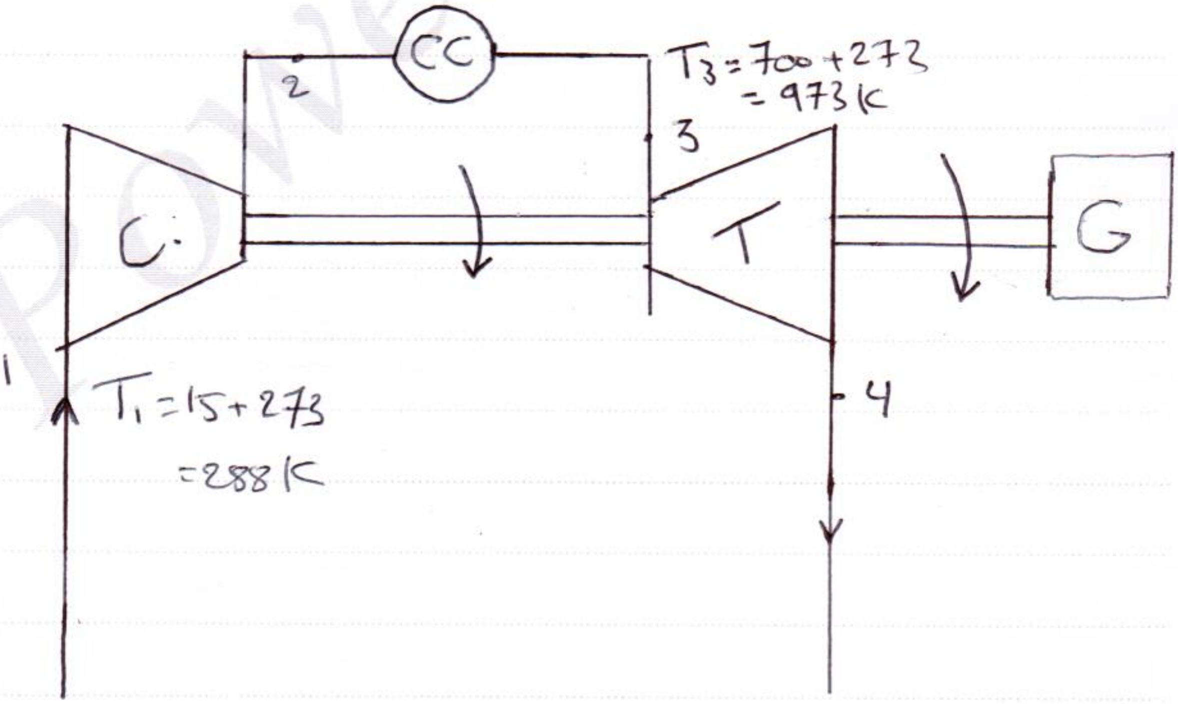


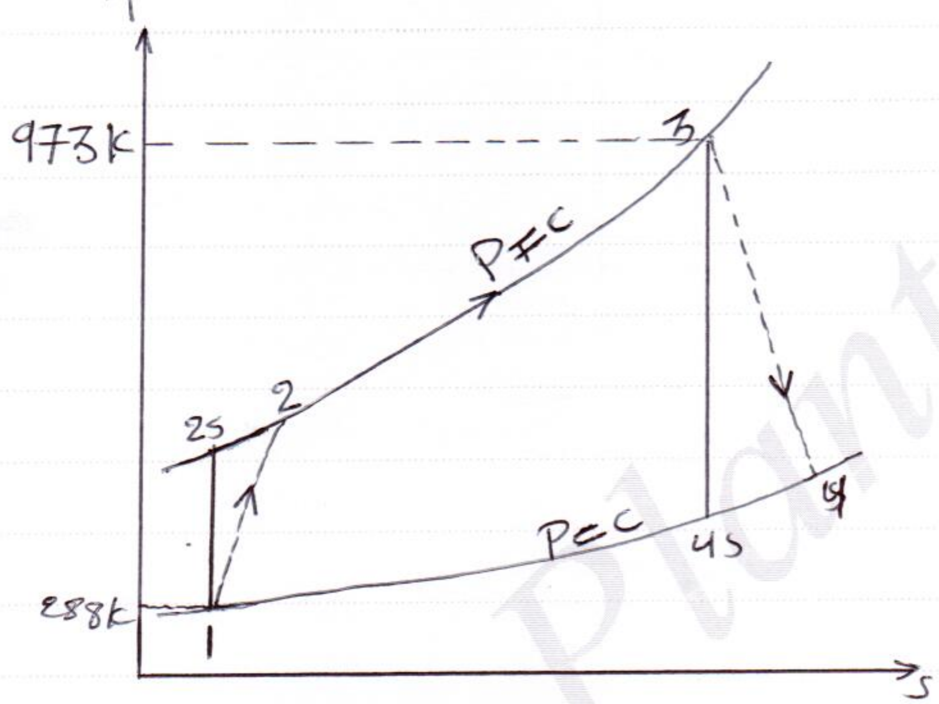
$$\eta_t = \frac{Cp_g(T_3 - T_4)}{Cp_g(T_3 - T_{4s})} = \frac{T_3 - T_4}{T_3 - T_{4s}}$$

$$\eta_c = \frac{Cp_a(T_{2s} - T_1)}{Cp_a(T_2 - T_1)} = \frac{T_{2s} - T_1}{T_2 - T_1}$$

Ex/ A gas turbine unit has a pressure ratio of 10/1 and a maximum cycle tempressure of 700 °C. The isentropic efficiencies of the compressor and turbine are 0.82 and 0.85 respectively. Calculate the power output of the turbine when the air enters the compressor at 15 °C at the rate of 15 Kg/s. Take $CP = 1.005$ and $\gamma = 1.4$ KJ/Kg K for the compression process, and take $CP = 1.11$ KJ/KgK and $\gamma = 1.33$ for the expansion process. Also Calculate η_{th} ?

Solution :-





$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}$$

$$T_{2s} = 288 \times (10)^{\frac{0.4}{1.4}} = 556\ K$$

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$0.82 = \frac{556 - 288}{T_2 - 288} \Longrightarrow T_2 = \overset{614.8\ K}{[illegible]}\ K$$

For turbine

$$\eta_t = \frac{T_3 - T_4}{T_3 - T_{4s}}$$

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$$\frac{T_3}{T_{4s}} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}$$

$$T_{4s} = \frac{973}{10^{\frac{0.333}{1.333}}} = 547.4\ K$$

$$0.85 = \frac{973 - T_4}{973 - 547.4} \Rightarrow T_4 = 611.2\ K$$

$$W_c = CP\,(T_2 - T_1)$$
$$= 1.005\,(614.8 - 288)$$
$$= 328.4\ KJ/Kg$$

$$W_t = CP\,(T_3 - T_4)$$
$$= 1.11\,(973 - 611.2)$$
$$= 401.6\ KJ/Kg$$

Thus, $W_{net} = W_t - W_c$
$$= 401.6 - 328.4$$
$$= 73.2\ KJ/Kg$$

$P_{output} = \dot{m}_a * W_{net}$
$$= 15 * 73.2 = 1098\ KW$$

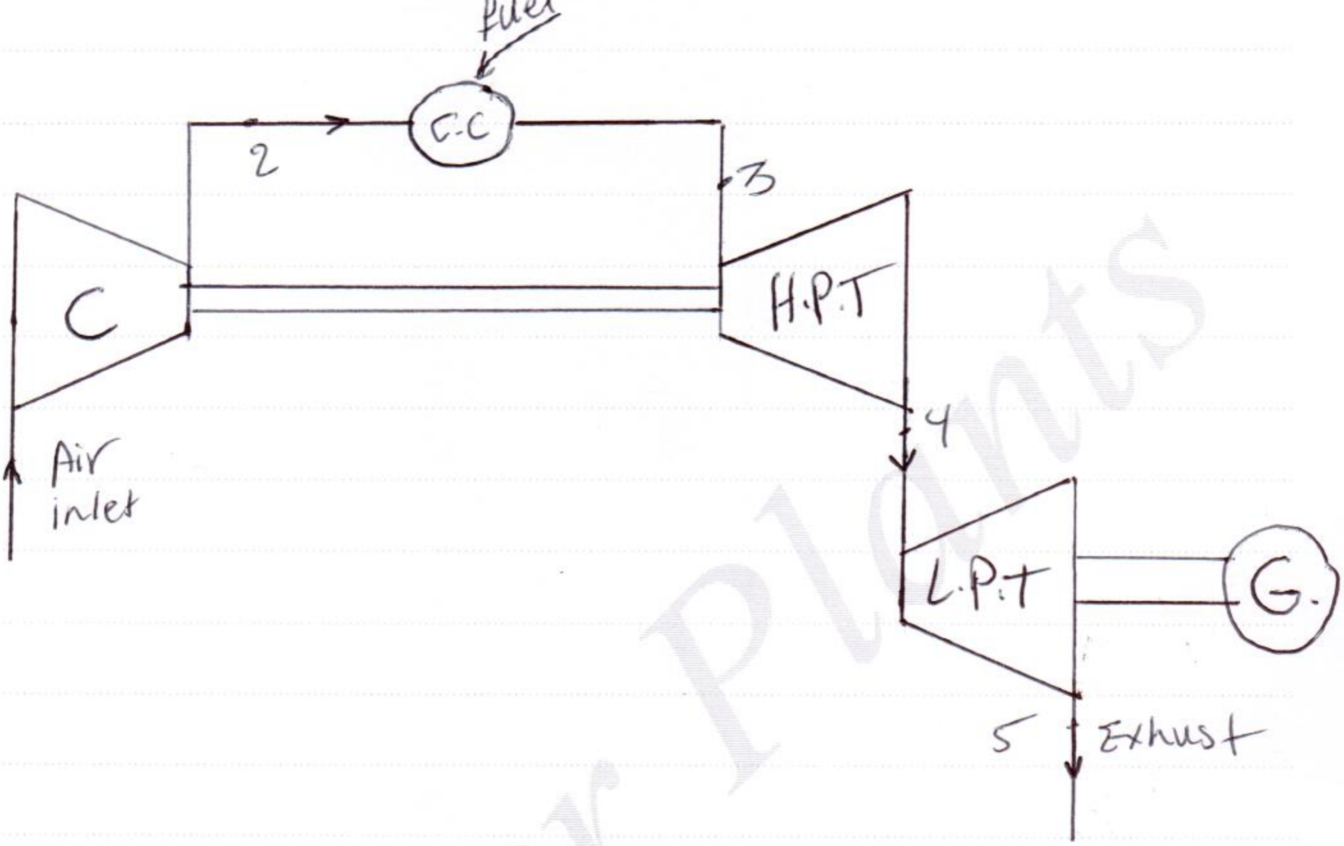
$Q_{add} = Cp_g(T_3 - T_2)$
$= 1.11(973 - 614.8)$
$= 397.6$ KJ/Kg

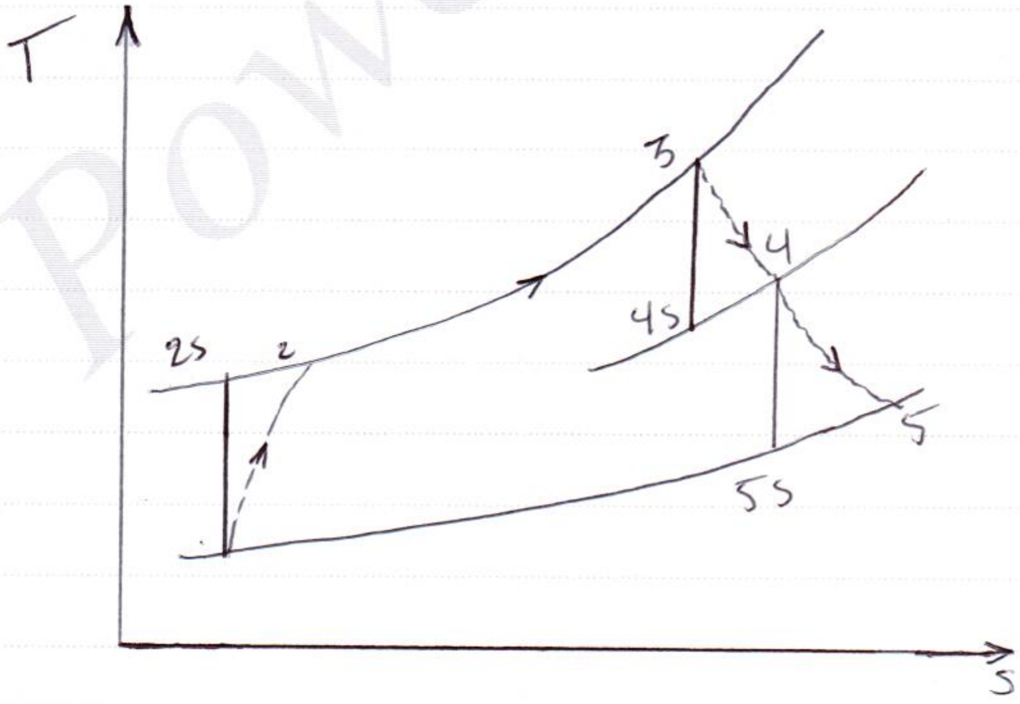
$$\eta_{th} = \frac{W_{net}}{Q_{add}} = \frac{73.2}{397.6} = 18.4\ \%$$

Use of a power turbine

It is sometimes more convenient to have two seperate turbines, one of which drives the compressor while the other provides the power output.

The first, or high-pressure (HP) turbine, is called as the compressor turbine while the other, or low-pressure (LP) turbine is called as the power turbine.


fuel
C.C
2
3
C
H.P.T
4
Air inlet
L.P.T
G.
5
Exhust


T
3
4
4s
2s
2
5
5s
s

as stated before, work of HP turbine is equal to the work of the Compressor.

Thus, $W_{H.P.T} = W_c$

$$CP_g(T_3 - T_4) = CP_a(T_2 - T_1)$$

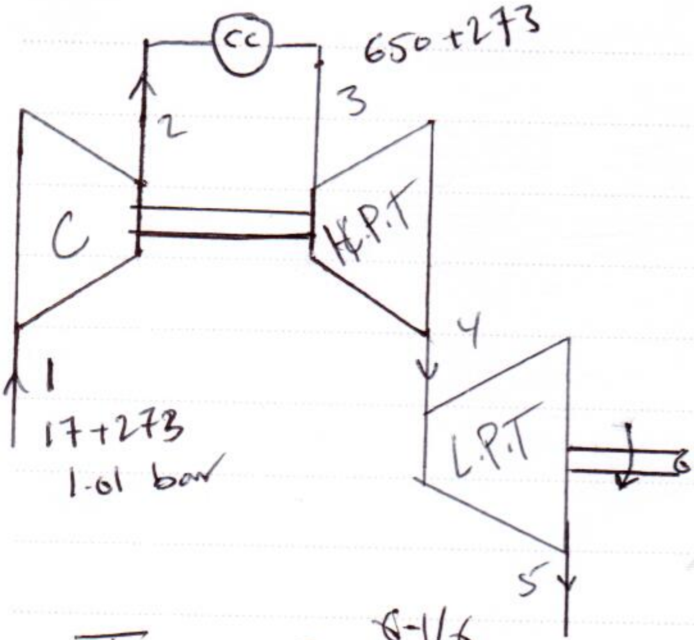
And, $W_{net} = W_{L.P.T}$

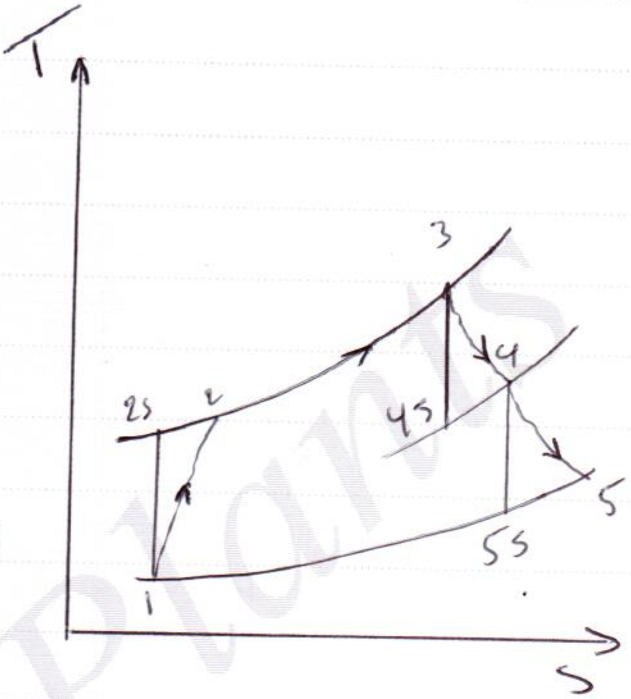
$$W_{net} = CP_g(T_4 - T_5)$$

Ex/ A gas turbine unit takes in air at 17°C and 1.01 bar and the pressure ratio is 8/1. the compressor is driven by the H.P.T and the L.P.T drives a sperate shaft. The isentropic efficiencies of the compressor, and the HP and LP turbine are 0.8, 0.85, and 0.83 respectively Calculate the pressure and temprature of the gases entering the Power turbine, the net power developed by the unit per kg/s mass flow rate, and cycle efficiency

$CP_g = 1.15$, $\gamma_g = 1.333$, Maximum Cycle temp. = 650°C
$CP_a = 1.005$, $\gamma_a = 1.4$

Solution :—





$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}$$

$$T_{2s} = 290 \times 8^{\frac{0.4}{1.4}} = 525\ K$$

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$0.8 = \frac{525 - 290}{T_2 - 290} \Longrightarrow T_2 = 584\ K$$

Then, $W_c = Cp_a(T_2 - T_1)$

$$= 1.005 \times 294 = 295.5\ KJ/Kg$$

Now, the work output from H.P.T must be sufficient to drive the compressor,

$$W_{H.PT} = Cp_g\,(T_3 - T_4) = 295.5$$

$$1.11\,(923 - T_4) = 295.5$$

$$T_4 = 666\ K$$

$$\eta_{t\ H.P.T} = \frac{T_3 - T_4}{T_3 - T_{4s}} \Rightarrow 0.85 = \frac{923 - 666}{923 - T_{4s}}$$

$$T_{4s} = 620.5\ K$$

$$\frac{T_3}{T_{4s}} = \left(\frac{P_3}{P_4}\right)^{\gamma - 1/\gamma}$$

or, $$\frac{P_3}{P_4} = \left(\frac{T_3}{T_{4s}}\right)^{\frac{\gamma}{\gamma - 1}}$$

$$\frac{8 \ast 1.01}{P_4} = \left(\frac{923}{620.5}\right)^{\frac{1.333}{0.333}} \Longrightarrow P_4 = 1.65\ bar$$

To find the power output, it is necessary to evaluate T_5.

$$\frac{P_4}{P_5} = \frac{P_4}{P_3} \times \frac{P_2}{P_1} \quad (\text{since } P_2 = P_3 \text{ and } P_5 = P_1)$$

Therefore, $$\frac{P_4}{P_5} = \frac{8}{4.9} = 1.63$$

Then, $\frac{T_4}{T_{5s}} = \left(\frac{P_4}{P_5}\right)^{\frac{\gamma-1}{\gamma}}$

$$T_{5s} = \frac{666}{1.131} = 588\ K$$

$$\eta_{L.P.T} = \frac{T_4 - T_5}{T_4 - T_{5s}}$$

$$0.83 = \frac{666 - T_5}{666 - 588} \Longrightarrow T_5 = 601.2\ K$$

Then, $W_{L.P.T} = CP_g\,(T_4 - T_5)$

$$= 1.15\,(666 - 601.2)$$

$$= 74.5\ KJ/Kg$$

$P_{output} = m_a * W_{L.P.T}$

$$= 1 * 74.5 = 74.5\ KW$$

$Q_{add} = CP_g\,(T_3 - T_2)$

$$= 1.15 * (923 - 584)$$

$$= 390\ KJ/Kg$$

$$\eta_{cycle} = \frac{W_{net}}{Q_{add}} = \frac{74.5}{390} = 19.1\ \%$$

Modifications of Brayton Cycle

Generally, the thermal efficiency of brayton cycle is low. Thermal efficiency can be increased by incorporating thermal refinements in the simple cycle such as :-

- Intercooling between compressor stages
- Reheating between turbine stages
- Regeneration

The thermal refinements can raise the plant efficiency to over 30% and thereby obliterate the advantage of fuel possessed by diesel or steam power plants.

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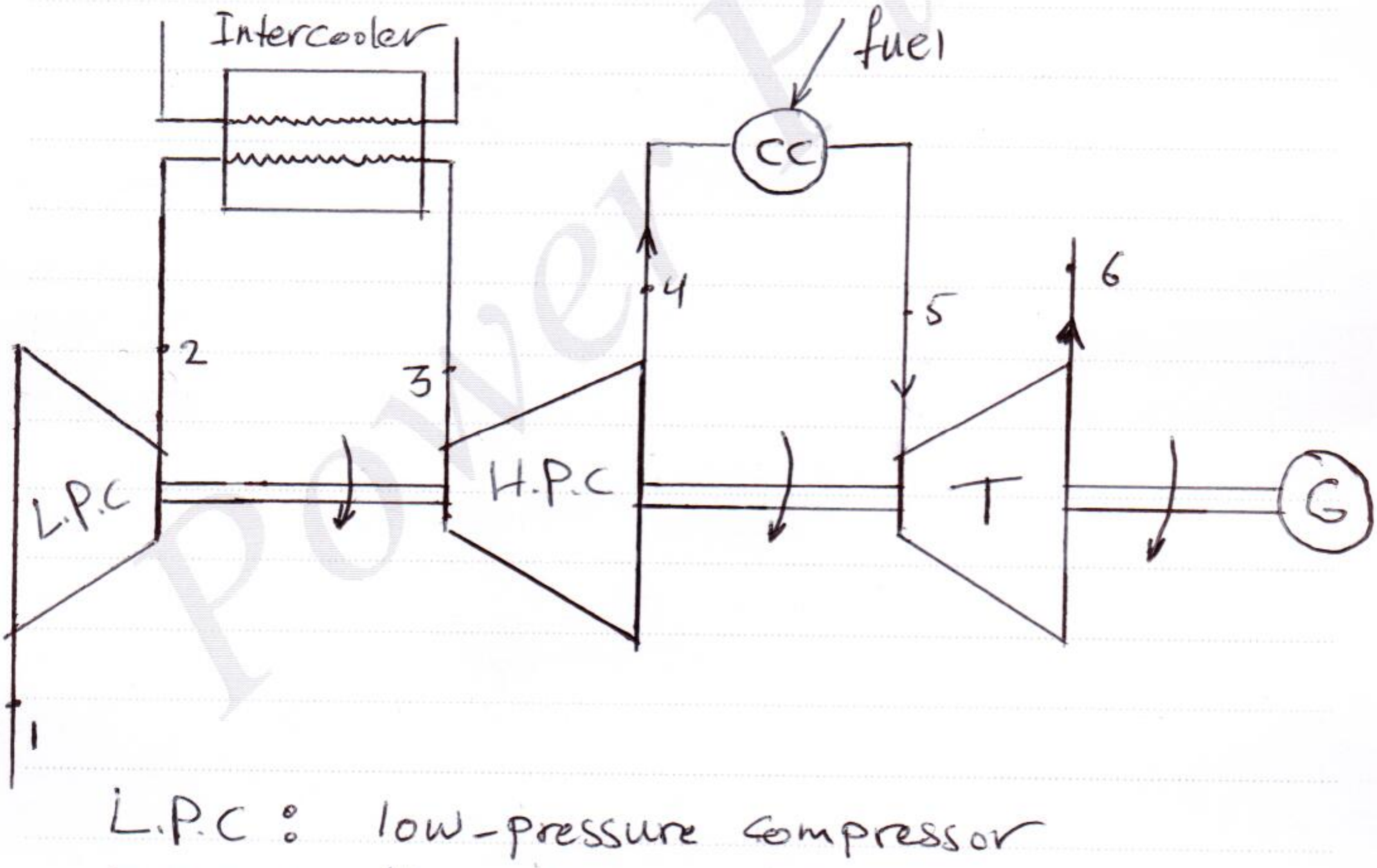
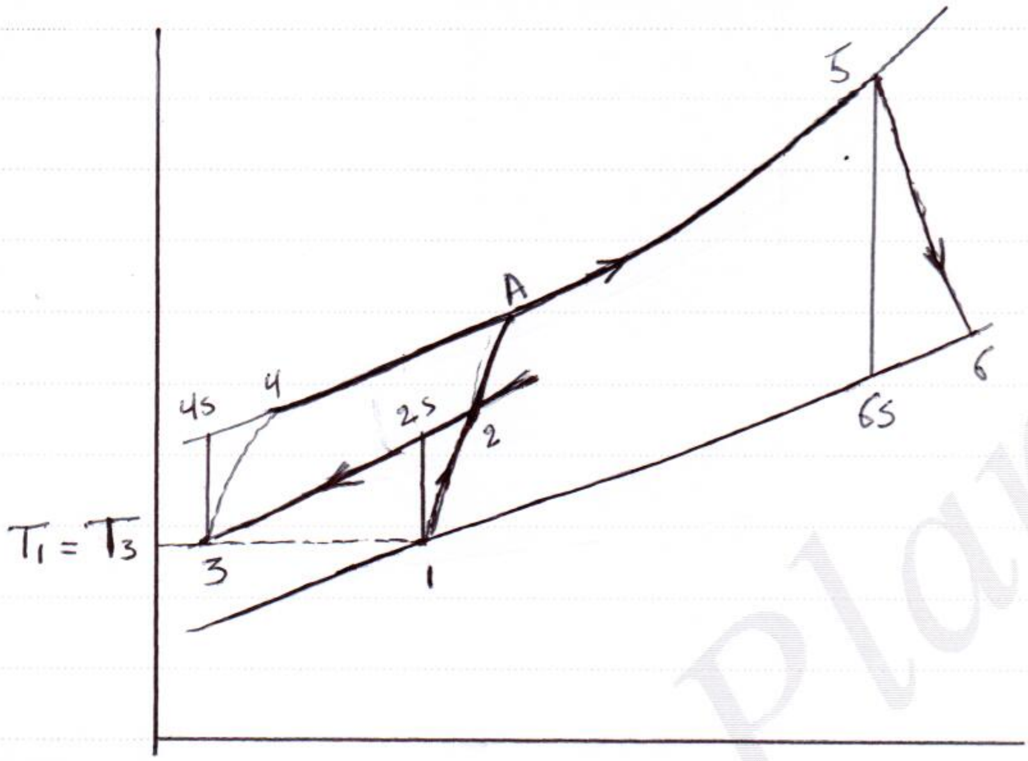
Intercooling

Net work of gas turbine can be increased by reducing negative work i.e. compressor work.

Multistaging of compression process with intercooling in between is one of the approaches for reducing compression work.



L.P.C : low-pressure compressor
H.P.C : High-Pressure Compressor



1-2 : Air is compressed ~~thr~~ across the L.P.C

2-3 : Air is sent to intercooler where tempreture is reduced from T_2 to T_3

3-4 : Air is compressed across the H.P.C

4-5 : Heat is added to the compressed air

5-6 : Air is expanded across the turbine to produce work.

In case of perfect intercooling,

$$T_1 = T_3 \quad \text{and} \quad \frac{P_2}{P_1} = \frac{P_4}{P_3}$$

T-s daigram shows that with absence of intercooling, the exiting tempreture would be T_A while with intercooling this state ia at 4

$$T_A > T_4$$

The reduced tempreture at compressor exit leads to lowering Work of the compressor and thus increasing net work.

$$W_c = W_{L.P.C} + W_{H.P.C}$$
$$= Cp_a (T_2 - T_1) + Cp_a (T_4 - T_3)$$

$$W_t = CP_g (T_5 - T_6)$$

$$W_{net} = W_t - W_c$$
$$= W_t - (W_{L.P.C} + W_{H.P.C}) \rightarrow$$

$$Q_{add} = CP_g (T_5 - T_4)$$

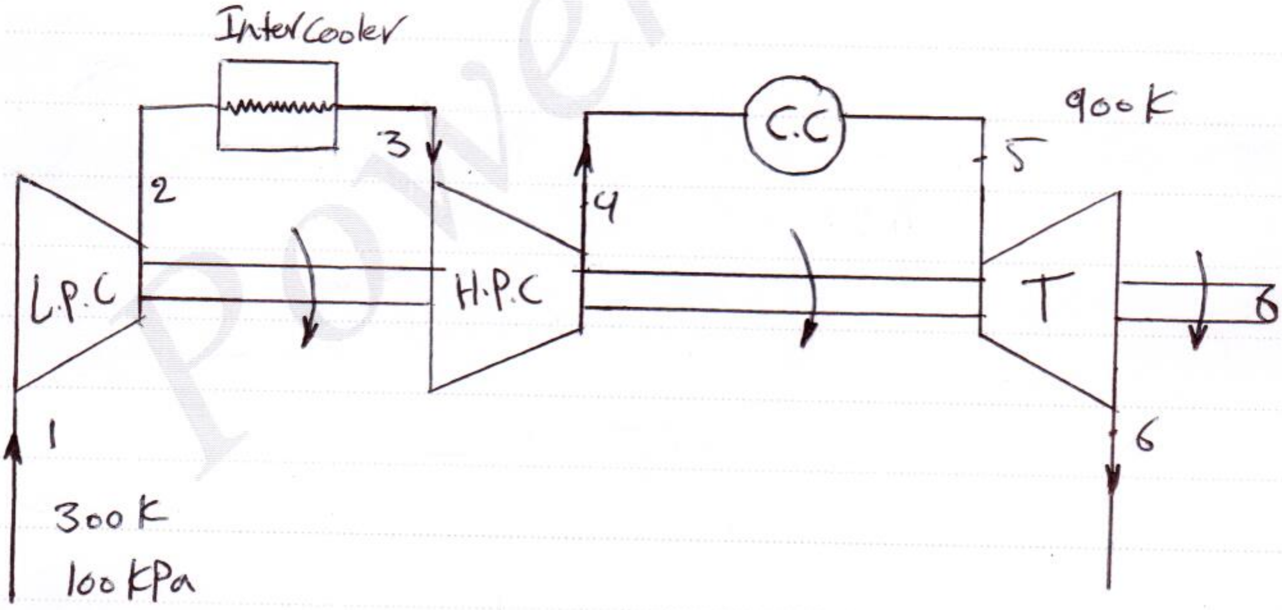
$$\eta = \frac{CP_g (T_5 - T_6) - CP_a [(T_2 - T_1) + (T_4 - T_3)]}{CP_g (T_5 - T_4)}$$

EX/ In a brayton cycle gas turbine power plant, the minmum and maximum tempretures are 300 K and 900 K respectively. Air is compressed from 100 KPa to 1000 KPa in a two-stage compressor with intercooling between. Consider that the inter-cooling tempreture is equal to the inlet temp. to the first compressor. Also, compression ratio between the two stages are equal.

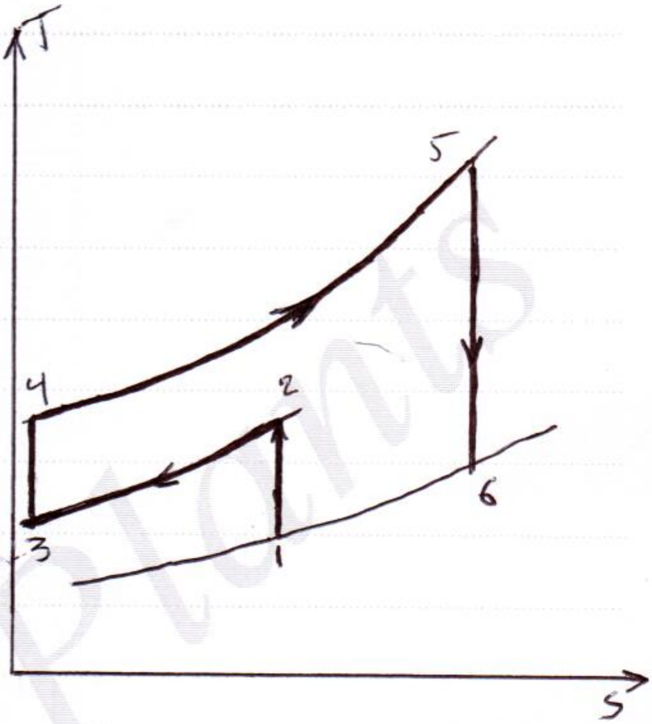
Take $Cp_g = 1.15$, $\gamma_g = 1.333$

$Cp_a = 1.005$, $\gamma_a = 1.4$

Calculate thermal efficiency of the plant?



Solution:—



It is given that

$T_1 = T_3$

$$\frac{P_2}{P_1} = \frac{P_4}{P_3}$$

$$\frac{P_4}{P_1} = \frac{1000}{100} = 10$$

$$\frac{P_4}{P_1} = \frac{P_4}{P_3} \cdot \frac{P_2}{P_1}$$

$$\therefore \frac{P_2}{P_1} = \sqrt{\frac{P_4}{P_1}} = \sqrt{10} = \frac{P_4}{P_3}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} \Longrightarrow T_2 = 300 \times \left(\sqrt{10}\right)^{\frac{0.4}{1.4}} = 416.8\ K$$

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}} = 300 \left(\sqrt{10}\right)^{\frac{0.4}{1.4}} = 416.8\ K$$

$$W_c = W_{L.P.C} + W_{H.P.C}$$

$$W_c = C_{pa}(T_2 - T_1) + C_{pa}(T_4 - T_3)$$

$$= 1.005\,(416.8 - 300) * 2$$

$$= 234.7 \text{ KJ/Kg}$$

$T_5 = 900$ (Max temp.)

$$\frac{T_5}{T_6} = \left(\frac{P_5}{P_6}\right)^{\gamma-1/\gamma}$$

$$T_6 = \frac{900}{\left(\frac{1000}{100}\right)^{\frac{0.333}{1.333}}} = 506.3 \text{ K}$$

$$W_t = C_{pg}(T_5 - T_6)$$

$$= 1.15\,(900 - 506.3)$$

$$= 452.75 \text{ KJ/Kg}$$

$$W_{net} = W_t - W_c$$

$$= 452.75 - 234.7$$

$$= 218 \text{ KJ/Kg}$$

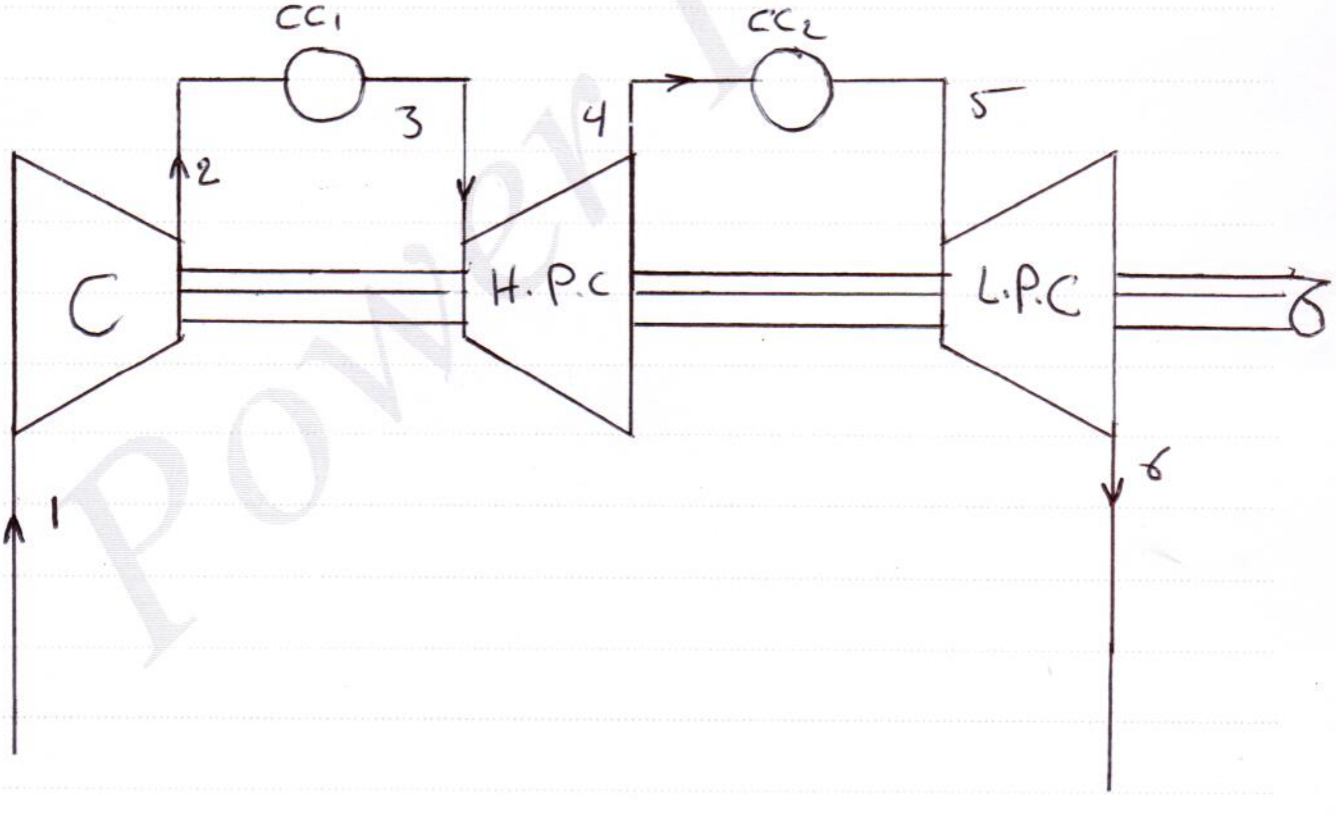
$$Q_{add} = C_{pg}(T_5 - T_4)$$

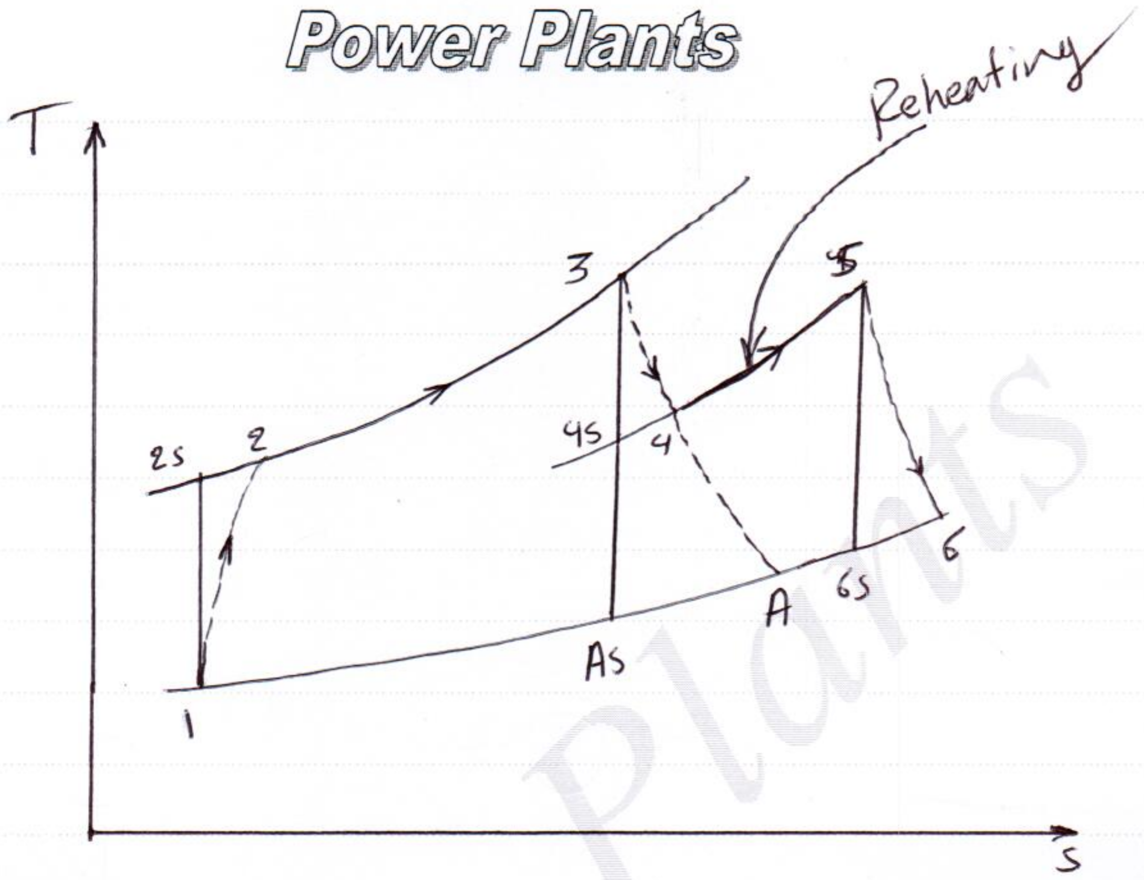
$$= 1.15\,(900 - 416.8) = 555.7 \text{ KJ/Kg}$$

$$\eta_{cycle} = \frac{W_{net}}{Q_{add}} = \frac{218}{555.7} = 39.22\%$$

Reheating

In order to maximize the work available from the simple gas turbine cycle, enthalpy of fluid entering gas turbine is increased. Also, expand its expansion upto the lowest possible enthalpy value.





1-2 : Air is compressed across the compressor

2-3 : Heat is added through first Combustion chamber

3-4 : Air is expanded across H.P. turbine

4-5 : Air is reheated by adding heat through the Second Comb. chamber.

5-6 : Air is expanded across L.P. turbine

The work of the two stages turbine is greater that of single expansion.

$$\therefore \ (T_3 - T_4) + (T_5 - T_6) > (T_3 - T_A)$$

$$W_c = Cp_a (T_2 - T_1)$$

$$W_{net} = W_{H.P.T} + W_{L.P.T} - W_c$$

$$W_{H.P.T} = Cp_g (T_3 - T_4)$$
$$W_{L.P.T} = Cp_g (T_5 - T_4)$$

For perfect reheating, $T_3 = T_5$

$$Q_{add} = Q_{add\,cc_1} + Q_{add\,cc_2}$$
$$= Cp_g (T_3 - T_2) + Cp_g (T_5 - T_4)$$

So, Efficiency for reheat cycle

$$\eta_{reheat} = \frac{Cp_g [(T_3 - T_4) + (T_5 - T_6)] - Cp_a (T_2 - T_1)}{Cp_g [(T_3 - T_2) + (T_5 - T_4)]}$$

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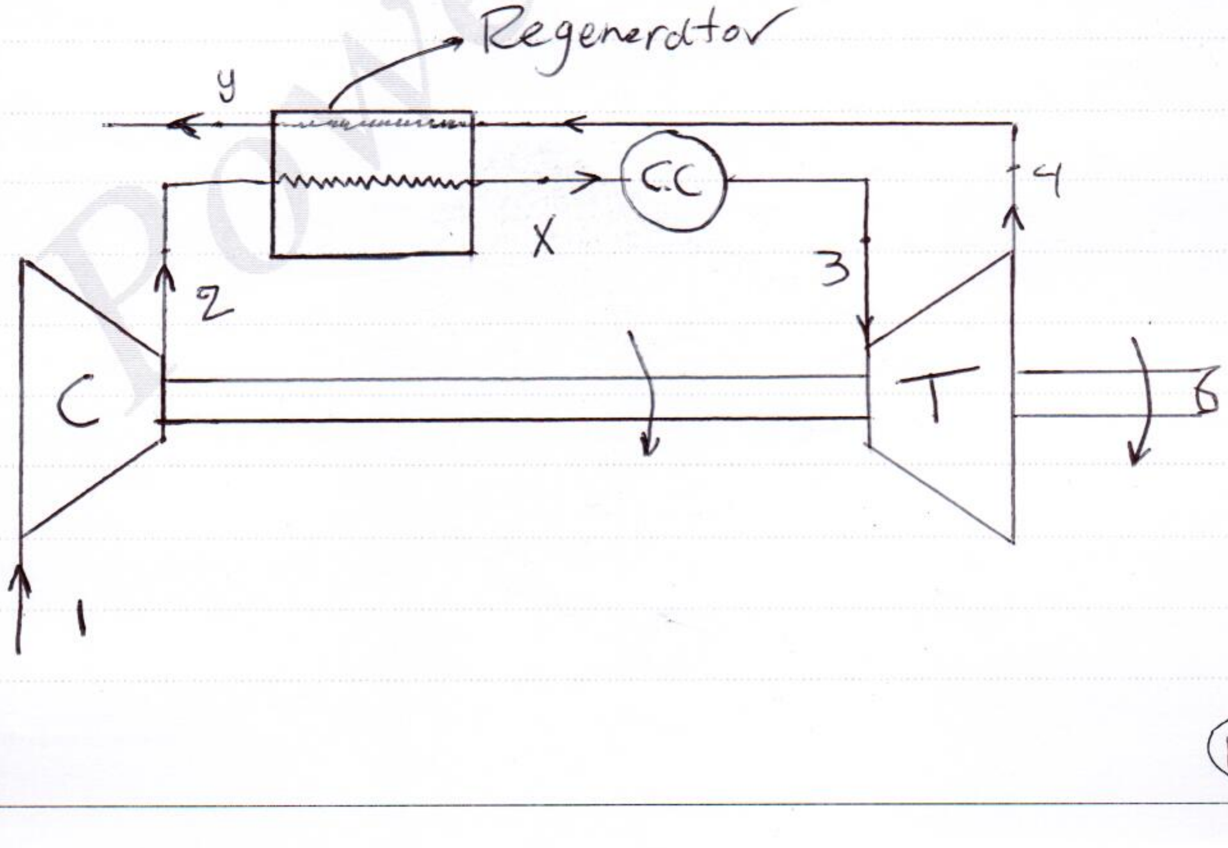
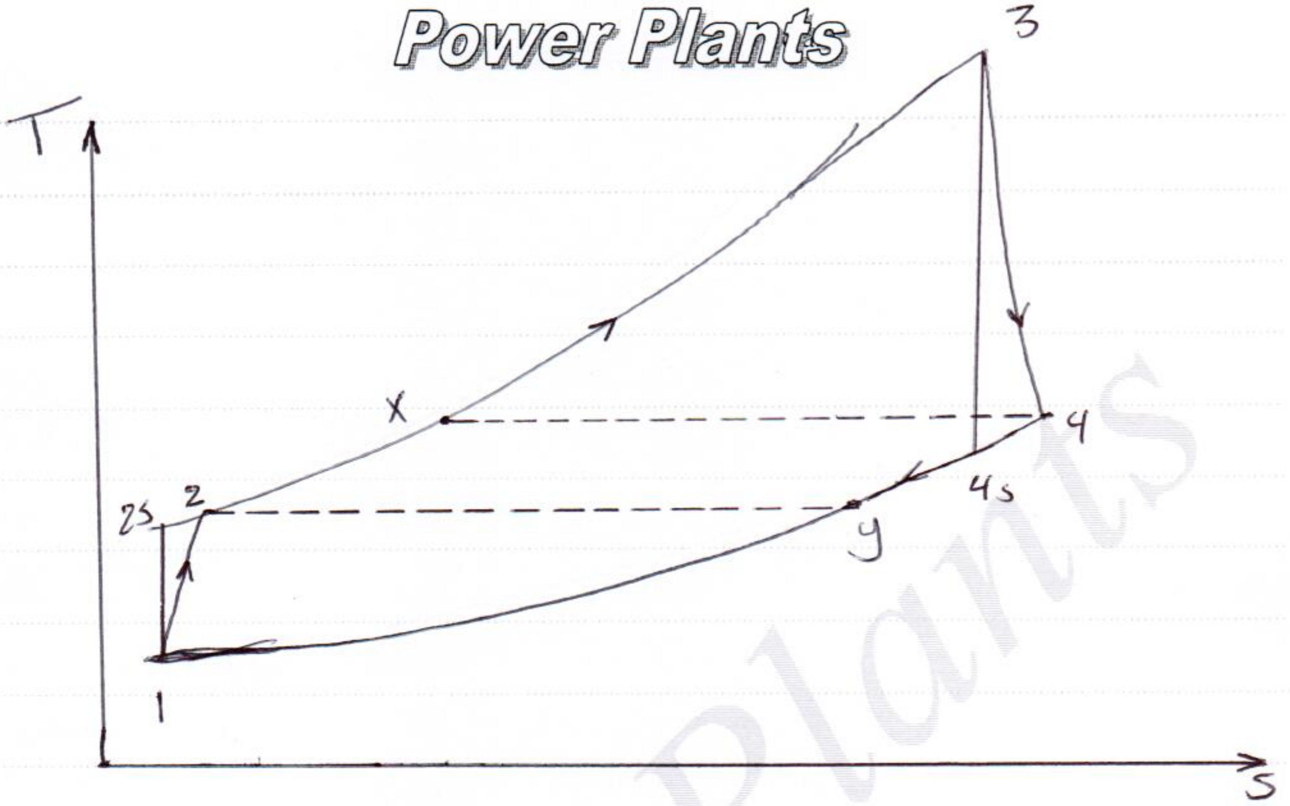
Regeneration

The turbine exhaust tempreture of a gas turbine is normally above ambient temprature. Accordingly, the hot turbine exhaust has a potential for using. One way of utilizing this Potential is by means of a heat exchanger called a regenerator

A regenerator allows the air exiting the Compressor to be preheated before entering the Combustor, thereby reducing the amount of fuel that must be burned in the Combustor.





The regenerator shown is a counterflow heat exchanger. Ideally, no frictional pressure drop occures in either stream.

The turbine exhaust gas is cooled from state 4 to state y while the air exiting the compressor is heated from state 2 to state x.

If there is no losses in the heat exchanger, Then,

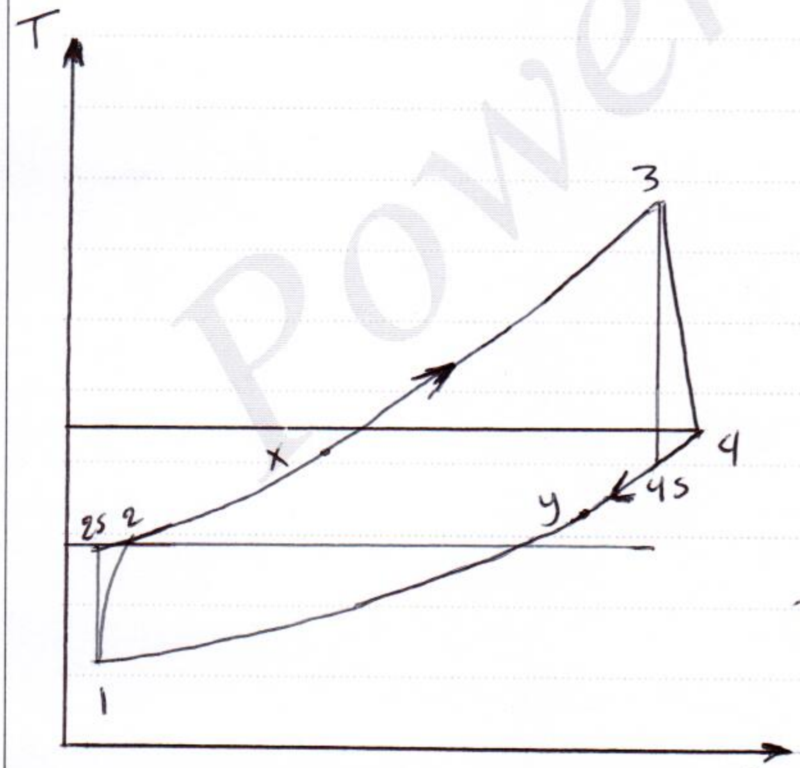
$$\dot{m}_a Cp_a \left(T_x - T_2 \right) = \dot{m}_a Cp_g \left(T_4 - T_y \right)$$

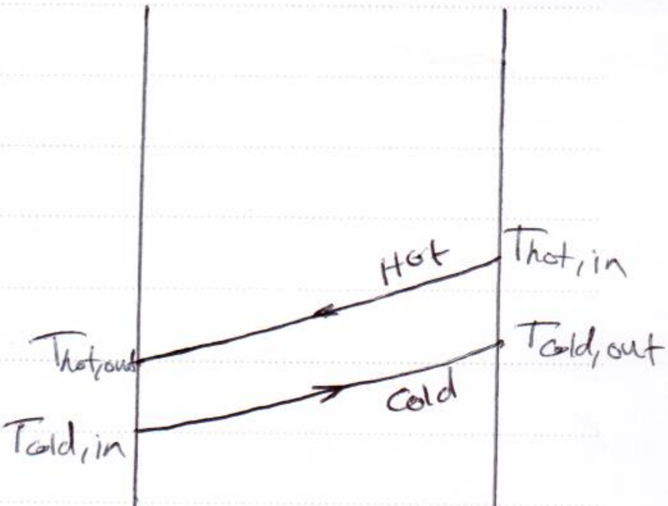
which means the heat given up by the gases must be equal to the heat recieved by the air.

$$\left.\begin{array}{l} T_4 = T_x \\ T_y = T_2 \end{array}\right\} \text{For ideal heat exchanger}$$

In practice, this is impossible

$T_4 > T_x$, $T_y > T_2$





Heat exchanger effectivness

It is defined as heat recieved by the air to the maximum possible heat which could be transferred from the gases in the heat exchanger

There fore,

$$\text{Effectivness } \epsilon = \frac{\dot{m}_a C_{P_a}(T_x - T_2)}{\dot{m}_a C_{P_g}(T_4 - T_2)}$$

Thermal ratio

$$\text{Thermal ratio} = \frac{\text{temperature rise of the air}}{\text{Max. temperature difference avaiable}}$$

$$= \frac{T_x - T_2}{T_4 - T_2}$$

$$Q_{add} \text{ (without HX)} = C_{P_g}(T_3 - T_2)$$

$$Q_{add} \text{ (with HX)} = C_{P_g}(T_3 - T_x)$$

It is obvious that

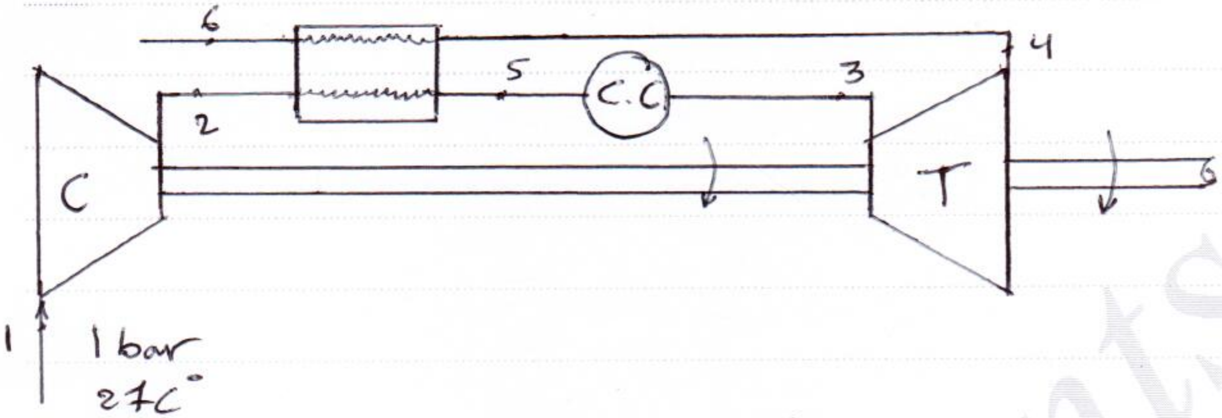
$$Q_{add\,(with\ HX)} < Q_{add\,(without\ HX)}$$

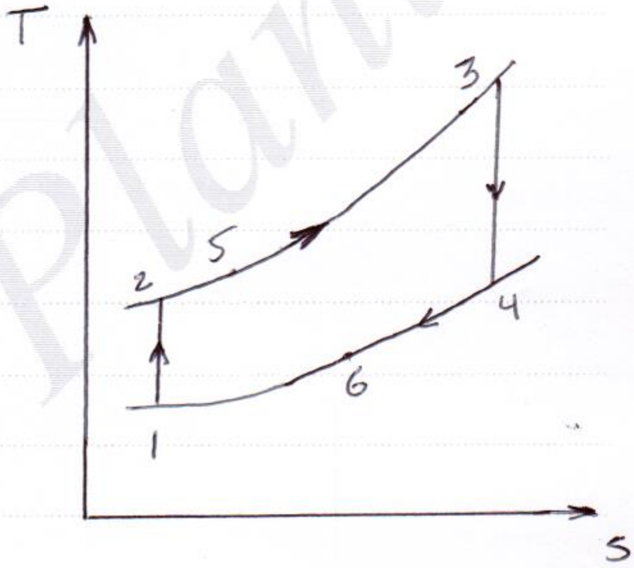
$$W_{net} = Cp_g(T_3 - T_4) - Cp_a(T_2 - T_1)$$

$$\eta_{regen.} = \frac{Cp_g(T_3 - T_4) - Cp_a(T_2 - T_1)}{Cp_g(T_3 - T_x)}$$

Ex/ In a gas turbine, air is supplied at 1 bar, 27°C into compressor having compression ratio of 8. The air leaving combustion chamber is heated upto 1100 K and expanded upto 1 bar. A heat exchanger having effectivness of 0.8 is fitted at exit of turbine for heating the air before its inlet into combustion chamber. Assume that,
$CP = 1.0032$ KJ/Kg.K (for all processes)
$\gamma_a = 1.506$, $\gamma_g = 1.346$

Determine: specific work output of the plant
thermal efficiency of the plant.
work ratio





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

$$T_2 = 300 * (8)^{\frac{0.506}{1.506}}$$

$$T_2 = \overset{603.32\ K}{\cancel{1100\ K}}$$

$$T_3 = 1100\ K$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\gamma-1/\gamma} \Rightarrow T_4 = \frac{1100}{(8)^{\frac{0.346}{1.346}}}$$

$$T_4 = 644.53\ K$$

$$\in = \frac{CP_a(T_5 - T_2)}{CP_g(T_4 - T_2)}$$

$$0.8 = \frac{T_5 - 603.32}{644.53 - 603.32}$$

$$\Rightarrow T_5 = 636.28\ K$$

$W_c = Cp_a(T_2 - T_1)$

$= 1.0032\,(603.32 - 300) = 304.3$ KJ/Kg

$W_t = Cp_g\,(T_3 - T_4)$

$= 1.0032\,(1100 - 644.53) = 456.93$ KJ/Kg

$W_{net} = W_t - W_c = 152.6$ KJ/Kg (specific work output)

$$\eta_{cycle} = \frac{W_{net}}{Q_{add}}$$

$Q_{add} = Cp_g(T_3 - T_5)$

$= 1.0032\,(1100 - 636.28) = 465.2$ KJ/Kg

$$\eta = \frac{152.6}{465.2} = 32.81\ \%$$

$$\text{Work ratio} = \frac{W_t - W_c}{W_t} = \frac{W_{net}}{W_t}$$

$$= \frac{152.6}{456.93} = 0.334$$

Ex/ A 5000 KW gas turbine generating set operates with two compressor stages with intercooling between stages; the overall pressure ratio is 9/1. A HP turbine is used to drive the compressors. and a LP turbine drives the generator. The temperature of gases at entry to the HP turbine is 650 °C and the gases leaving the LP turbine are passed through a heat exchanger to heat the air leaving the HP stage compressor. Gases are reheated to 650°C after expansion in H.P.T The compressors have equal pressure ratios and intercooling is complete between stages. The air inlet temperature to the unit is 15°C.

Assume that: η_c for both combressors is 0.8

η_t = = turbines is 0.85

The heat exchanger thermal ratio is 0.75.

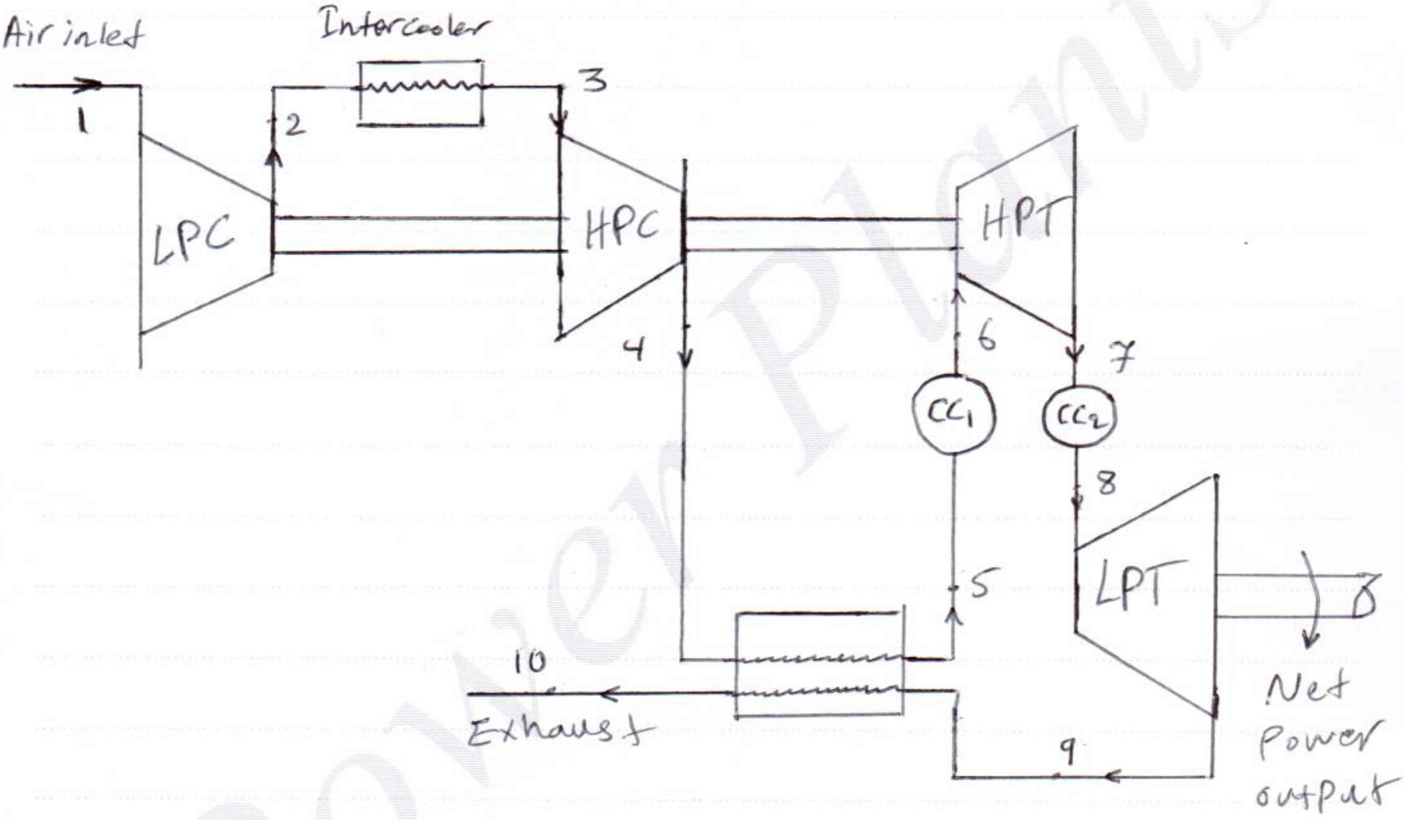
A mechanical efficiency of 98% can be assumed for both the power shaft and the compressor turbine shaft. Determine :-

(i) the cycle efficiency (ii) the work ratio

(iii) the mass flow rate.

For air take $C_P = 1.005$ KJ/Kg , $\gamma = 1.4$
For gas take $C_P = 1.15$ KJ/Kg , $\gamma = 1.333$

Solution :-



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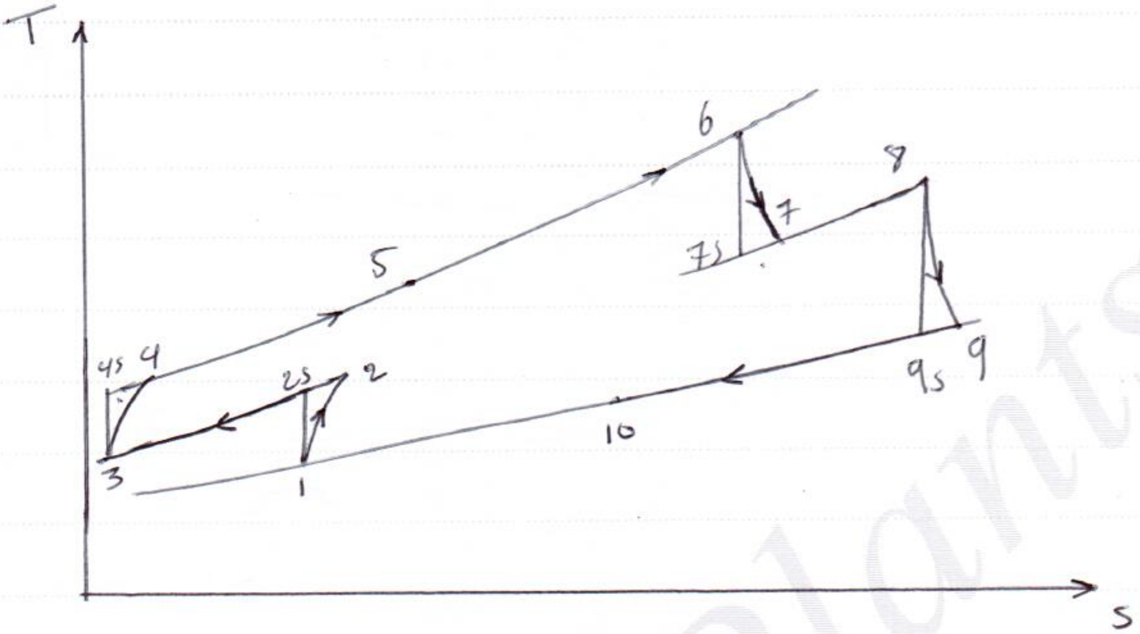

Since the pressure ratio and isentropic efficiency of each compressor is the same, then the work input required for each compressor is the same.

$$T_1 = T_3 \quad , \quad T_2 = T_4$$

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}$$

$$\frac{P_2}{P_1} = \sqrt{9} = 3$$

$$T_{2s} = 288 + (3)^{\frac{0.4}{1.4}} = 394\,K$$

$$\eta_{c\,LPC} = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$0.8 = \frac{T_{2s} - 288}{T_2 - 288} \Longrightarrow T_2 = 420.5 \text{ K}$$

$$W_{LPC} = Cp_a (T_2 - T_1)$$

$$= 1.005 (420.5 - 288)$$

$$= 133.1 \text{ KJ/Kg}$$ [For each compressor]

$$T_{4s} = T_{2s} = 394$$

$$T_4 = T_2 = 420.5$$

The HP turbine is required to drive both compressors and to overcome mechanical friction

$$W_c = W_{c_1} + W_{c_2}$$

$$= 133.1 + 133.1$$

$$= 266.2 \text{ KJ/Kg}$$

$$W_{HPT} = \frac{W_c}{\eta_m} = \frac{266.2}{0.98} = 272 \text{ KJ/Kg}$$

Therefore,

$$272 = Cp_g\,(T6 - T7)$$

$$272 = 1.15\,(923 - T7)$$

$$T7 = 686.5\,K$$

$$\eta_{H.P.T} = \frac{T6 - T7}{T6 - T7s}$$

$$0.85 = \frac{923 - 686.5}{923 - T7s} \Rightarrow T7s = 645\,K$$

$$\frac{T6}{T7s} = \left(\frac{P6}{P7}\right)^{\gamma-1/\gamma} \quad \text{or} \quad \frac{P6}{P7} = \left(\frac{T6}{T7s}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{P6}{P7} = \left(\frac{923}{645}\right)^{\frac{1.333}{0.333}} = 4.19$$

$$\frac{P6}{Pa} = \frac{P6}{P7} \cdot \frac{P8}{Pa} \quad , \quad P7 = P8$$

$$\frac{P8}{Pa} = \frac{\overset{9}{\cancel{4.19}}}{4.19} = 2.147$$

$$\frac{T_8}{T_{9s}} = \left(\frac{P_8}{P_9}\right)^{\gamma-1/\gamma}$$

$$T_{9s} = \frac{923}{(2.147)^{\frac{0.333}{1.333}}} = 762.6\ K$$

$$\eta_{LPT} = \frac{T_8 - T_9}{T_8 - T_{9s}}$$

$$0.85 = \frac{923 - T_9}{923 - 762.9} \Rightarrow T_9 = 786.7\ K$$

$$\text{Net work output} = Cp_g\,(T_8 - T_9) * 0.98$$
$$= 1.15\,(923 - 786.7) * 0.98$$
$$= 153.7\ KJ/Kg$$

$$\text{Thermal ratio} = \frac{T_5 - T_4}{T_9 - T_4}$$

$$0.75 = \frac{T_5 - 420.5}{786.7 - 420.5}$$

$$T_5 = 695.2\ K$$

Heat supplied $= CP_g (T_6 - T_5) + CP_g (T_8 - T_7)$

$= 1.15 \left[(923 - 695.2) + (923 - 686.5) \right]$

$= 534$ KJ/Kg

$$\eta_{cycle} = \frac{W_{net}}{Q_{add}} = \frac{153.7}{534} = 28.8\%$$

$$\text{Work ratio} = \frac{\text{Work}_{net}}{\text{gross work}}$$

gross work $= W_{H.P.T} + W_{L.P.T}$

$$= 272 + \frac{153.7}{0.98} = 429 \text{ KJ/Kg}$$

$$\text{Work ratio} = \frac{153.7}{429} = 0.358$$

$P_{output} = \dot{m} * W_{net}$

$$\dot{m} = \frac{5000}{153.7} = 32.6 \text{ Kg/s}$$

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Sheet 2

Q1/ A gas turbine has an overall pressure ratio of 5 and maximum cycle temperature of 550 C. The turbine drives the compressor and an electric generator, the mechanical efficiency of the drive being 97%. The ambient temperature is 20 °C and air enters the compressor at rate of 15 Kg/s: $\eta_c = 86\%$

$\eta_t = 83\%$

$Cp_a = 1.005$, $\gamma = 1.4$
$Cp_g = 1.15$, $\gamma = 1.333$

Determine: Power output, Cycle efficiency
Work ratio

(660.3W, 12.1%, 0.169)

Q2/ In a marine gas turbine unit, a HP stage turbine drives the compressor, and a LP stage turbine drives the propeller through suitable gearing. The overall pressure ratio is 4/1, the mass flow rate is 60 Kg/s

Maximum temperature is 650C, and the air intake conditions are 1.01 bar and 25°C.
$\eta_c = 0.8$, $\eta_{H.P.T} = 0.83$, $\eta_{LP.T} = 0.85$.
The Mechanical ~~losses~~ efficiency of both shafts is 98%. Calculate:
(i) Pressure between turbine stages
(ii) Cycle efficiency
(iii) Shaft Power

(1.57bar / 14.9% , 4560W)

Q3/ For the same unit in Q2, Calculate cycle efficiency when a heat exchanger is fitted. Assume a thermal ratio of 0.75

(23.4%)

Q4/ In a gas turbine generating set, two stages of compression are used with an intercooling between stages. The HP turbine drives the HP compressor, and LP turbine drive the LP Compressor and the generator. The exhaust from the LP turbine Passes through a heat exchanger which transfers heat to the air leaving the HP compressor. There is

a reheat combustion chamber between turbine stages which rises the gas temperature to 600C, which is also the gas temperature at entry to the HP turbine. the overall pressure ratio is 10/1, each compressor having the same pressure ratio, and the air temperature at entry to the unit is 20C. The heat exchanger thermal ratio may be taken as 0.7 and intercooling is complete between compressor stages.
Assume isentropic efficiencies of 0.8 for both compressor stages, and 0.85 for turbine stages and 2% of the work of each turbine is used in overcoming friction. Calculate:
(i) power output for a mass flow rate of 115 kg/s
(ii) overall efficiency of the plant.

(14460 kW, 25.7%)

University of Anbar

College of Engineering

Mechanical Eng. Department

Power Plants

Chapter Three

Diesel Power Plants

Tutor

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Diesel Power Plants

Introduction to Diesel Power Plants

Since the invention of diesel engines, diesel engine plants are finding increased application as either continuous or peak load source of power generation. Due to the economy of operation, Diesel power plants are used to generate power in the range of 1–50 MW capacities and are extensively used to supplement hydroelectric or thermal power stations, namely, for starting from cold and in emergency conditions. Diesel power plants are more efficient than any other heat engines of comparable size. It is available at very short delivery times and can be started quickly and brought into service. It can burn fairly in a wide range of fuels. If may be rapidly extended to keep pace with load growth by adding generating units of suitable sizes.

IC Engine Nomenclature

The figure below shows a typical spark ignition engine. Different components of the engine are discussed below.

1. Cylinder

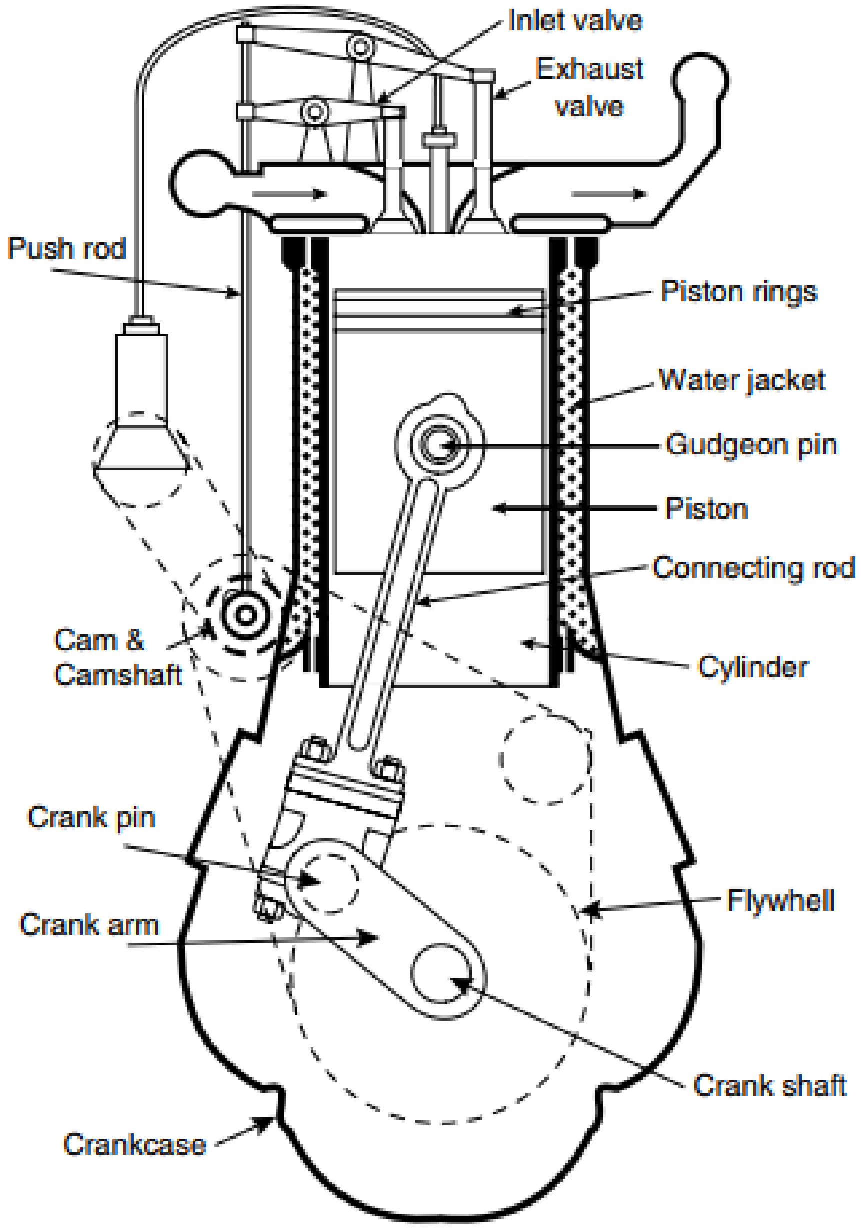
Cylinder is the most important component of the engine where combustion of fuel takes place. The cylinder is supported in position by the cylinder block at the top end and is covered by cylinder head. To reduce the wear and tear, cylinder is fitted with sleeves. Power is developed in the cylinder.

2. Piston

The piston reciprocates inside the cylinder. It is a hollow cylindrical block that tightly fits inside the cylinder. The energy of the expanding gas is transmitted by the piston through *gudgeon pin* to the connecting rod. Grooves are made circumferentially on the top portion of the piston in which fit metallic *piston rings*. These rings form a gas tight joint so that no *charge* (fuel + air mixture) leaks into the crankcase. They also conduct heat from the piston to the cylinder walls.

3. Connecting rod

It connects the piston and the crank by gudgeon pin and crank pin, respectively. The function of the connecting rod is to transfer the reciprocating motion of the piston to the crankshaft.



4. Crank arm, crankshaft and crankcase

Crank arm connects the connecting rod and the crankshaft. Connecting rod and crank arm translate the reciprocating motion of the piston into rotary motion of the crankshaft. Crank pin connects the connecting rod and crank arm, whereas the other end of the crank arm is secured to the crankshaft. Crankshaft is supported in the bearings attached to the crankcase. Crankcase is the main body of the engine and houses crankshaft and other parts. It also acts as a sump for the lubricating oil.

5. Inlet and exhaust valves

Inlet and exhaust valves admit the *charge* inside the engine cylinder and discharge the products of combustion to the atmosphere, respectively. They are operated by valve mechanism. A camshaft is driven by the crankshaft through timing gears. Lobed cams on the camshaft actuate the push rods and rocker arms for opening the valves against the valve spring force. The valves are also called as *poppet valves*.

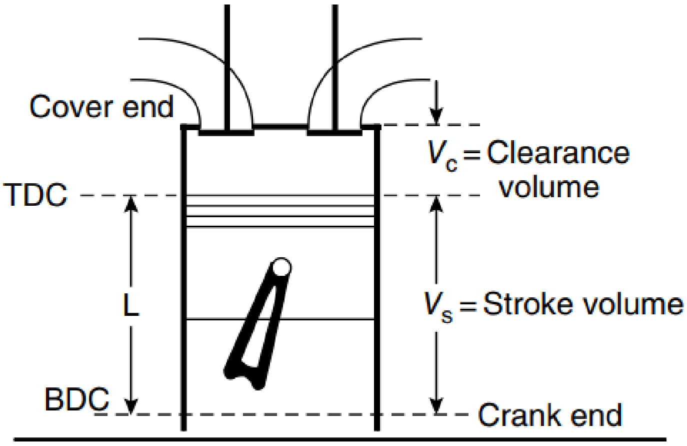
6. Fly wheel

A fly wheel is used to smooth out the power pulses and hence to obtain uniform rotation of the crankshaft, as power stroke exists only for a part of the total time. It is mounted on the crankshaft.

Standard Terminology

Consider a piston cylinder arrangement of an IC engine as shown in Figure below

1. Cylinder bore (D)
   It is the inner diameter of the working cylinder.



2. Piston area (A)

   It is the cross-sectional area of the cylinder

3. Stroke (L)

   It is the distance through which the piston travels from crank end to the cover end. Stroke is also equal to twice the crank radius.

4. Top dead centre (TDC)

   It is the position of the piston farthest from the crankshaft. In horizontal engines, it is also called inner dead centre.

5. Bottom dead centre (BDC)

   It is the position of the piston nearest to the crankshaft. In horizontal engines, it is also called outer dead centre.

6. Displacement volume or swept volume (VS)

   It is the volume covered by the piston between TDC and BDC. It is also called as stroke volume.

$$VS = A \times L$$

7. Clearance volume (VC)

   It is the volume on the combustion side of the piston at TDC.

8. Cylinder volume (V)

   It is the sum of piston stroke volume and clearance volume.

$$V = VS + VC$$

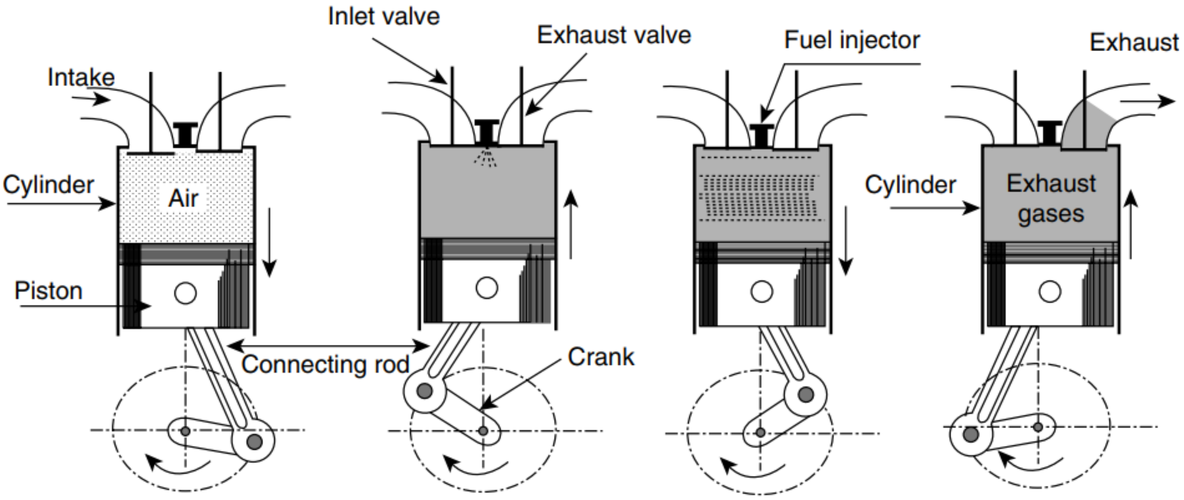
9. Compression ratio (rv)

   It is the ratio of cylinder volume and the clearance volume.

$$r_v = \frac{v}{v_C}$$

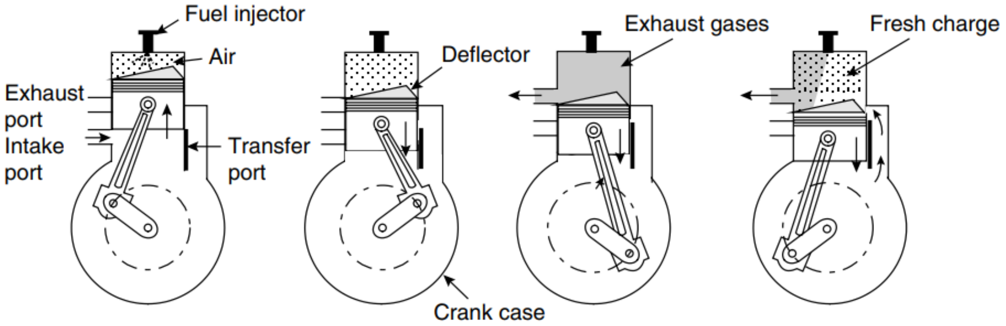
Four-Stroke Diesel Engine

A four-stroke diesel engine is similar to a four-stroke petrol engine except for the mode of combustion. Combustion is initiated by injecting fuel from a fuel injector instead of a spark plug. Air alone is compressed and hence the name compression ignition engine or CI engine.



Two-Stroke Diesel Engine

A typical two-stroke diesel engine is shown in figure below. It consists of a piston-cylinder arrangement and a fuel injector mounted on the cylinder head. The crankcase in hermetically sealed and the cylinder is provided with inlet and exhaust ports. The transfer port is diametrically opposite to the exhaust port but slightly below its level.



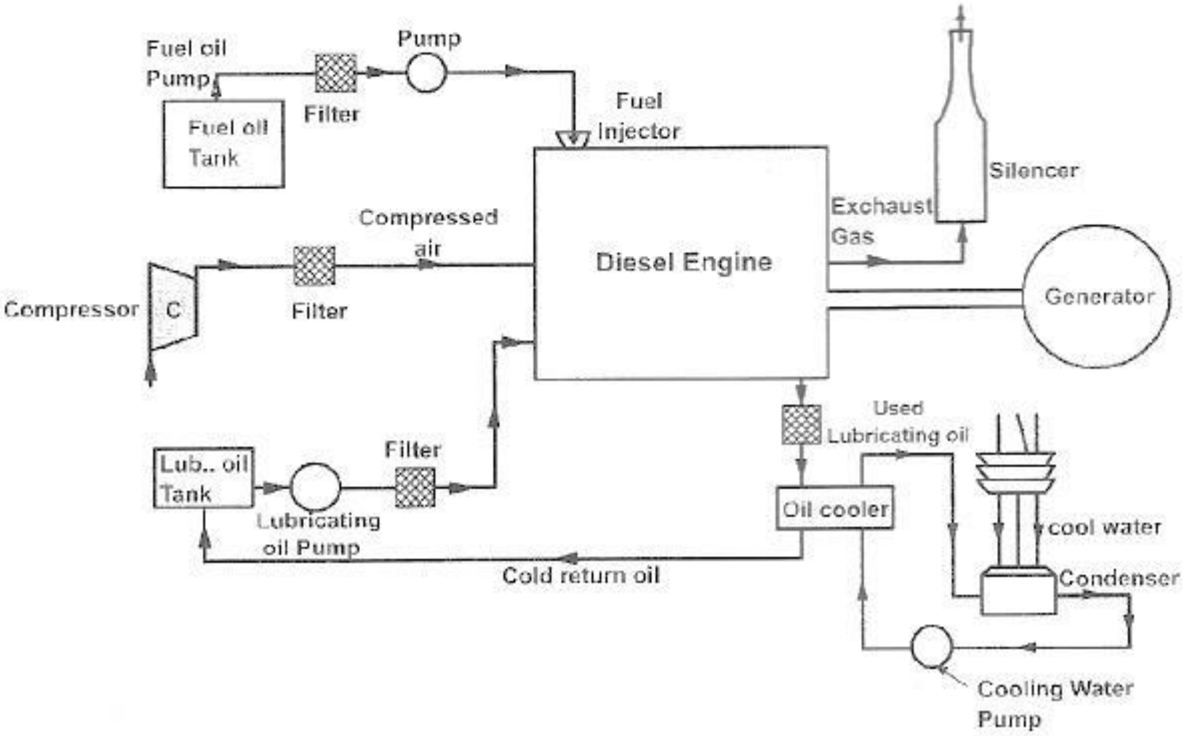
(a)
Compression
Air-taken into crankcase

(b)
Combustion
All ports closed

(c)
Exhaust
Intake and Transfer ports covered

(d)
Scavenging
Transfer port open

Diesel Power Plant Layout



1. Engine

It is the main component that develops required power. The engine is directly coupled to the generator.

2. Fuel system

Pump draws diesel from storage tank and supplies it to the small day tank through the filter. Day tank supplies the daily fuel need of engine. The day tank is usually placed high so that diesel flows to engine under gravity. Diesel is again filtered before being injected into the engine by the fuel injection pump. The fuel is supplied to the engine according to the load on the plant.

3. Air intake system

Air filters are used to remove dust from the incoming air. Air filters may be dry type, which is made up of felt, wool or cloth. In oil bath type filters, the sir is swept over a bath of oil so that dust particles get coated.

4. Exhaust system:

In the exhaust system, silencer (muffler) is provided to reduce the noise.

5. Engine lubrication system:

Due to the presence of friction, wear and tear of the engine parts takes place reducing the engine life. The lubricant introduced forms a thin film between the rubbing surfaces and prevents metal to metal contact. The various parts that require lubrication are cylinder walls and pistons, crank pins, gudgeon pins, big end and small end bearings, etc. The maintenance of proper lubrication system for all moving parts is an important problem in the operation of an IC engine.

The purpose of lubrication is;

(i) to reduce the power required to overcome friction,
(ii) to increase the power output
(iii) to increase the engine life

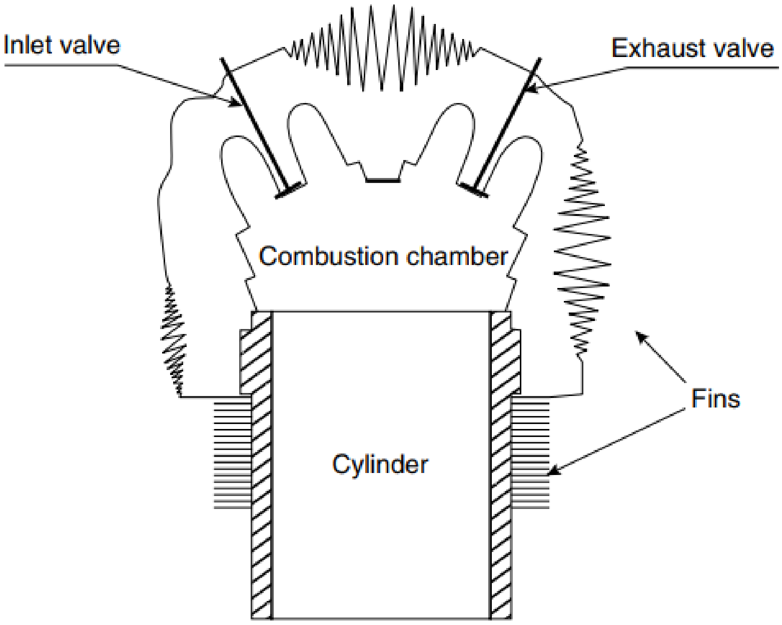
Improper lubrication results in the breakdown of the lubricating films, causing piston seizure and serious damage to the engine.

6. Cooling system

During the process of converting the thermal energy to mechanical energy, high temperatures are produced in the cylinders of the engine as a result of combustion. A large portion of heat from the products of combustion is transferred to the cylinder head and walls, piston and valves. This excess heat if not carried away by an efficient cooling system will damage the engine.

- Air cooling

In this system, atmospheric air is circulated around the engine cylinder to dissipate the excess heat. Heat transfer area is increased by providing fins on the cylinder and cylinder head and air is passed over them. Air cooling is used for small engines and aircraft engines. Using the fins increases the heat transfer surface by about 5–10 times its initial value. The number of cast fins may be 2–4 in number per centimetre or 4–6 fins per centimetre in case of machined fins. The spacing between the fins is limited to 2–5 mm and height of the fin varies from 20 to 50 mm.



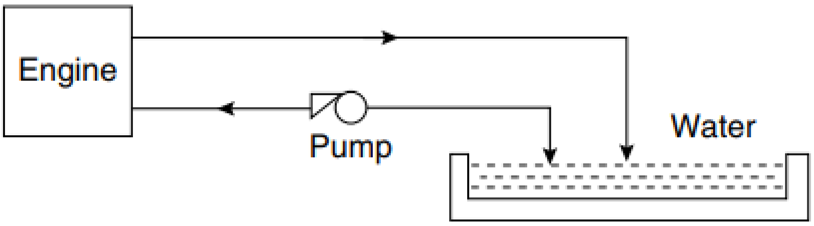
- Water cooling

In this system, the cylinder and cylinder head are enclosed in a water jacket. The water jacket is connected to a radiator or heat exchanger normally at the front end of the vehicle. Water is made to circulate through the water jacket, which cools the engine.

The hot water returns to the radiator where it exchanges heat with atmospheric air. The cold water is again re-circulated.

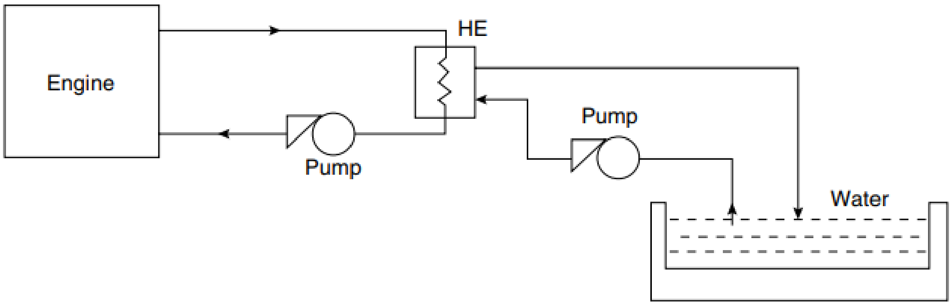
✓ Open- or single-circuit system

In this system pump draws water from cooling pond and forces it into the main engine jackets. Water, after circulating through the engine, returns to the cooling pond. The engine jacket is subjected to corrosion because of the dissolved gases in the cooling water.



✓ Closed- or double-circuit system

In this system, raw water is made to flow through a heat exchanger when it takes up the heat of jacket water and returns back to the cooling pond or tower.



About 25–35 per cent heat is lost by cooling water, which is known as jacket water loss. The rate of flow of water should be adjusted to maintain outlet cooling water temperature to 60°C and rise in temperature of cooling water is limited to 11°C. Water used for cooling should be free from impurities.

Supercharging

It is well known that the power output of an engine increases with an increase in amount of air in the cylinder at the beginning of compression stroke. This is because air allows burning more quantity of fuel. Supercharging is a process that helps to increase the suction pressure of the engine above atmospheric pressure and the equipment used for this purpose is known as supercharger. The advantages of supercharged engines are as follows:

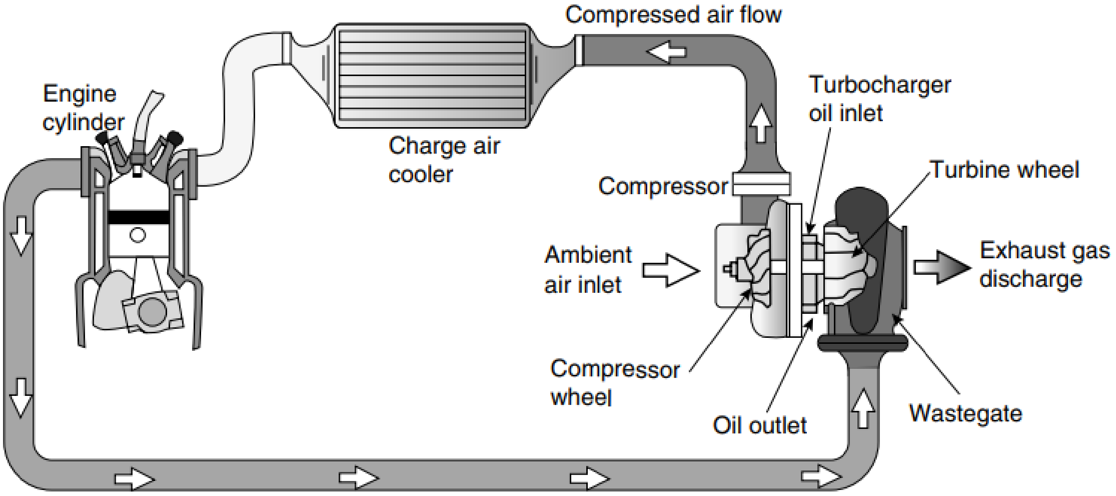
(i) Power increase: By supercharging the engine, the engine output can be increased by 30–50 per cent at the same speed of the engine.

(ii) Fuel economy: The combustion in supercharged engine is better as it provides better mixing of the air and fuel than un-supercharged engine. Hence, the specific fuel consumption of a supercharged engine is less than a natural aspirated engine. The thermal efficiency of a supercharged engine is also higher.

(iii) Mechanical efficiency: The mechanical efficiency of a supercharged engine is better than a natural aspirated engine at the same speed. This is because the power increase due to supercharging increases faster than the rate of increase in friction losses.

(iv) Knocking: Supercharging reduces the possibility of knocking in diesel engines because delay period is reduced with an increase in supercharged pressure. Actually, supercharging results in smoother running of the engine. It has been found that four-stroke engines are more easily adaptable to supercharging than two-stroke engines.

Due to the number of advantages of supercharging mentioned above, modern diesel engines used in diesel plant are generally supercharged. By supercharging, the size of the engine is reduced for a given output and consequently the space requirements and civil engineering works also reduced.



Advantages and disadvantages of Diesel power plant

Such any type of generation plants, Diesel power plants have their advantages and disadvantages.

- ✓ Advantages;

1. Design and instillation are very simple.
2. Can respond to varying loads without any difficult.
3. Occupy less space.
4. Can be started and put on load quickly.
5. Overall capacity cost is lesser than that for steam plants.
6. Require less operating and supervision staff as compared with other plants.
7. The cost of building and civil works is low
8. These plants can be located very near to the load.

- ✓ Disadvantages

1. High operating cost.
2. High maintenance and lubrication cost.
3. Noise is serious problem.
4. Small life of diesel power plants (2-5 years) as compared to that of a steam power plant (25-30 years).

Applications of diesel power plant

1. Peak load plant
2. Mobile plants or outdoor units
3. Standby units
4. Emergency plant
5. Nursery station
6. Central stations

Diesel engine performance and operation

1. Power and mechanical efficiency

Power is the work done by the engine in unit time, which is the product of force and linear velocity. This can also be expressed in terms of product of engine torque and angular velocity. Torque measurement is done by a dynamometer and speed is measured using a tachometer as discussed earlier. Power developed by the engine at the shaft output is called brake power, denoted by BP.

If T = torque developed, kN m
N = engine speed, rps

then, brake power is given by

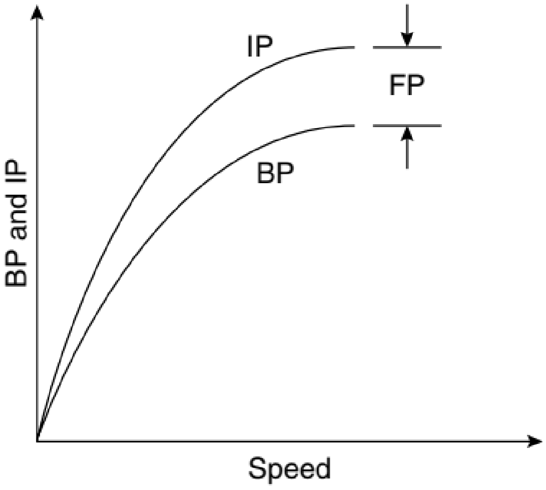
$$BP = 2\pi\, NT \text{ kW}$$

The total power actually developed on the pistons of the engine is called indicated power, denoted by IP. This indicated power is always greater than brake power, because a part of the indicated power is spent in overcoming friction of the bearings, pistons and other mechanical parts of the engine. Some of this power is also spent in induction of fuel air charge and exhaust gases delivery. Hence, the difference between the indicated power and brake power is known as friction power, denoted by FP. Thus,

$$IP = BP + FP$$

The ratio of power delivered by the engine (*BP*) to the total power developed within the engine (*IP*) is known as mechanical efficiency, denoted by η_m.

$$\eta m = \frac{BP}{IP} = \frac{IP - FP}{IP} = 1 - \frac{FP}{IP}$$



2. Indicated Mean effective pressure

Indicated MEP can be defined as the theoretical constant pressure that can be imagined to be exerted during each power stroke of the engine to produce power equal to indicated power, *IP*. It is denoted by *p*im.

If p_{im} = indicated MEP, kN/m^2

L = stroke length, m

A = area of the piston, m2

N = rotational speed, rps

n = number of revolutions required for each power stroke delivered per cylinder

= 2 for four-stroke engine; = 1 for two-stroke engine

x = number of cylinders in the engine

$$\text{then } IP = p_{im} \times L \times A \times N \times \frac{x}{n} \text{ kW}$$

3. Thermal efficiency

Thermal efficiency of the engine is defined as the ratio of output to the energy supplied by the combustion of fuel. If the output is based on the indicated power, it is known as indicated thermal efficiency, and if the output is based on brake power, it is known as brake thermal efficiency. Thus, indicated thermal efficiency

$$\eta_{\mathrm{i}} = \frac{\text{Indicated power}}{\text{Energy supplied}}$$

$$\eta_{\mathrm{i}} = \frac{IP}{m_{\mathrm{f}} \times CV_{\mathrm{f}}}$$

Brake thermal efficiency,

$$\eta_{\mathrm{b}} = \frac{\text{Brake power}}{\text{Energy supplied}}$$

$$\eta_{\mathrm{b}} = \frac{BP}{m_{\mathrm{f}} \times CV_{\mathrm{f}}}$$

where mf = mass or volume of fuel, kg/s or m^3/s and CVf = calorific value of fuel, kJ/kg or kJ/m^3

4. Relative efficiency

The relative efficiency or efficiency ratio is the ratio of the actual efficiency of the engine to the theoretical efficiency of the engine.

Relative efficiency,

$$\eta_{\mathrm{r}} = \frac{\eta_{\mathrm{actual}}}{\eta_{\mathrm{airstandard}}}$$

5. Heat balance

Heat balance gives an idea about the amount of heat supplied and the amount of heat utilized in the system. It gives useful information about the performance of the engine. The heat balance calculations are done generally either on minute basis or hour basis.

✓ Heat supplied by the engine

Heat supplied by the engine by burning *m*f kg of fuel is given by

$$Q_A = m_f \times CV_f$$

where CV_f is the lower calorific value of the fuel.

✓ Heat utilized by the system

(i) Heat equivalent of $BP = BP \times 60$ kJ/min

(ii) Heat lost to cooling water

Let, m_w = Mass flow rate of water, kg/min
C_{pw} = Specific heat of water, kJ/kg K
T_{wo} = Outlet temperature of water, °C
T_{wi} = Inlet temperature of water, °C

then heat lost to cooling water is

$$Q_w = m_w\, C_{pw}\, (T_{wo} - T_{wi})$$

(iii) Heat lost to exhaust

Let m_g = mass flow rate of exhaust gas, kg/min
C_{pg} = specific heat of gas
T_{ge} = exhaust gas coming out of the engine, °C
T_a = ambient temperature, °C

then heat carried away by exhaust gases.

$$Q_g = m_g\, C_{pg}\, (T_{ge} - T_a) \text{ kJ/min}$$

(iv) Heat lost due to radiation, convection and leakage of gases is known as unaccounted heat.

Unaccounted heat loss = QA - [(i) + (ii) + (iii)]

Ex1/ During a test on a four-stroke cycle oil engine the following data and results were obtained

Speed of the engine = 360 rpm

Indicated mean effective pressure = 560 kN/m^2

Effective brake load = 70 N

Effective brake radius = 0.6 m

Swept volume of cylinder = 12 liters

Fuel consumption = 0.0016 kg/s

Calorific value of fuel = 44,000 kJ/kg

Cooling water circulation = 0.10 kg/s

Cooling water outlet temperature = 68°C

Cooling water inlet temperature = 35°C

Specific heat capacity of water = 4.18 kJ/kg K

Energy to exhaust gases = 34 kJ/s

Determine the indicated and brake outputs and the mechanical efficiency. Draw up an overall

energy balance in kJ/s and as a percentage.

Solution:

$$IP = p_{\text{im}}\, LAN \times \frac{x}{n};\ x = 1,\ n = 2$$

Now,

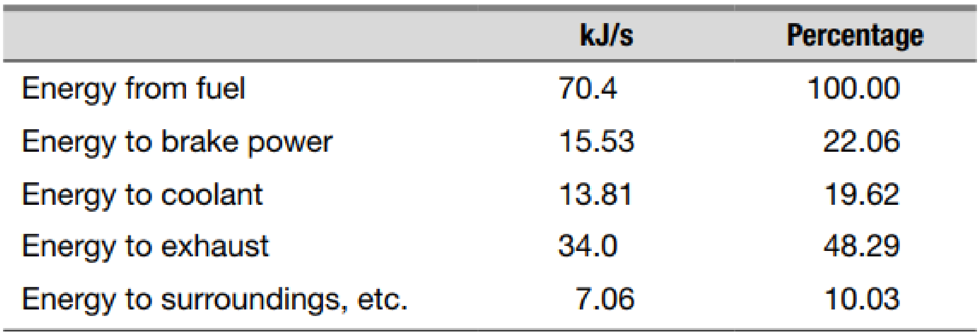
$$\begin{aligned}
\text{swept volume of the cylinder} &= V_S = LA \\
&= 12\ l \\
&= 12 \times 10^{-3}\ \text{m}^3
\end{aligned}$$

$$\text{Indicated power} = 560 \times 12 \times 10^{-3} \times \frac{360 \times 1}{60 \times 2}$$

$$\begin{aligned}
\text{Brake power} &= 2\pi\, NT \\
&= (2\pi \times 6 \times 9.81 \times 70 \times 0.6) \times 10^{-3} \\
&= 15.53\ \text{kW}
\end{aligned}$$

$$\text{Mechanical efficiency} = \frac{BP}{IP} \times 100 = \frac{15.53}{20.16} \times 100 = 77.03\%$$

$$\begin{aligned}
\text{Energy from fuel} &= \text{Fuel consumption} \times \text{Calorific value of fuel} \\
&= 0.0016 \times 44{,}000 \\
&= 70.4\ \text{kJ/s} \\
\text{Energy to brake power} &= 15.53\ \text{kW} = 15.53\ \text{kJ/s} \\
\text{Energy to coolant} &= m_w \times C_{pw}\,(T_{wo} - T_{wi}) \\
&= 0.10 \times 4.186\,(68 - 35) \\
&= 13.81\ \text{kJ/s} \\
\text{Energy to exhaust (given)} &= 34\ \text{kJ/s} \\
\text{Energy to surroundings, etc.} &= \text{Energy from fuel} - [\text{Energy to } BP + \text{Energy to coolant} \\
&\quad + \text{Energy to exhaust}] \\
&= 70.4 - (15.53 + 13.81 + 34) \\
&= 7.061\ \text{kJ/s}
\end{aligned}$$



	kJ/s	Percentage
Energy from fuel	70.4	100.00
Energy to brake power	15.53	22.06
Energy to coolant	13.81	19.62
Energy to exhaust	34.0	48.29
Energy to surroundings, etc.	7.06	10.03

Ex2/ In a trial of a four-cylinder, four-stroke petrol engine of 90 mm bore and 100 mm stroke, the net dynamometer load was 1400 N at a radius of 460 mm, when the speed was 2200 rpm. At the same speed and throttle opening, the engine required 4 kW to motor it with the ignition switched off.

(i) Calculate the mechanical efficiency and indicated mean effective pressure.

(ii) During a 3 min run at this speed and power, the engine used 2.4 kg of petrol of calorific value 42,980 kJ/kg and 100 kg of cooling water with a temperature rise of 40°C.

Draw up a heat balance for the test in kJ/min.

Solution:

(i) Brake Power

Brake power, $BP = 2\pi NT = 2\pi \times \frac{2200}{60} \times 1400 \times 0.46 \times 10^{-3}$

$BP = 148.37$ kW

Frictional power, $FP = 4$ kW

Indicated power $=$ Brake power + Frictional power

$= 148.37 + 4 = 152.37$ kW

$$\text{Mechanical efficiency} = \frac{BP}{IP}$$

$$= \frac{148.37}{152.37} \times 100 = 97.37\%$$

Indicated mean effective pressure

$$p_{\text{im}} = \frac{\text{Indicated power}}{AL\frac{N}{2}} = \frac{152.37 \times 10^3}{\frac{\pi}{4}(0.09)^2 \times 0.1 \times \frac{2200}{2 \times 60} \times 4 \times 10^5}$$

$= 32.66$ bar

(ii) Heat Input $=$ Fuel consumption × Calorific value of fuel

$$= \frac{2.4}{3} \times 42,980$$

$= 34,384$ kJ/min

Heat to jacket cooling water

$$= m_w C_{pw} \Delta T = \frac{100}{3} \times 4186 \times 40$$

$= 5581.33$ kJ/min

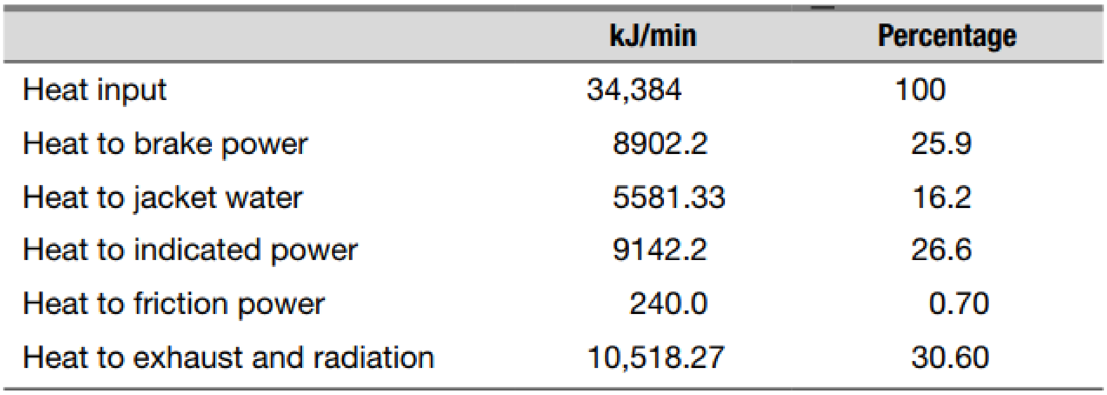
Heat equivalent to $BP = 148.37 \times 60 = 8902.2$ kJ/min

Heat equivalent to $IP = 152.37 \times 60 = 9142.2$ kJ/min

Heat equivalent to $FP = 4 \times 60 = 240$ kJ/min

Heat to exhaust and radiation, etc. = 10,518.27 kJ/min

Heat balance for 1 min



	kJ/min	Percentage
Heat input	34,384	100
Heat to brake power	8902.2	25.9
Heat to jacket water	5581.33	16.2
Heat to indicated power	9142.2	26.6
Heat to friction power	240.0	0.70
Heat to exhaust and radiation	10,518.27	30.60

Q/ A full-load test on a two-stroke engine gave the following data: speed = 450 rpm; brake load = 460 N; indicated MEP = 3 bar; fuel consumption = 5.4 kg/h; jacket water flow rate = 440 kg/h; temperature rise of cooling water = 36°C. Temperature of exhaust gases = 355°C; room temperature = 20°C, *CV* of fuel = 42,000 kJ/kg; cylinder bore = 200 mm; stroke = 270 mm; brake drum diameter= 1500 mm; mean specific heat of exhaust gases = 1.02 kJ/kg K. Determine the indicated thermal efficiency and draw heat balance sheet

Ans: 30.29%, 25.81%, 29.24%, 11.39%, 33.56%

University of Anbar

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Power Plants

Chapter Four

Economics of Power Plants

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Power Plants

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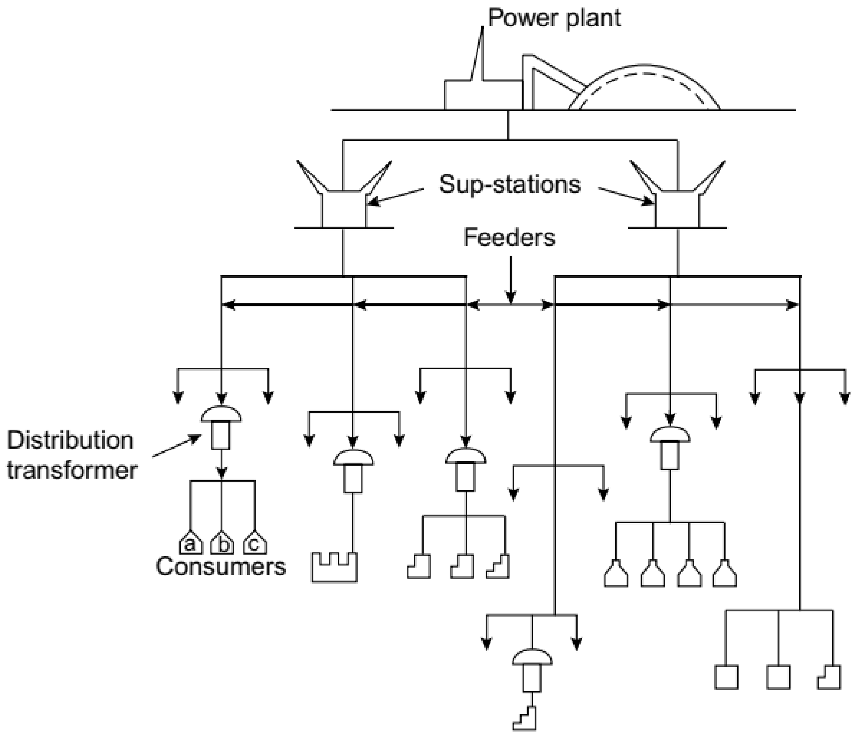
Economics of Power Plants

Introduction

The load required by the consumer does not remain constant with respect to time (hour, day or month), and it fluctuates according to his requirements. The problem of variable load is an important one because each kilowatt-hour energy is to be put on the transmission line at as low production cost as possible. The cost of generation and transmission is dependent not only on the improved operating conditions, such as turbine and generators efficiencies, but also on the first cost of equipment, which can be reduced by using simplified control and by eliminating the various auxiliaries and regulating devices.

Figure below shows the general arrangement of the electrical power generation, transmission and distribution system. The energy is sent to the substations that are located at the ends of the primary distribution system. The energy from the substation is then carried through the feeders to the distribution transformers. Each transformer is connected to the systems of one or more customers by short low-voltage lines.



Types of Loads

In a power station, load on the system refers to a device that taps the electric energy from an electric energy system. Various types of loads on the system are as follows:

(a) *Domestic load:* This load consists of lights, fans, refrigerators, television, water pumping motors, etc. Domestic loads vary during different times of a day, and hence has low load factor ranging from 10 to 12 per cent.

(b) *Industrial load:* This load consists of all types of power requirements from industries and varies from industry to industry. Large-scale industries require 500 kW and above; medium-scale industries require 25–100 kW, whereas small-scale industries require around 25 kW.

(c) *Municipal load:* This load consists of load due to street lighting, water treatment, pumping and drainage purpose. Street lights are on during the night time, whereas water pumping is done generally during off-peak hours, to ensure improved load factor.

(d) *Commercial load:* This load consists of lighting for shops, fans and restaurants. This type of load happens more during day time as compared with domestic load. Due to seasonal usage of heaters and air conditioners, load on the system also varies.

(e) *Irrigation load:* This load is due to electric supply to irrigation pumps and motors and is generally supplied during night hours.

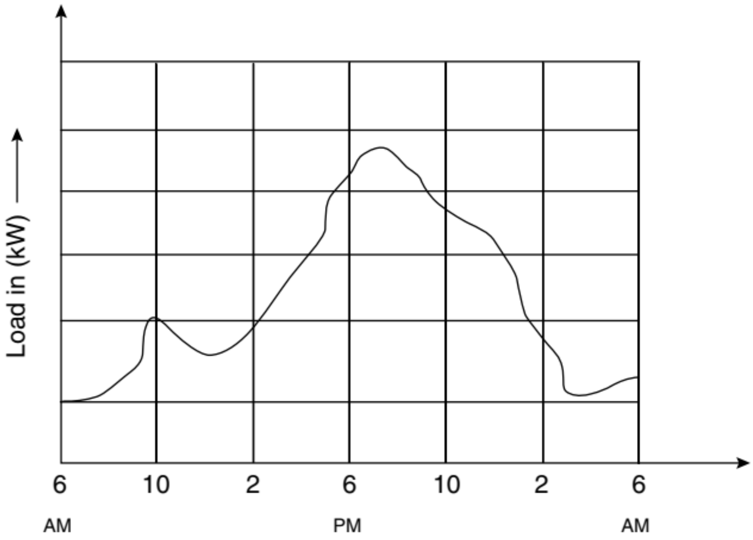
Load Curve

Since a consumer of electric power always uses the power as and when required, the load will also be changing with time and will not be constant.

A curve showing the load demand (variations) of consumer with respect to time is known as load curve. If the time is in hours, then the load curve is known as daily load curve. If the time is in days, the load curve is known as monthly load curve.

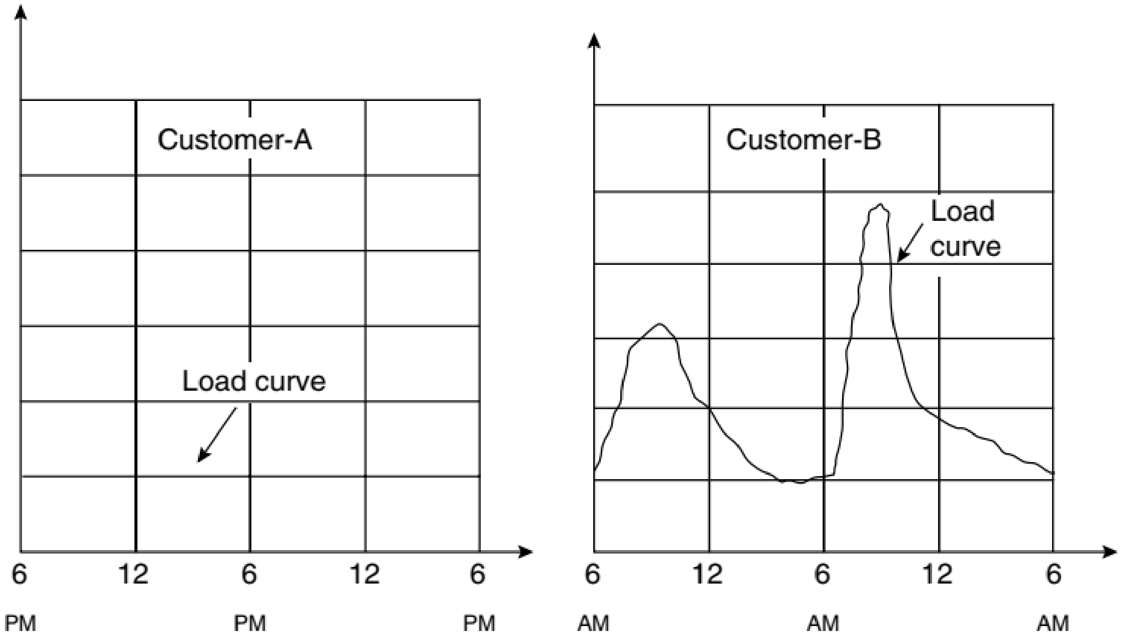
The demand load curve of a power plant is generally found out by adding all the loads in addition the effects of the factors such as unexpected changes in weather.

Figure below shows a load curve of a consumer. The area under the load curve gives the total energy consumed by the customer.



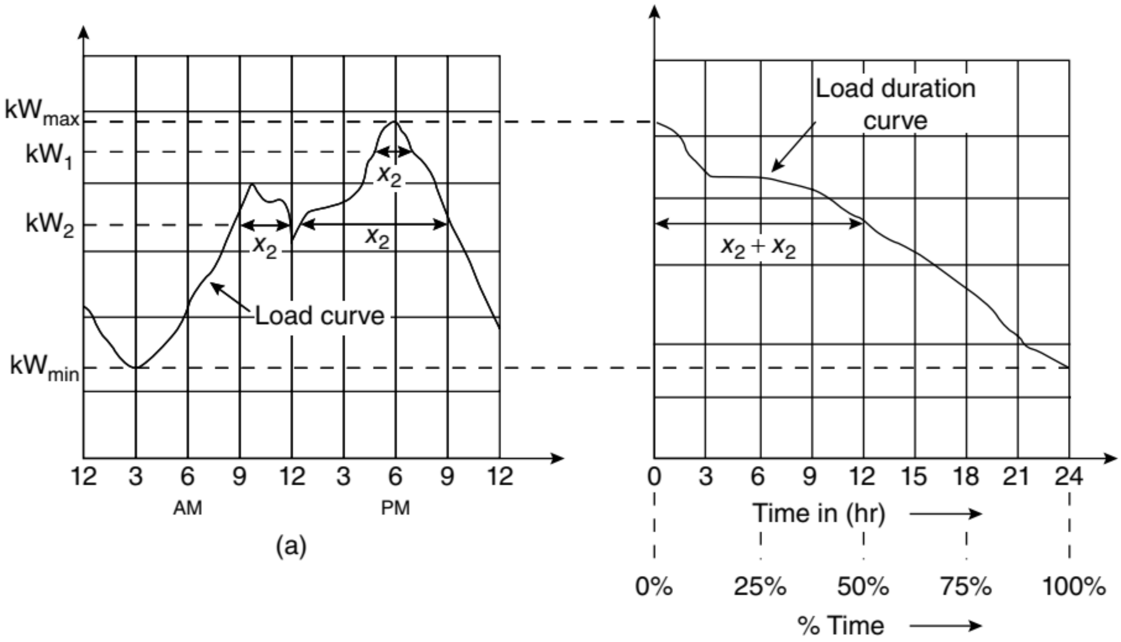
The following figure shows two customers A and B consuming the same amount of energy but with a different nature of consumption.

In the second case, the peak load is far greater than the first therefore the generating capacity of the plant required to supply the load of B is greater than the capacity required to supply the load of A. The plant designed for customer B is not only bigger in size, but it also runs under load (part load) conditions for majority of the period. Therefore, the cost of energy supplied to B may be hundred per cent greater than the cost of energy supplied to A even the total energy consumed by both customers is same.



Load Duration Curve

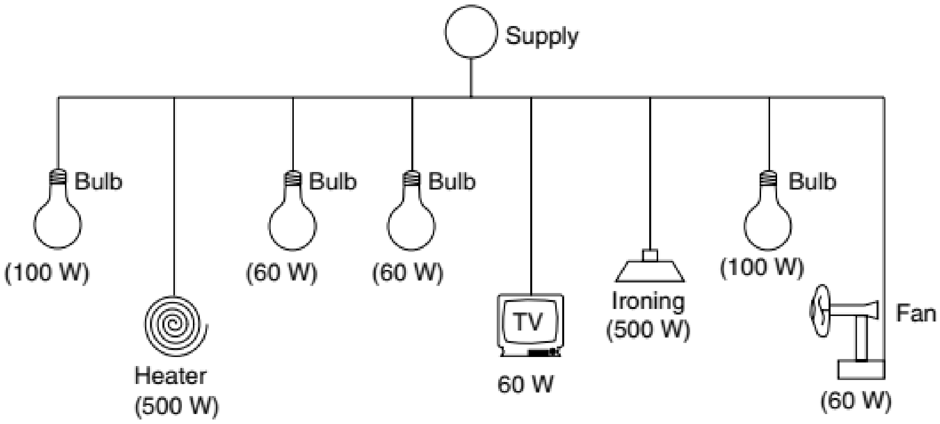
Load duration curve is a rearrangement of daily load curve with loads set up in descending order of magnitude. The areas under the load duration curve and corresponding load curve are equal and give kilowatt-hour of energy for that period.



Terminology used in power supply

Some common terms used in connection with power supply are defined as follows:

- *Connected load:* The connected load is the sum of ratings in kilo-watt of the equipment installed in the consumer's premises. The connected loads in the premises of a consumer.

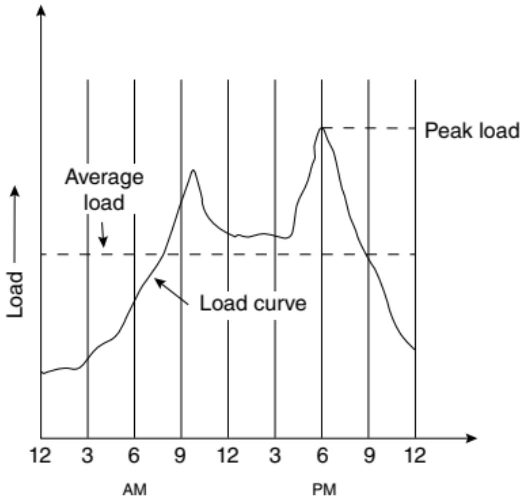


- *Maximum demand:* The maximum demand is the maximum load that a consumer uses at any time. It is always less than connected load or equal to connected load. When all the equipment fitted in the consumer's house run to their fullest extent simultaneously, then the maximum demand becomes equal to connected load.
- *Demand factor:* It is defined as the ratio of maximum demand to connected load. The maximum value of the demand factor is unity.

$$Demand\ factor\ = \frac{Maximum\ demand}{Total\ connected\ load} < 1$$

- *Average load:* The average load is the ratio of the area under the load curve (energy in kW hr) to the time period (24 hr) considered to draw the load curve.

$$Average\ load\ = \frac{Energy\ consume\ in\ 24\ h}{24} = \frac{Area\ under\ the\ load\ curve}{24}$$



- *Load factor*: it is the ratio of the average power to the maximum demand

$$load\ factor\ = \frac{Average\ \ load}{Maximum\ demand}$$

- *Diversity factor:* The diversity factor is the ratio of the sum of the maximum demands of the individual consumers and the simultaneous maximum demand of the whole group during a particular time.

$$Diversity\ factor\ = \frac{Sum\ of\ individual\ demand}{Maximum\ demand\ of\ entire\ group}$$

- *Utilization factor*: it is the ratio of maximum demand to the total capacity of the plant.

$$Utilization\ factor\ = \frac{maximum\ demand}{Plant\ capacity}$$

- *Plant capacity factor*: it is the ratio of actual energy produced in kWh to the maximum possible energy that could have been produced during the same period.

$$Plant\ capacity\ factor\ = \frac{E}{C\ \times t}$$

Where E = the actual energy produced in kWh,

C = capacity of the plant in kW,

t = total number of hours in the given period.

- *Plant use factor*: It is the ratio of energy produced in given time to maximum possible energy economic that could have been produced during the actual number of hours of operation.

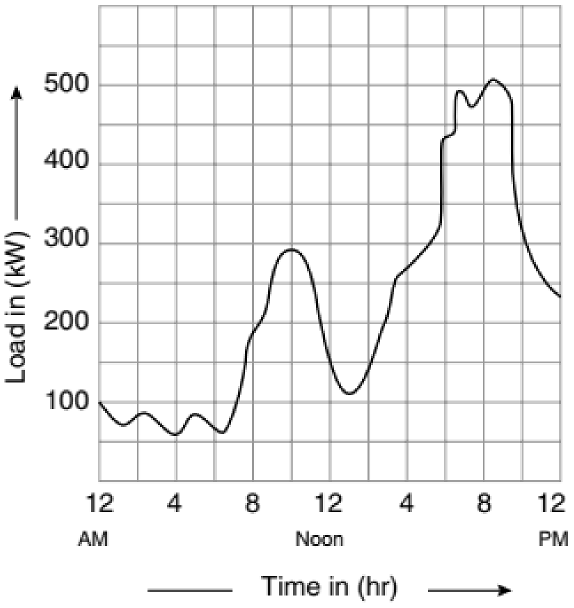
$$Plant\ use\ factor\ = \frac{E}{C\ \times \bar{t}}$$

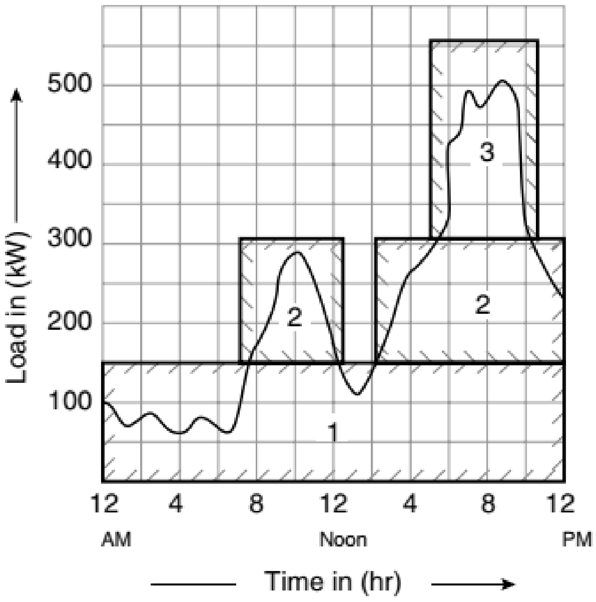
Where, $\bar{t}$ = the actual number of hours the plant in operation

Selection of the number and size of units

As the load on the power plant is not constant and varies continuously, it is not economical to run a single generating unit meeting the variable load. The number and size of the generating units is decided based on the annual load curve of the station. The number and size of the units selected must perfectly match with the station load curve to ensure highest efficiency of the generating units.

Consider the following load curve as shown in the figure below. The curve shows wide variations in load for the 24 hr considered from a minimum of 60 kW to a maximum of 500 kW. For this kind of situation, single unit is not recommended. However, the total generating capacity can be matched by selecting a number of generating units to fit the load curve. In this case, three units can be employed according to the load on the station, viz. three in numbers.





Ex: The maximum demand of a power plant station is 96,000 kW of daily load curve is described as follows;

Time (hr)	0-6	6-8	8-12	12-14	14-18	18-22	22-24
Load (MW)	48	60	72	60	84	96	48

Determine the load factor of power station.

Solution:

Energy generated = Area under the load curve

$= 48 \times 6 + 60 \times 2 + 72 \times 4 + 60 \times 2 + 84 \times 4 + 96 \times 4 + 48 \times 2$

$= 1632$ MWh $= 1632 \times 10^3$ KWh

$$\text{Average load} = \frac{1632 \times 10^3}{24} = 68000 \text{ KW}$$

Maximum demand = 96000 KW

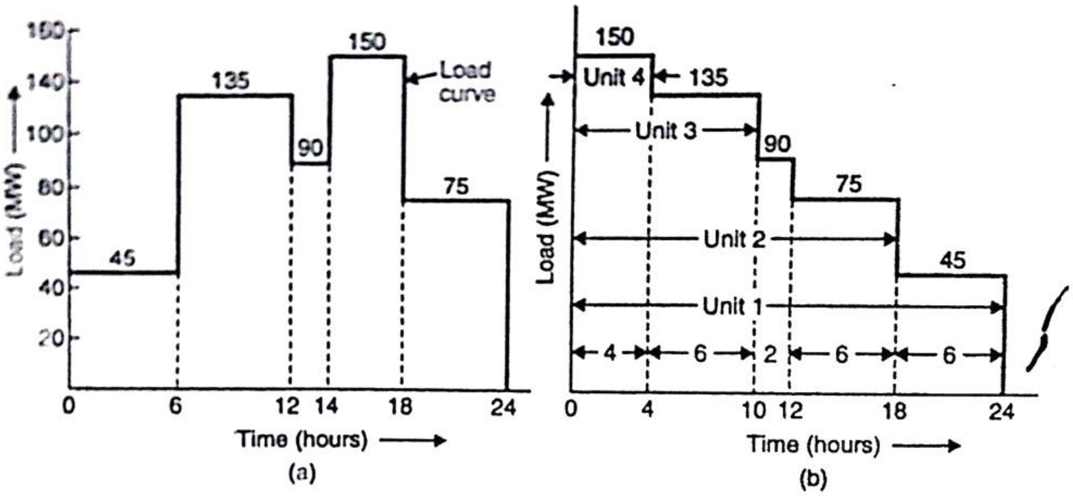
$$\text{load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{68000}{96000} = 0.71$$

Ex: A power station has to supply loads as follows:

Time (hr)	0-6	6-12	12-14	14-18	18-24
Load (MW)	45	135	90	150	75

1. Draw the load curve
2. Draw load duration curve
3. Choose suitable generating units to supply the load
4. **4.** Calculate the plant capacity factor

Solution:



(a) (b)

Load duration curve will indicate the operation schedul
of different generating units

1. One generating unit (unit 1) of 45 MW
(run for 24 h)

2. Second generating unit (unit 2) of 45 MW
(run for 18 h)

3. Third generating unit (unit 3) of 45 MW
(run for 10 h)

4 Fourth generating unit (unit 4) of 15 MW (run for 4 h)

one additional unit (unit 5) should be kept as standby. Its capacity should be equal to the capacity of biggest set, i.e., 45 MW

Energy generated $= 45*6 + 135*6 + 90*2 + 150*4 + 75*6 = 2310$ MWh

Average load $= \frac{2310*10^3}{24} = 96250$ KW

Maximum load $= 150*10^3$ KW

load factor $= \frac{\text{Average load}}{\text{Maximum demand}} = \frac{96250}{150000} = 0.64$

Plant capacity factor $= \frac{E}{C*t}$

C = Capacity of the plant $= 45*4 + 1*15 = 195$ MW

$\therefore$ P.C.F $= \frac{2310*10^3}{195*10^3 * 24} = 0.49$

Ex: On the basis of annual operation, the use factor and capacity factor of a central plant are 0.6 and 0.4, respectively. Find out the number of hours of its operation during the year.

Solution:

$$\text{Plant use factor} = \frac{E}{C * t}$$

$$\text{Plant Capacity factor} = \frac{E}{C * \bar{t}}$$

$$= \frac{E}{C * 8760}$$

$$\frac{\text{use factor}}{\text{Capacity factor}} = \frac{E}{C * \bar{t}} * \frac{C * 8760}{E}$$

$$\frac{0.6}{0.4} = \frac{8760}{\bar{t}}$$

$$\Rightarrow \bar{t} = 5840 \text{ hr}$$

Ex/ a daily load factor curve of a power station follow the equation [N =56 + 24t – t^2], where N is the load (MW) and t is the time (hr). The plant supplies three substations A, B, C whose load factors are 0.625, 0.5, and 0.8 respectively. The total load distribution ratios between the substations as 1:1.3:1.5. Find;

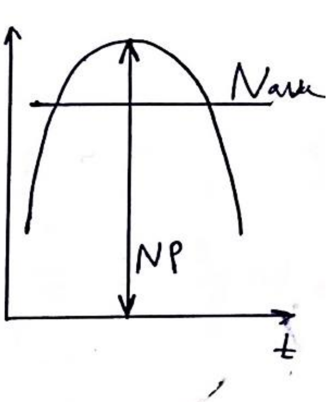
1. Average and peak load of each substation
2. Diversity factor between them and the plant.

Solution:

Area under the curve - Energy consumed/day

$= \int_0^{24} 56 + 24t - t^2)\, dt$

$= \left[56t + 12t^2 - \frac{t^3}{3}\right]_0^{24} = 3648$ MW.hr



$N_{av.} = \frac{3648}{24} = 152$ MW

$1 + 1.3 + 1.5 = 3.8$

$\therefore N_{av.A} = 152 \cdot \frac{1}{3.8} = 40$ MW

$N_{av.B} = 152 \cdot \frac{1.3}{3.8} = 52$ MW

$N_{av.C} = 152 \cdot \frac{1.5}{3.8} = 60$ MW

$NP_A = \frac{40}{0.625} = 64$ MW

$NP_B = \frac{52}{0.5} = 164$ MW

$NP_C = \frac{60}{0.8} = 75$ MW

To get the peak load (N_p) of the plant:,
We drive the equation and equates it to Zero

$$\frac{dN}{dt} = 24 - 2t = 0$$

$$\therefore t = 12 \Longrightarrow \text{Max. load at } t = 12$$

$$N_p = 56 + 24(12) - (12)^2$$
$$= 200 \text{ MW}$$

$$\text{Diversity factor} = \frac{64 + 104 + 75}{200} = 1.215$$

The principles of power plant design

The following factors should be considered while designing a power plant:

1. Simplicity of design
2. Low capital cost
3. Low cost of energy generated
4. High efficiency
5. Low maintenance cost
6. Low operating cost

Cost Analysis

The cost of a power system depends upon whether:

1. An entirely new power system has to be set up, or
2. An existing system has to be replaced, or
3. An extension has to be provided to the existing system.

The cost includes:

- ✓ Capital Cost or fixed cost which include the following:
    - Initial cost (Cost of land, building, equipment, installation and cost of designing and planning the station)
    - Depreciation cost
    - Taxes
    - Insurance
- ✓ Operational cost includes the following:
    - Fuel cost
    - Operating labour cost
    - Maintenance cost
    - Supervision
    - Supplies ((a) water for feeding boilers, condensers, and for general use (b) lubricating oils, …, etc)

How to minimize power generation cost

The cost of power generation can be reduced by:

1. Selecting equipment of longer life and proper capacities.
2. Carrying out proper maintenance of power plant equipment to avoid plant breakdowns.

3. Running the power stations at high load factor
4. Increasing the efficiency of the plant.

Ex: A power plant is need to be built to supply power for residential area according to the following data;

Daily load = 69125 kW

h for steam exiting the boiler = 3240 kJ/kg

h for feed water = 418 kJ/kg

Price of 1 kg of fuel = 1 $/kg.fuel

CV of fuel = 40,000 kJ/kg

Estimated life time for the station = 25 years

Four companies present their offers as follows;

	Firm A	Firm B	Firm C	Firm D
Capital invested (P), $	115,000	135,000	146,500	177,966
Boiler efficiency	0.73	0.77	0.79	0.81
Specific steam consumption	5.63	5.207	5.793	5.1

The value of the plant materials that will be sold after 25 years = 0.05 P

Other fixed charges = 0.08 P

Find the best offer out of the 4 firms through finding the price of producing power unit ($/kW.hr) daily energy = 69125 KW

Annual energy = 69125 * 365 = 25250000 KW.hr

mass of fuel needed to produce 1 kg of steams,

$$= \frac{m_s (h_s - h_{fw})}{\eta_b * 40000} = \frac{1 * (3240 - 418)}{\eta_b * 40000} \quad \frac{kg_f}{1\,kg_s}$$

mass of fuel needed to produce 1 KW.hr

$$= \frac{3240 - 418}{\eta_b * 40000} \cdot \overset{\frac{kg_s}{kW.h}}{S.S.C} \qquad \frac{kg_f}{1\,kW.hr}$$

$$\text{mass of fuel needed annually} = \frac{3240 - 418}{\eta_b . 40000} * S.S.C * \underset{25250000}{} \quad kg_f$$

$$\text{Running Cost} = \frac{3240 - 418}{\eta_b . 40000} * S.S.C * 25250000 * 1$$

$$= 1781387.5 * \frac{S.S.C}{\eta_b} \quad \$$$

Fixed charges

Scrap value = 0.05 P , Capital invested = P

∴ Net deprection value = P − 0.05 P = M

Annual dep. $= \frac{M}{n} = \frac{0.95P}{25}$

other fixed charges $= 0.08P$

$\therefore$ Total fixed charges $= \frac{0.95P}{25} + 0.08P = 0.118P$

Total annual charges = Fixed ch. + Running ch.

$= 0.118P + 1781387.5 + \frac{S.S.C}{\eta_b}$ ——— ①

Now, We can compute the price of power unit for all firms using equation ①

- Firm A

Total annual charges $= \left[0.118 \times 115000 + 1781387.5 + \frac{5.63}{0.73}\right]$

$= 13{,}752{,}216$ \$

Cost / unit energy = total annual charges / Annual energy

$= 13752216 / 25250000 = 0.54$ \$ / KW.hr

Firm B

Total annual charges = 12062273.7 \$

Cost / unit energy = 0.47 \$ / KW.hr

Firm C

Total annual charges = 1308043.7 \$

Cost / unit energy = 0.51 \$ / kW.hr

Firm D

Total annual charges = 1123714.5 \$

Cost / unit energy = 0.44 \$ / kW.hr

It can be concluded that the best offer is from Firm D since it offer the lowest cost for unit energy compared with

Nuclear Power Plants

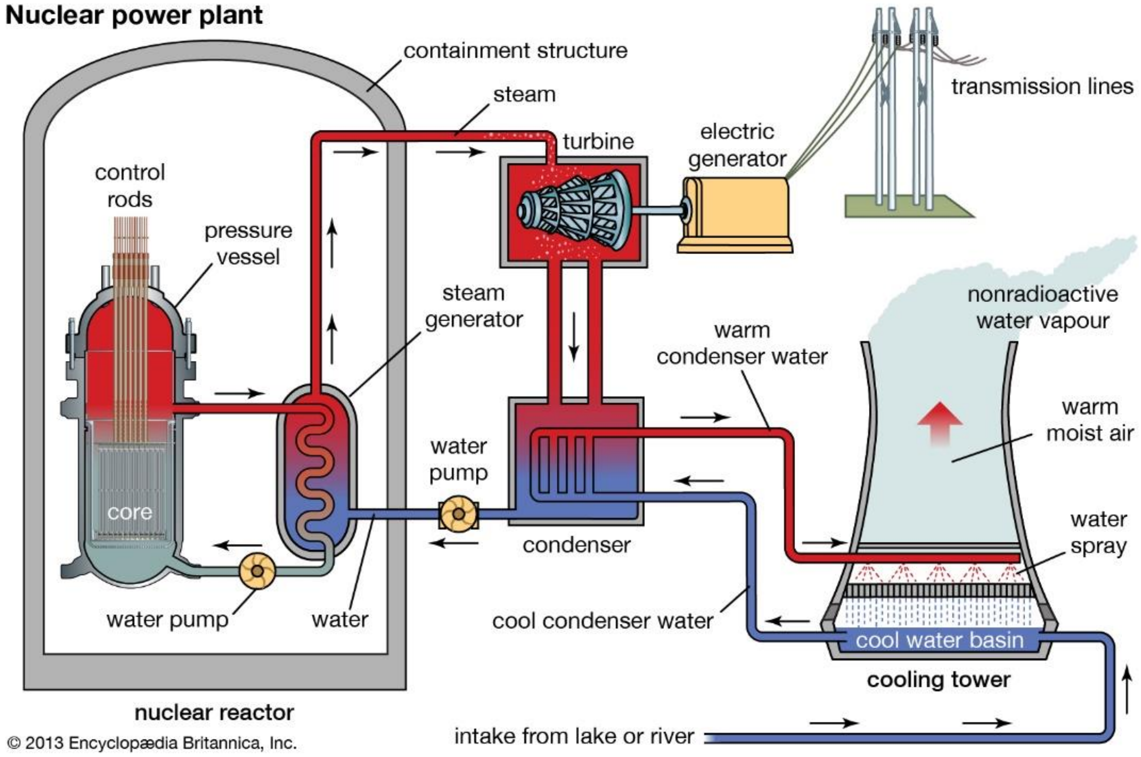
Nuclear power plants are a type of power plant that use the process of nuclear fission in order to generate electricity. They do this by using nuclear reactors in combination with the Rankine cycle, where the heat generated by the reactor converts water into steam, which spins a turbine and a generator. Nuclear power provides the world with around 11% of its total electricity.

Advantages of nuclear power plants

(i) Less space requirement
(ii) Consumes very small quantity of fuel
(iii) Not affected by changes in weather conditions
(iv) Large fuel storage facility is not required

Disadvantages of nuclear power plants

(i) High initial and maintenance costs
(ii) Radioactive wastes should be disposed off carefully
(v) Requires trained operators



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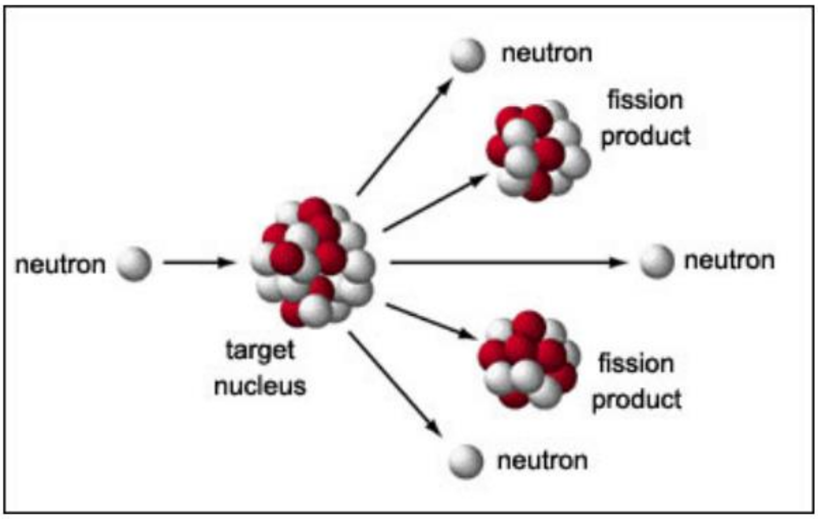
Nuclear fission

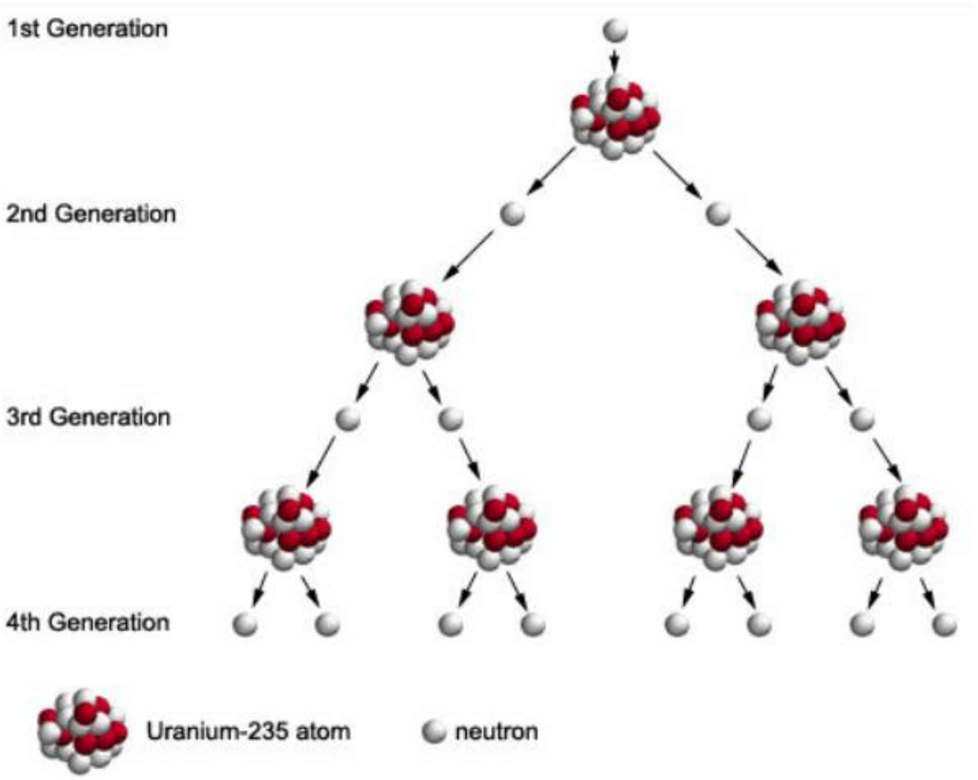
The nuclear fuel most commonly used for commercial nuclear power plants is uranium (denoted by the chemical symbol U). Uranium is a metallic chemical element commonly found on the earth's crust.

A nuclear reaction occurs when an atom is induced to split or "fission", and as a consequence, it releases a large amount of energy.

A nuclear reaction starts with a U-235 atom that is induced to split by shooting a neutron at it. When the U-235 atom absorbs the neutron it momentarily becomes a U-236 atom. The nucleus of the U-236 atom is relatively unstable, and it quickly breaks up into two different atoms and releases two to three free neutrons in the process.



The free neutrons that are released are very important for the continuation of the nuclear reaction or what is known as a nuclear chain reaction. A chain reaction occurs when the neutrons released by the fission of a U-235 atom are absorbed by other U-235 atoms, causing further fission reactions, which in turn release more neutrons and cause further fission reactions



Nuclear Reactor Components

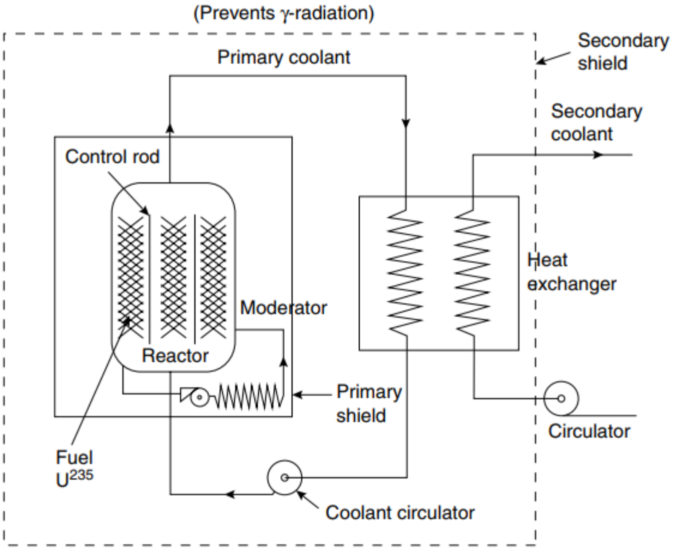
1. Fuel

In a thermal nuclear reactor, the fission induced by neutrons using a fuel isotope U235 is one of the several isotopes used in nuclear power generation

Fuel isotope + Neutron → Fission fragments + Neutrons + Energy

2. Control rods

Material in the core which slows down the neutrons released from fission so that they cause more fission. It is usually water, but may be heavy water or graphite.



3. Coolant

The function of the coolant is to remove the heat released by fission. The coolant should have high specific heat, high conductivity, good chemical stability, good pumping characteristics and low neutron-absorption cross section. Coolant can be either liquid or gaseous.

e.g. water, air, CO_2, He, sodium, bismuth, potassium, organic.

4. Shielding

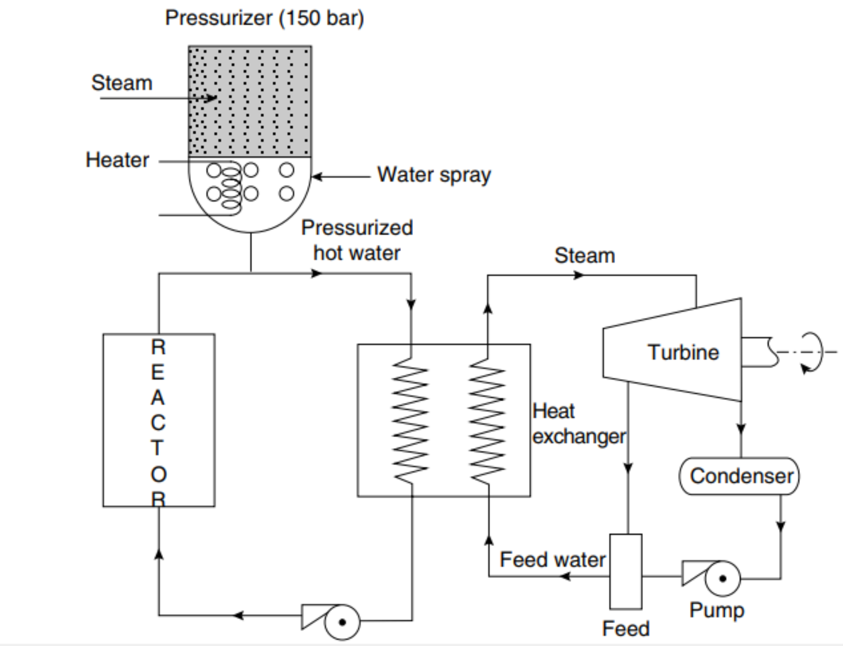
Shielding prevents the passage of radiation to the outside of the reactor. The primary shield prevents the leakage of neutron and gamma radiation present in the cooling circuits due to activation of the coolant as it passes through the core. Shields for external circuit where only gamma radiation may be present are made up of steel, lead, polyethylene and concrete. Concrete is used mostly due to its low cost.

Main types of nuclear reactor

1. Pressurized water reactor (PWR)

A pressurized water reactor (PWR) power plant is composed of two loops in series. One is the coolant loop called primary loop and the other is the water steam or working fluid loop.

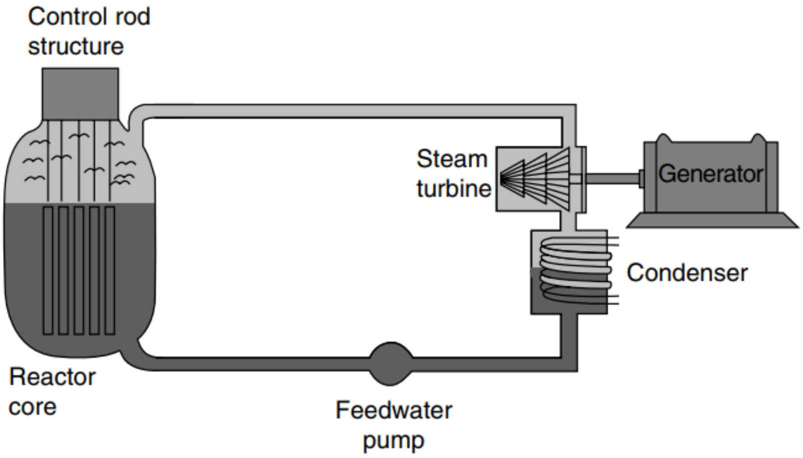
Hot water from the reactor flows to a steam generator where heat is transferred to water and steam in the secondary cooling system, which operates at a lower pressure. The primary coolant then flows from the steam generator to the primary cooling pump, where it is pumped back to the reactor.



The pressurizer is a pressure vessel with a heater at the bottom and a water spray at the top. The top of the pressurizer is filled with steam at primary system pressure (150 bar). If the primary loop pressure drops, the heater is energized to increase the steam content in the pressurizer and thus increases the pressure of primary cooling system. If the primary system pressure is too high; cold pressurized water is sprayed into the steam, condensing the steam and hence reducing the primary system pressure.

2. Boiling Water Reactor (BWR)

In the BWR, the coolant is in direct contact with the heat-producing nuclear fuel and boils in the same compartment in which the fuel is located. The reactor pressure is maintained at 70 bar. As water and vapour coexist in the core, a BWR produces saturated steam at about 285°C. The disadvantage of this reactor is that any fuel leak might make the water radioactive and the radioactivity would reach the turbine and the rest of the loop in all probability.



Factors for Site Selection of Nuclear Power Plants

1. **Availability of Water:** working fluid
2. **Distance from Populated Area:** danger of radioactivity
3. **Nearness to the load center:** reduction in transmission cost
4. **Disposal of Waste:** radioactive waste
5. **Accessibility by Rail and Road:** transport of heavy equipment