CHAPTER- : VAPOUR OR STEAM POWER CYCLE

Vapour power cycles are external combustion systems in which the working fluid is alternatively vapourised and condensed.

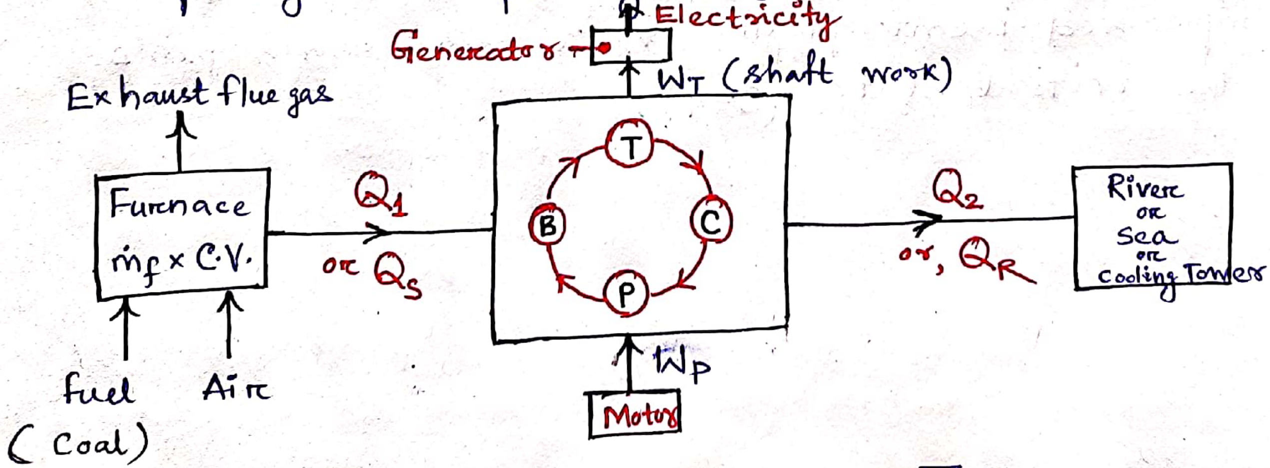
→ Water/Steam is easily available, is cheap, is chemically stable and physiologically harmless and as such is the most commonly used working fluid. Due to its use as the working substance in vapour power cycle, the cycle is often referred to as steam power cycle.

→ A vapour power cycle works on following thermodynamic cycles:

① Carnot Cycle (Imaginary Cycle and can not be possible in practice)
② Rankine Cycle (Practical cycle for Steam Power Plant)

Operation/Working: A steam power plant/fossil fuelled-power plant produces/generates electricity using water as the working fluid. Energy released by the burning of fuel (say, coal) is transferred to water in the Boiler (B) to generate steam at a high pressure and temperature. Steam then expands in the turbine (T) to a low pressure and temp. to produce shaft work (i.e., power o/p).

The low pressure & temp. steam leaving the turbine is condensed into water in the condenser (C) where cooling water from a river/sea or cooling tower circulates carrying away the latent heat released during condensation. Then the condensate i.e, water is then fed back to the boiler by the pump (P). In this way the cycle goes on repeating itself.



For the above cyclic operation, $\sum_{cycle} Q_{net} = \sum_{cycle} W_{net} \Rightarrow Q_1 - Q_2 = W_T - W_P$

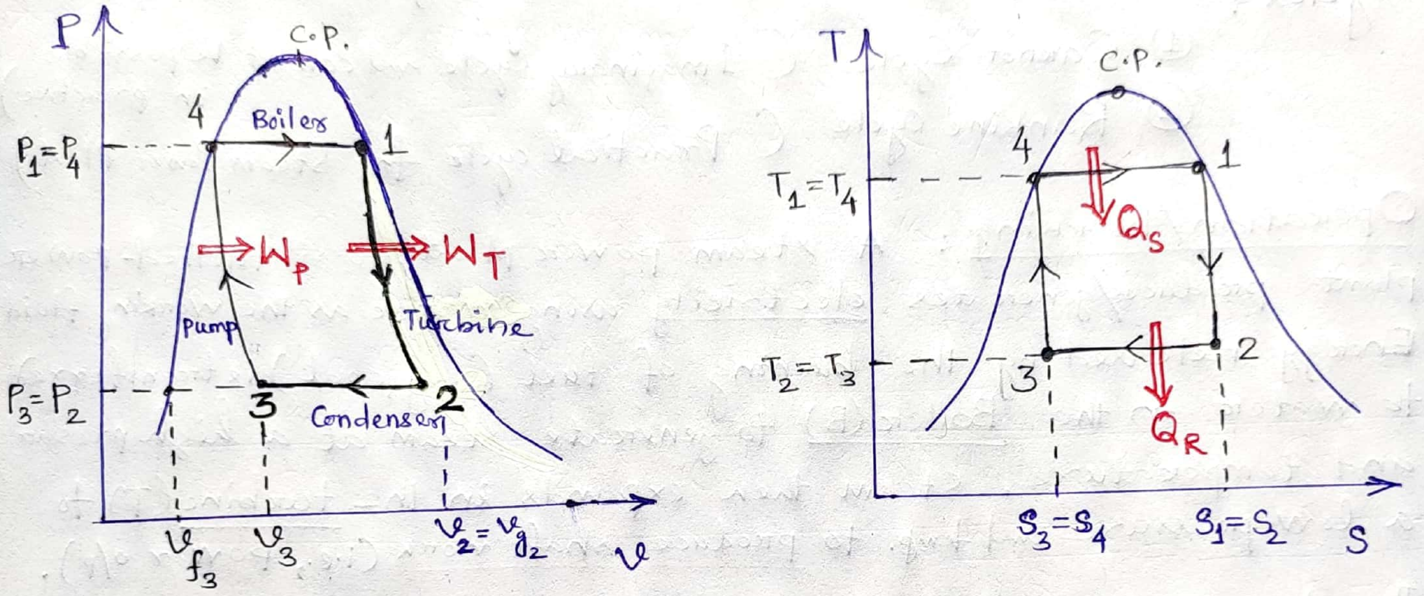
Carnot Cycle

The Carnot cycle is an ideal cycle but non-practical cycle for a steam power plant.

The Carnot cycle gives the maximum possible thermal efficiency for a cycle operating on selected maximum and minimum temperature ranges.

The Carnot Vapour Cycle for steam power plant consists of

- → TWO reversible adiabatic processes (Isentropic Process)
- → TWO reversible isothermal processes



In the cycle, the working substance water (or steam) is heated reversibly and isothermally in a boiler (process 4-1), expanded isentropically in a turbine (1-2), condensed reversibly and isothermally in a condenser (2-3) and compressed isentropically by a compressor or pump to the initial state (3-4).

By applying the S.F.E.E. to each of the steady-flow devices,

Boiler : Heat supplied isothermally to the water to produce steam is given by

$$Q_s = h_1 - h_4$$

Turbine : Workdone by adiabatic expansion of steam,

Turbine work or shaft work, $W_T = h_1 - h_2$

Condenser : Heat rejected isothermally from the steam during condensation

$$Q_R = h_2 - h_3$$

Pump : Workdone on steam during adiabatic compression in the pump or compressor is given by

$$W_P = h_4 - h_3$$

Performance Parameters

The performance criteria of a steam power plant are the thermal-efficiency, work ratio and specific steam consumption.

Thermal or Cycle Efficiency (η_{th}):

$$\eta_{th} = \frac{\text{Network output}}{\text{Heat supplied}} = \frac{W_{net}}{Q_s}$$

$$= \frac{W_T - W_P}{Q_s} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}$$

In terms of highest temp (T_1) and lowest temp (T_2) under which the Carnot Cycle operates,

$$\eta_{th,Carnot} = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

The efficiency of a Carnot cycle engine depends upon the limits of temp. and is independent of the nature of working substance.

Work ratio : Work ratio $= \frac{\text{Net work o/p}}{\text{Turbine work}} = \frac{W_{net}}{W_T} = \frac{W_T - W_P}{W_T}$

$$= 1 - \frac{W_P}{W_T}$$

→ A low work ratio implies large pump work (W_P). or The larger the pump work, lower is the work ratio.

Steam rate or Specific Steam Consumption (SSC):

The steam rate or specific steam consumption is defined as the flow rate of steam per unit power developed.

$$\text{SSC or Steam rate} = \frac{\text{Steam flow rate} \rightarrow kg/s}{\text{Power output} \rightarrow kW} = \frac{1\ kg/s\ \text{Steam}}{W_{net},\ kW}$$

$$= \frac{1\ kg/s}{W_T - W_P} = \frac{3600}{W_T - W_P},\ kg/kW\text{-hr}$$

$$= \frac{3600}{W_{net}},\ kg/kW\text{-hr}.$$

** The quantity of working fluid governs the size of the components of the plant. More SSC, greater is the plant size. More SSC also implies less net work o/p (W_{net}) for the same quantity of heat supplied (Q_s) and hence, lower η_{th} and higher operating cost. Thus, SSC or steam rate is an index of the capital cost and operating cost of the steam power plant.

SSC↑, Plant size↑, Capital cost↑, W_{net}↓, η_{th}↓, operating cost↑

Heat rate: Sometimes, the cycle thermal efficiency is expressed as heat rate which is a measure of the rate of heat input, Q_s required to produce unit work output (1 kW).

$$\text{Heat rate} = \frac{\dot{Q}_S \rightarrow kJ/s}{W_{net} \rightarrow kW} = \frac{3600\,\dot{Q}_S \rightarrow kJ/hr}{W_{net} \rightarrow kW} = \frac{3600}{\eta_{th}},\ kJ/kW\text{-hr}$$

Rankine Cycle

The Rankine cycle is an ideal cycle for steam-power plant which operates/works in a vapour-power cycle.

→ It consists of

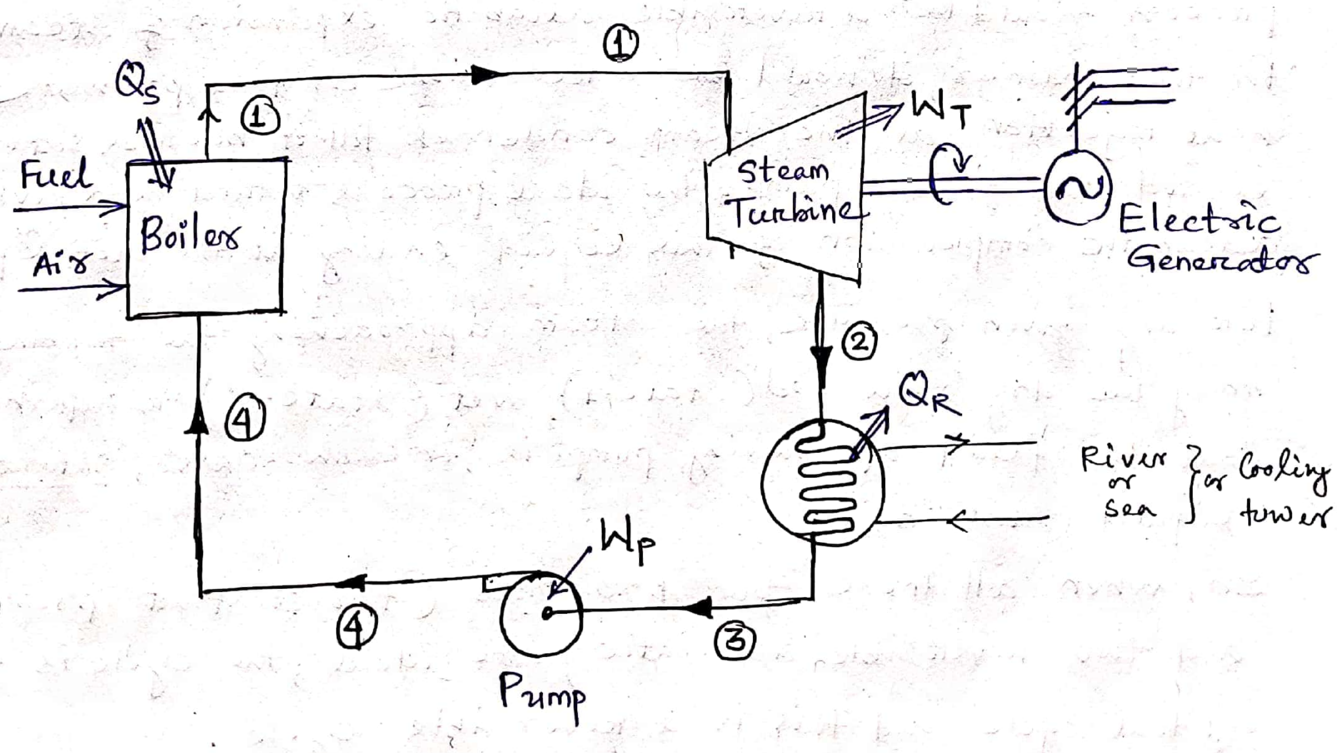
- TWO reversible adiabatic processes
- TWO reversible constant pressure processes.

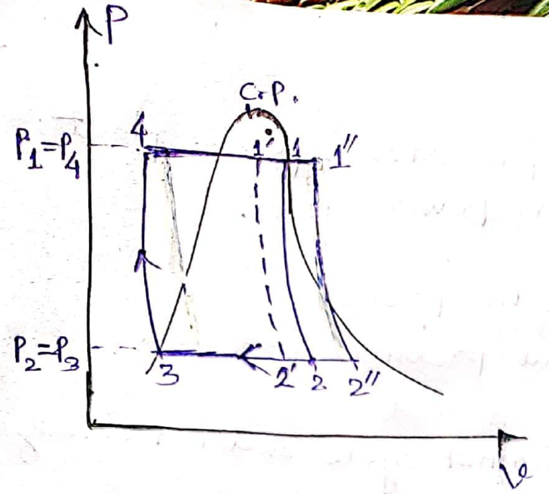
→ The Rankine cycle is a modified Carnot cycle and is techically feasible cycle. It differs from the Carnot cycle in the following respects:

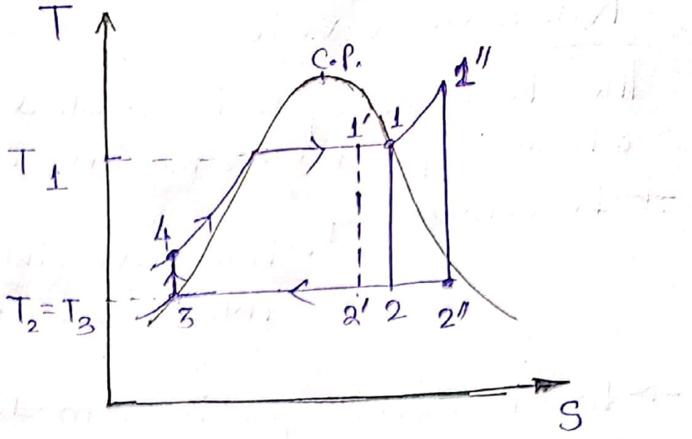
① The condensation process is allowed to proceed to completion; the exhaust steam from the engine/steam turbine is completely condensed. At the end of condensation process, the working fluid is only liquid and not a mixture of liquid and vapour

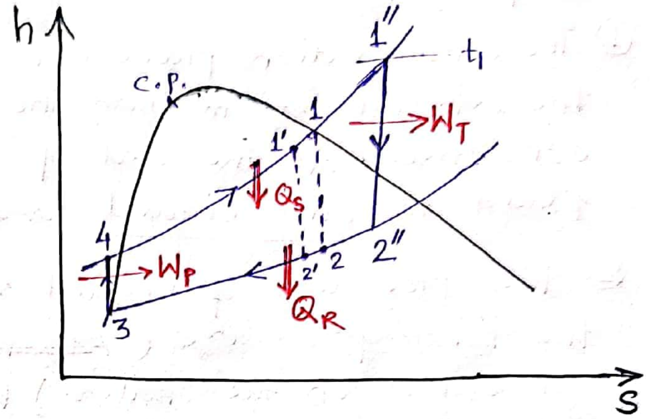
② The pressure of liquid water can be easily raised to the boiler pressure (~~steam~~ pressure at which steam is being generated in the boiler) by employing a smaller sized pump.

* In addition, the steam may be superheated in the boiler so as to obtain exhaust steam of higher quality. That will prevent pitting and erosion of turbine blades.









By considering the ideal Rankine cycle,
For the steam boiler, it is a reversible constant pressure heating process of water to form steam, for the steam turbine, the ideal process would be a reversible adiabatic expansion of steam, for the condenser, it would be a reversible constant pressure heat rejection as the steam condenses till it becomes saturated liquid and for the pump, the ideal process would be a reversible adiabatic compression of this liquid ending at the initial pressure.

For any given pressure, the steam approaching the turbine may be dry saturated (state-1), wet (state-1') or superheated (1'') but the fluid approaching pump is, in each case, saturated-liquid (state-3).

So, when all these four processes (two constant pressure and two reversible adiabatic) are ideal, the cycle is a ideal cycle and this is a reversible cycle.

As the steam turbine, condenser, pump and boiler associated with a Rankine Cycle are steady-flow devices, by applying S.F.E.E to each of the above component, we get

Boiler : Heat supplied to water, $Q_S = h_1 - h_4$, kJ/kg

Turbine : Turbine work, $W_T = h_1 - h_2$, kJ/kg

Condenser : Heat reject to cooling liquid, $Q_2 = h_2 - h_3$, kJ/kg

Pump : Pump work, $W_P = h_4 - h_3$, kJ/kg

Net work o/p of the cycle, $W_{net} = W_T - W_P$

Also, for a cyclic process, $\oint \delta W = \oint \delta Q$

$$\Rightarrow \boxed{W_{net} = Q_S - Q_R}$$

or, $$\boxed{W_T - W_P = Q_S - Q_R}$$

The thermal efficiency of Rankine cycle is given by

$$\boxed{\eta_{Rankine} = \frac{W_{net}}{Q_S} = \frac{Q_S - Q_R}{Q_S} = \frac{W_T - W_P}{Q_S}}$$

* The compression process in the pump is being carried out with liquid only for which the specific volume (v_{f_3}) is small. Consequently, the pump work $(h_4 - h_3)$ as compared to the work o/p from the steam turbine and thus, can be ignored.

The the cycle efficiency approximately becomes,

$$\boxed{\eta_{th} \cong \frac{W_T}{Q_S} = \frac{h_1 - h_2}{h_1 - h_4}}$$

Work Ratio : Work ratio $= \frac{W_{net}}{W_T} = \frac{W_T - W_P}{W_T} = 1 - \frac{W_P}{W_T}$

Specific Steam Consumption (SSC) or Steam rate :

$$\text{Steam rate or SSC} = \frac{\dot{m}_s}{W_{net}} = \frac{\dot{m}_s}{W_T - W_P}, \frac{kg}{kW\text{-}sec}$$

$$= \frac{3600}{W_T - W_P}, \; kg/kW\text{-}hr$$

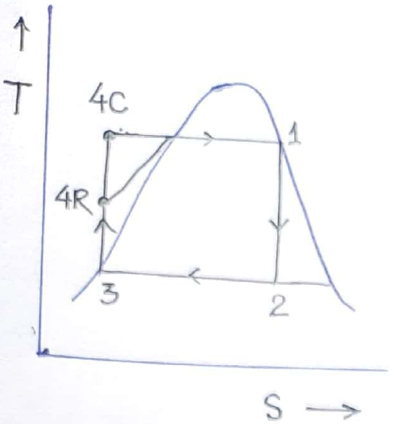
Heat rate :

$$\text{Heat rate} = \frac{3600 Q_1}{W_T - W_P} = \frac{3600}{\eta_{th}}, \; kJ/kW\text{-}hr$$

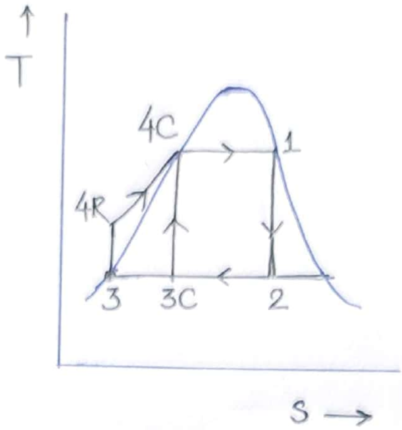
$W_{rev, flow} = -\int_3^4 v.dP$, it is obvious that the reversible steady-flow work is closely associated with the specific-volume of fluid (v) flowing through the flow devices. The larger the specific volume, the larger the reversible work produced or consumed by the steady-flow devices. Therefore, every effort should be made to keep the specific-volume of a fluid as small as possible during a compression-process (like in a pump) to minimize the work input and large as possible, during an expansion process to maximize the work output.

In steam power plant, the pump handles liquid, which has a very small sp. volume (v_f) and the turbine handles vapour, whose sp. volume (v_g) is many times larger. Therefore, the work O/p of the turbine is much larger than the work I/p to the pump. This is one of the reasons for the overwhelming popularity of steam power plants in electric power generation.

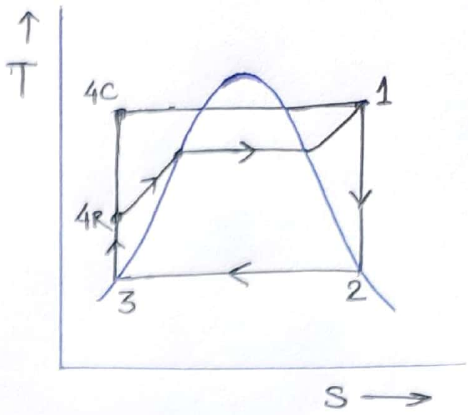
Comparison of Rankine and Carnot Cycle



(Fig - a)



(Fig-b)



(Fig-c)

- The reversible adiabatic expansion in the turbine, the constant temperature heat rejection in the condenser and the reversible adiabatic compression in the pump, are similar characteristics features of both the Rankine (R) and Carnot (C) cycles.
- The heat addition process in the Rankine cycle is reversible and at constant pressure while in the Carnot cycle, it is reversible and isothermal.

From Fig-a and Fig-c, Q_2 is same for both cycles and since Q_1 is more for Rankine cycle, $\eta_{Carnot} > \eta_{Rankine}$

- The Carnot cycle can not be realised in practice because the pump work is very large (Fig-a, b & c).

Means to Increase The Efficiency of Rankine Cycle

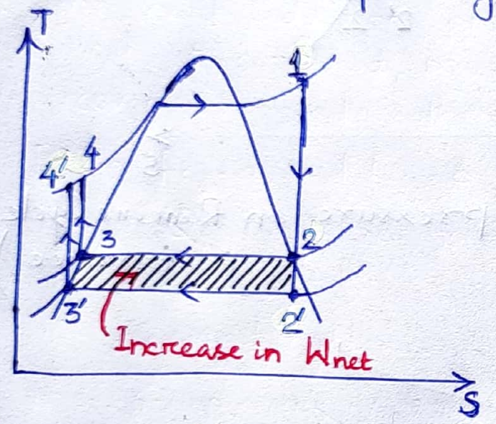
The methods to improve the thermal efficiency of the vapour power cycle are

- increasing the average temp. at which heat is added to the working fluid in the boiler.
- decreasing the average temp. at which heat is rejected from the working fluid in the condenser.

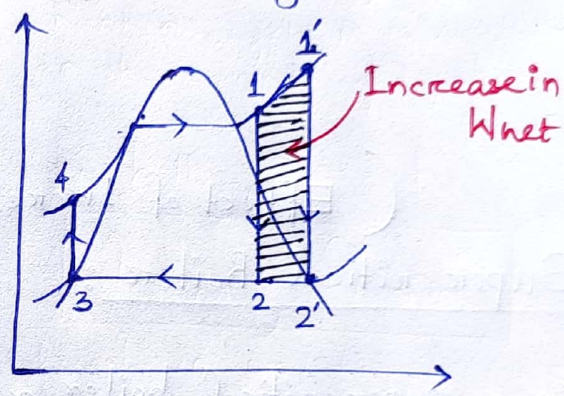
The means to accomplish above objectives are :

① **Lowering the Condenser Pressure :** The lowering of the operating pressure of the condenser automatically lowers the temp. of the steam and thus, the temp. at which heat is rejected decreases. By doing this, the heat input requirement also increases but this increase is small.

* The condensation pressure can not be lowered below the saturation pressure corresponding to the temp. of the cooling medium.



(Increase in Wnet owing to Lowering of the condenser pressure)



(Effect of superheating steam on Rankine Cycle Performance)

② **Superheating the steam to High Temperature :**

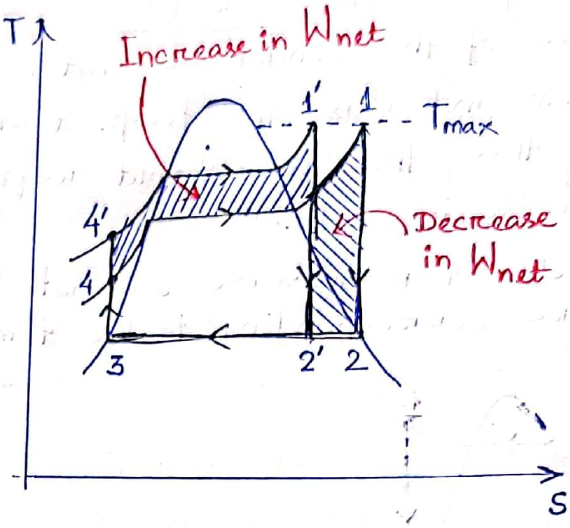
By superheating the steam to high temperatures, the average or mean temp. at which heat is added to the steam increases (i.e., $T_m \uparrow$) without increasing the boiler pressure. The effect of this superheating is to increase the Wnet and hence the cycle efficiency. Though it is advantageous to raise the steam temp. as high as possible by superheating, the maximum temp. is limited by metallurgical considerations (near about 620°c)

* Superheating the steam decreases the moisture content of the steam at the turbine exit.

③ Increasing the Boiler Pressure

An increase in the operating pressure of the boiler automatically raises the temperature at which boiling takes place. This in turn, increases the mean or avg. temp. (T_m) at which heat is added to the steam, which results in an increase in thermal efficiency of the cycle. by increasing W_{net}.

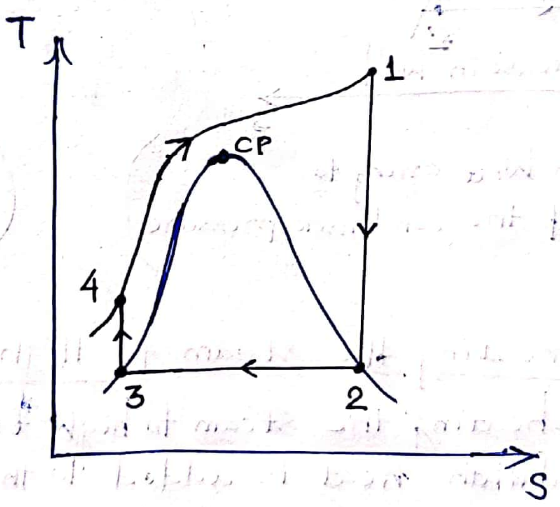
* For a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of the steam at the turbine exit increases. However, this undesirable effect can be corrected by reheating the steam.



(Effect of Increase of boiler pressure on Rankine Cycle performance)

Supercritical Boiler :-

In a supercritical boiler or 'once-through' boiler, steam is generated at a pressure above the critical point of 221.2 bar.



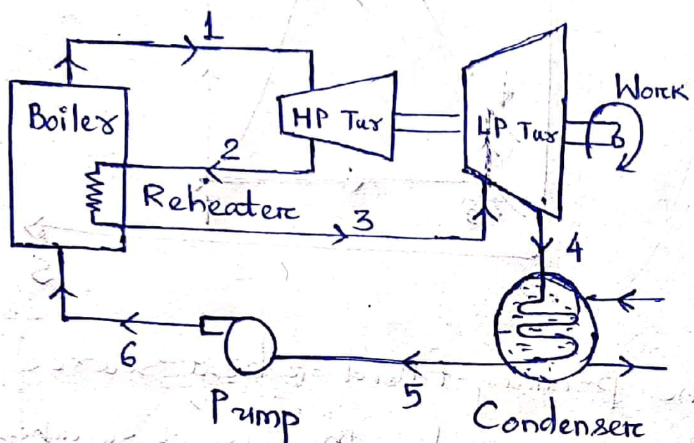
(A Supercritical Rankine Cycle)

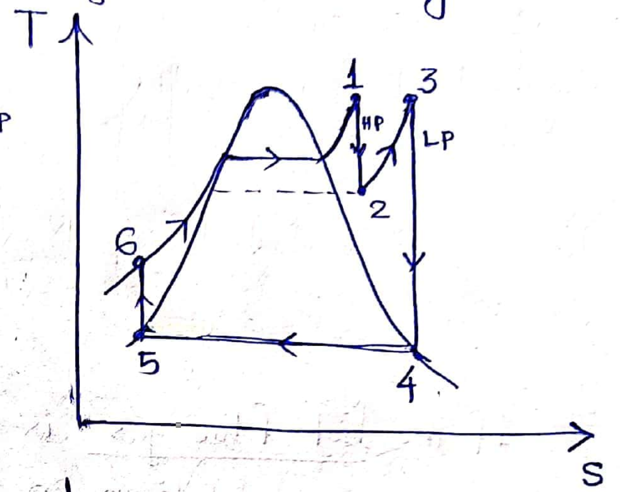
The Reheat Rankine Cycle :

→ Superheating the steam to very high temp.s before it enters the turbine in order to achieve an increase in T_{avg} or T_m at which heat is added to the steam. This will result in an increase in η_{th}.

→ With increase in superheat, the expansion line of steam in the turbine shifts to the right, as a result of which the quality of steam at turbine exit increases and performance of the turbine improves.

The reheat process in the ideal Rankine cycle is done by expanding the steam in the turbine in two stages and reheating it in between HP & LP turbines.





Heat supplied, $Q_S = Q_{Primary} + Q_{Reheat}$

$$= (h_1 - h_6) + (h_3 - h_2), \text{ KJ/kg}$$

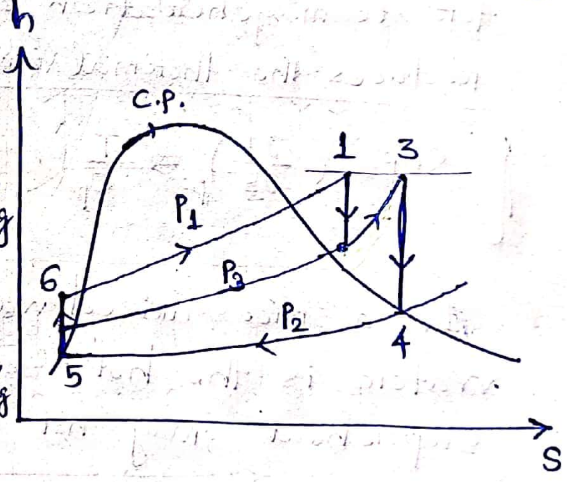
Turbine Work, $W_T = (W_T)_{HP} + (W_T)_{LP}$

$$= (h_1 - h_2) + (h_3 - h_4), \text{ KJ/kg}$$

Pump work, $W_P = h_6 - h_5$, KJ/kg

$\therefore W_{net} = W_T - W_P$

Reheat cycle efficiency, $\eta_{Reheat} = \dfrac{W_{net}}{Q_S}$



Advantages : ① The reheat cycle reduces the moisture content at the exit of the LP turbine and accordingly the erosion and corrosion problems in the turbine are eliminated.

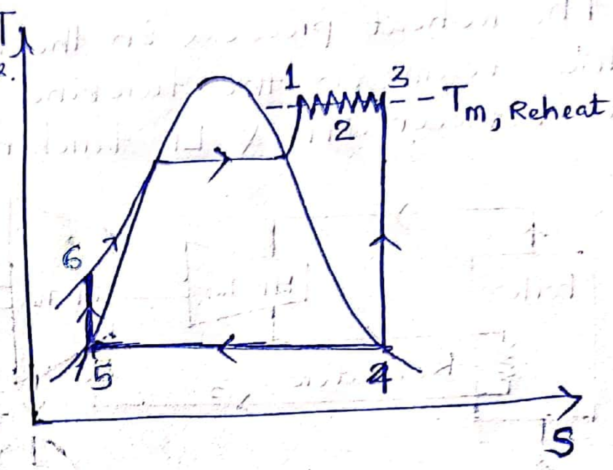
② Reheating increases the work o/p of the turbines and hence the efficiency of the cycle but not significantly.

Disadvantages: ① Reheating requires more maintenance.

② Increase in thermal efficiency is not influenced much by reheating as compared to expenditure incurred in reheating and T_m is not significantly influenced by the reheat process.

As the no. of stages increase, the expansion and reheat processes approaches an isothermal process at the max^m temp.

The optical no. of stages is determined by economical considerations.



If the hot flue gas is the primary fluid or heat source for steam generation in the power cycle, the use of superheat reduces the thermal irreversibility.

[Slope $\left(\frac{\partial T}{\partial s}\right)_P = \frac{T}{C_p}$. Since $(C_p)_{Water} > (C_p)_{Gas}$, therefore $\left(\frac{\partial T}{\partial s}\right)_{gas} > \left(\frac{\partial T}{\partial s}\right)_{Water}$]

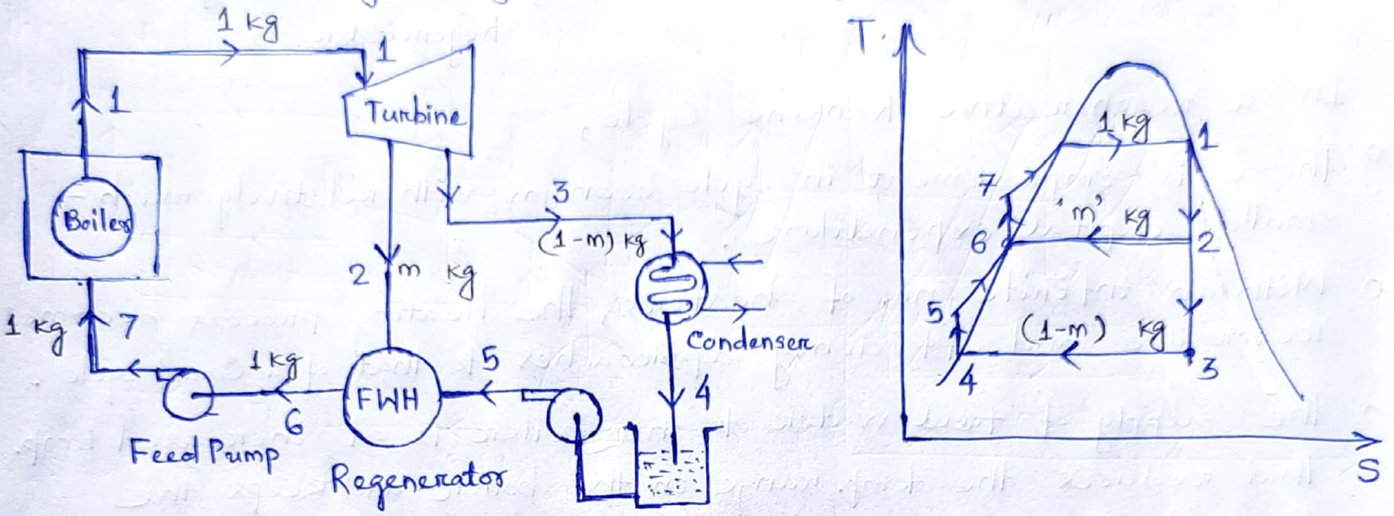
In a pressurised water reactor (PWR), the hot pressurised water is the hot source for steam generation, so the superheat may not be practical for PWR power plant.

Imp Therefore, fossil fuel steam generators as well as gas-cooled and Liquid metal cooled nuclear power plants employ superheat, while PWR power plants do not use superheat.

The Regenerative Rankine Cycle [Regenerative Feedwater Heating]

The mean temp. at which heat is added to the working fluid can be increased by preheating the feed water before it enters the boiler. For this purpose, part of the steam is withdrawn or extracted at some intermediate stage during expansion in the turbine. The rest of the steam expands in the turbine to the condenser pressure. The steam thus extracted is mixed with the feed water coming from the hot well.

Bleeding: The system of extracting steam from any point in the turbine and subsequently using it for heating the feed water is called bleeding.



A practical regeneration process is achieved by extracting or bleeding steam from the turbine at various parts. This steam is used to heat the feedwater. The device where the feedwater is heated is called a regenerator.

* A regenerator is also called a feedwater heater. It is essentially a heat exchanger where heat is transferred from the extracted/bled steam to the feedwater either by mixing or without mixing the two fluid streams.

- without mixing → Closed FWH
- mixing → Open or direct-contact FWH

Heat supplied in the boiler, $Q_s = h_1 - h_7$, kJ/kg

Workdone in the turbine, $W_T = 1(h_1 - h_2) + (1-m)(h_2 - h_3)$, kJ/kg

Work Input to Feed pumps, $W_P = (W_P)_{FP-1} + (W_P)_{FP-2}$

$$= (1-m)v_{f_4}(P_5 - P_4) + 1 \times v_{f_6}(P_7 - P_6)$$

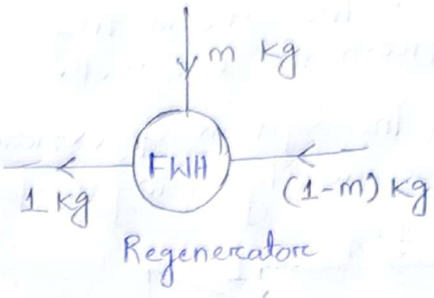
Thermal efficiency of the regenerative cycle, $\eta_{Regenerative} = \frac{W_T - W_P}{Q_S}$

Mass Flow rate of steam :

From energy balance for the FWH / Regenerator,

$$m \cdot h_2 + (1-m) h_{f_3} = h_{f_2}$$

$$\Rightarrow \boxed{m = \frac{h_{f_2} - h_{f_3}}{h_2 - h_{f_3}}}$$



In a regenerative Rankine Cycle,

- There is improvement in cycle economy with relatively much-smaller capital expenditure.
- With an infinite no. of heaters, the heating process becomes reversible and efficiency approaches to that of a Carnot cycle.
- The supply of feed water to the boiler is at increased temp. That reduces the temp. range in the boiler and keeps the thermal stress lower.
- The thermal efficiency of a regenerative cycle is always greater than that of a simple Rankine cycle regardless of where steam is tapped off.
- The regenerator dearates (removes the air that leaks in at the condenser) the feedwater which is necessary to prevent corossion in the boiler.
- The workdone per kg of steam decreases and such large capacity boiler is needed for a given o/p. The system also becomes complicated, less flexible and involves greater maintenance and capital cost due to installation of FWHs.

* Steam rate or specific steam consumption (ssc) increases by regeneration as specific work o/p is Low.

$$\left[\text{as steam rate} = \frac{3600}{W_{net}} \right]$$

Regenerator or Feed Water Heater (FWH) :

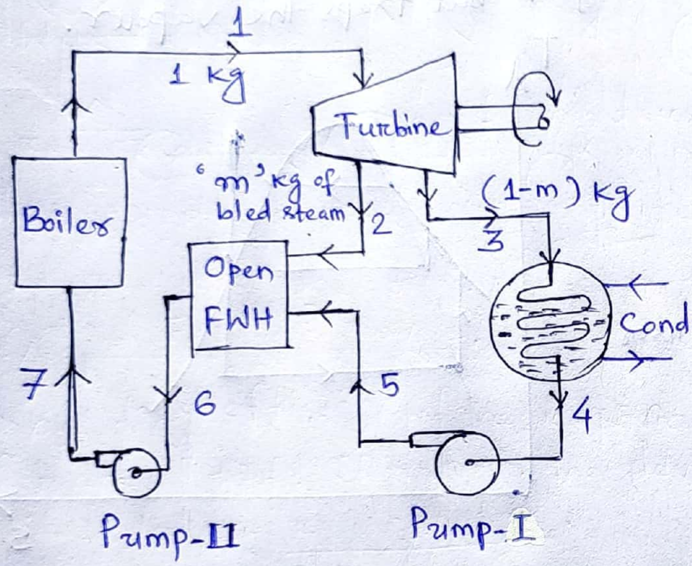
A feed water heater (FWH) or Regenerator is basically a heat exchanger where heat is transferred to the feed water by extracting the partially expanded steam from the turbine to heat the feed water that to be supplied to the boiler for steam generation.

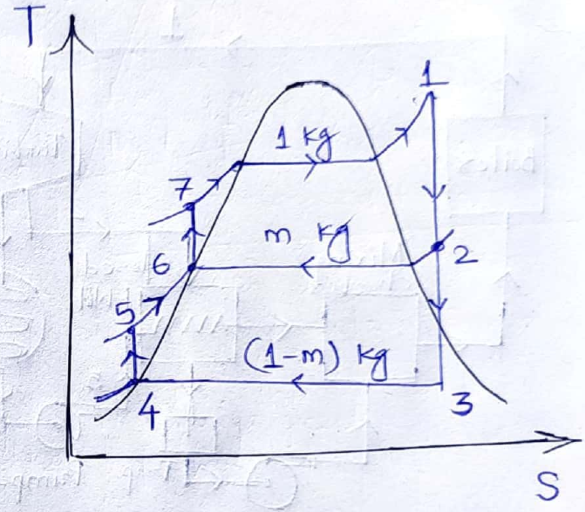
Heating of feedwater can be done in two ways :

- by directly heating/mixing (in a tank) : Open or Contact type FWH
- by indirectly heating (in shell and tube type heat exchangers) : Closed FWH

Open Feed Water Heater :

In an open FWH or contact-type FWH, the extracted or bled stream is allowed to mix with feedwater and both leave the heater at a common temp. and heater pressure in the form of saturated liquid.





(Fig: Open or Contact-type FWH)

Heat supplied in the boiler, $Q_s = h_1 - h_7$, kJ/kg

Heat rejected in the condenser, $Q_R = (1-m)(h_3 - h_4)$, kJ/kg

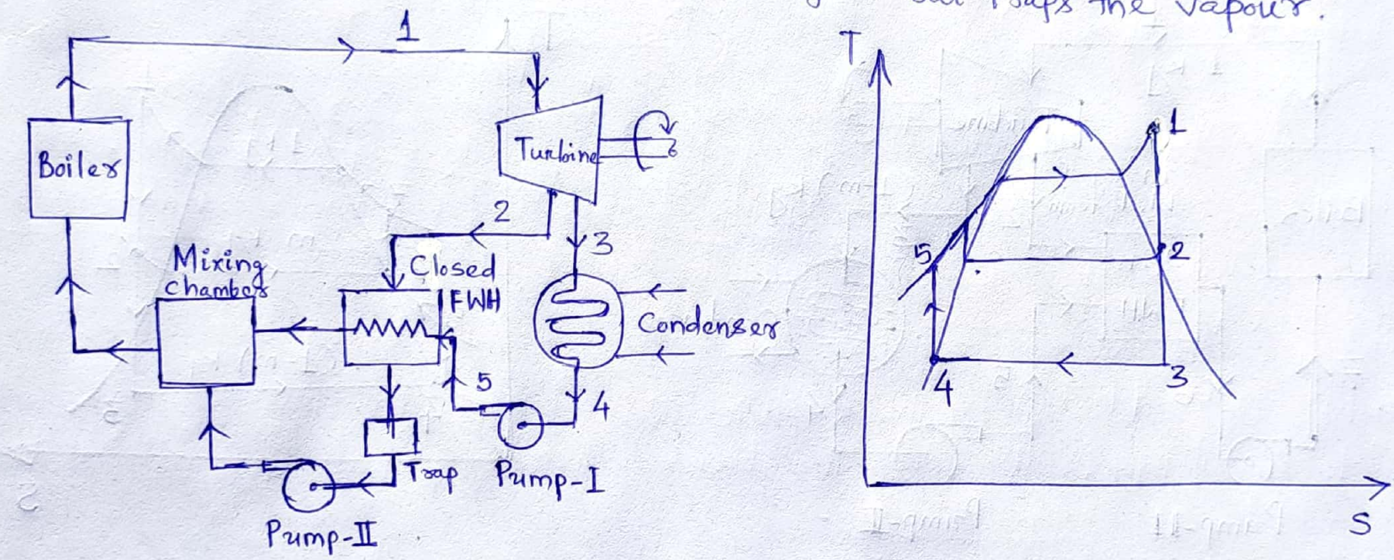
Work o/p from turbine, $W_T = (h_1 - h_2) + (1-m)(h_2 - h_3)$, kJ/kg

Work I/p to pumps, $W_P = (W_P)_I + (W_P)_{II}$

$= (1-m) v_{f_4} (h_5 - h_4) + 1 \times v_{f_6} (h_7 - h_6)$

Closed Feedwater Heater :

In a closed FWH, the fluids are kept in separate and not allowed to mix together. The feedwater flows through tubes in the heater and the extracted steam from the turbine condenses on the outside of the tubes in the shell. The heat released by condensation is transferred to the feedwater through the walls of the tubes. The feedwater is heated to the exit temp. of the extracted steam because temp. difference of at least a few degrees is required for any effective heat transfer to take place. The condensed steam is then pumped to the feedwater line or routed to another heater or to the condenser through a device called a trap, which allows the liquid to be throttled to a lower pressure region but traps the vapour.



(Fig- Regenerative Rankine Cycle with a closed FWH)

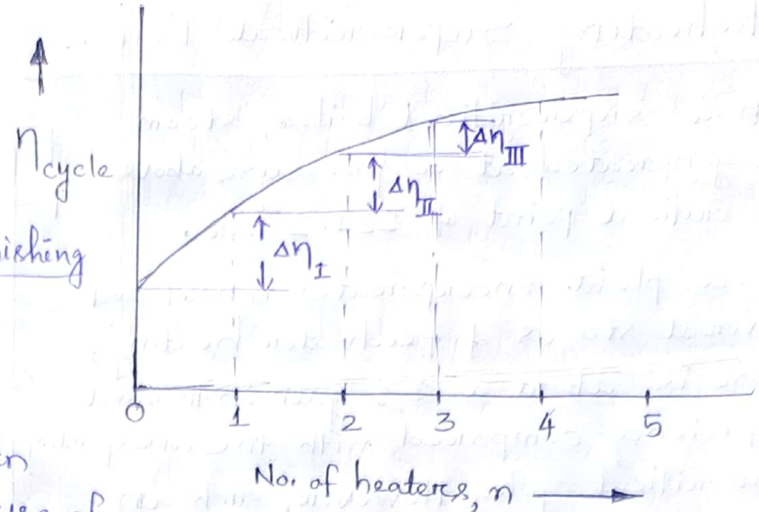
Imp

* As no. of stages of regeneration increases, the efficiency of Rankine cycle (η_{th}) approaches to Carnot because heat addition and rejection at constant temperature.

Thus heating of feedwater by steam 'bled' from the turbine, known as Regeneration, carnotizes the Rankine cycle.

Imp. Points

- Since cycle efficiency is proportional to gain in feedwater temp. $(\Delta t)_{FW}$, the efficiency gain follows the law of diminishing return with the increase in the no. of heaters.



- The greatest increment in efficiency occurs by the use of the first heater. The increments for each additional heater thereafter successively diminish.
- An increase in feedwater temp. $(\Delta t)_{FW}$ may, in some cases, cause a reduction in boiler efficiency.

So, the no. of feedwater heaters gets optimized. Five points of extractions are often used in practice. Some cycle use as many as nine (Maximum).

Comparison of Open and Closed Feedwater Heaters

→ Open FWH are simple, inexpensive and have good heat transfer characteristics. They also bring the feedwater to the saturation state. But a separate pump is required for each heater, to handle the feedwater.

→ Closed FWH are more complex because of internal pumping network, and thus they are expensive. The heat transfer is also less effective since the two streams are not followed to be ~~dir~~ in direct contact.

* To take the best of these systems, most steam power plants use a combination of open FWH and closed FWH.

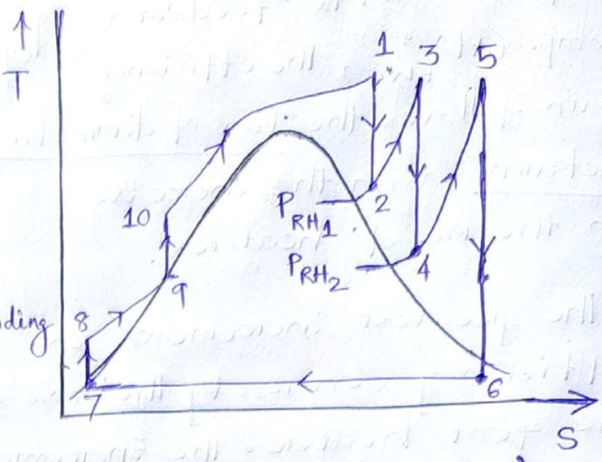
Imp The effects of regenerative feedwater heating for the same turbine output may be summarized as:

1. It significantly increases the cycle efficiency and reduces the heat rate (reducing operating cost).
2. It increases the steam flow rate (requiring bigger boiler)
3. It reduces the steam flow to the condenser (Needing smaller condenser)
4. If there is no change of boiler output, the turbine output drops.

Reheating Supercritical Boiler

In a supercritical boiler, steam is generated at a pressure above the critical point of 221.2 bar.

- If a plant incorporates reheat and several stages of feedwater heating, there is about a 2% gain in thermal efficiency compared with the corresponding subcritical cycle. However, such an increment is gained only at the expense of increased cost and complexity of the plant.



(Fig - Supercritical steam cycle with double reheat.)

- Double reheat needs to be incorporated to prevent the LP exhaust wetness from being excessive.

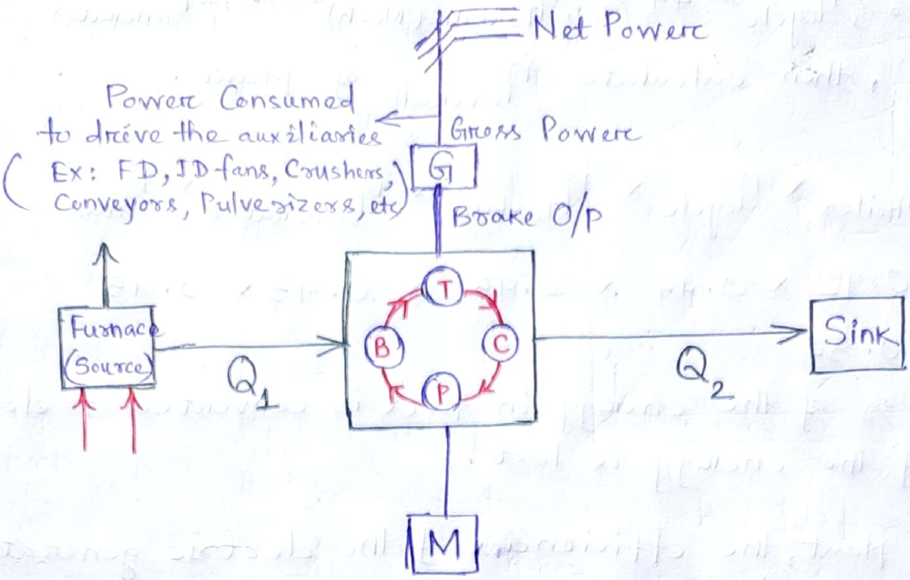
Deaerator :

It is an open-type/contact-type feedwater heater and is used for deaerating the feedwaters.

→ The dissolved gases like oxygen and CO_2 in water are removed by a deaerator (as the presence of these dissolved gases in water ~~decreases~~ makes the water corrosive, as they react with the metal to form Iron Oxide)

→ To neutralize the effect of residual dissolved oxygen and CO_2 gases in water, sodium sulphite (Na_2SO_3) or hydrazine (N_2H_4) is injected in suitable amount into the feedwater at the suction of the boiler feed pump.

Efficiencies In a Steam Power Plant



Boiler Efficiency (or Steam generator efficiency), η_{Boiler}:

$$\eta_{Boiler} = \frac{\text{Rate of energy absorption by water to form steam}}{\text{Rate of energy release by the combustion of fuel}}$$

$$= \frac{\dot{m}_s (h_1 - h_4)}{\dot{m}_f \times CV}$$, $\dot{m}_s$ = steam generation rate, $\dot{m}_f$ = fuel burning rate

Cycle Efficiency, η_{cycle}:

$$\eta_{cycle} = \frac{W_{net}}{Q_1} = \frac{W_T}{Q_1} = \frac{h_1 - h_2}{h_1 - h_4}$$ (Neglecting Pump work as being small)

Mechanical Efficiency of Turbine ($\eta_{Turbine}$):

$$\eta_{Turbine} \text{ or } \eta_{Turbine(Mech)} = \frac{\text{Brake O/P of the turbine}}{\text{Internal O/P of the turbine}} = \frac{\text{brake O/P}}{\dot{m}_s (h_1 - h_2)}$$

Generator Efficiency of Electric Alternator, $\eta_{Generator}$:

$$\eta_{Generator} = \frac{\text{Electrical O/P at generator terminals}}{\text{brake o/p of the turbine}} = \frac{MW \times 10^3}{\text{brake o/p in kW}}$$

Overall Efficiency of Power Plant ($\eta_{overall}$):

$$\eta_{overall} = \frac{\text{Power available at the generator terminals}}{\text{Rate of energy release by the combustion of fuel}} = \frac{MW \times 10^3}{\dot{m}_f \times CV}$$

$$\Rightarrow \boxed{\eta_{overall} = \eta_{Boiler} \times \eta_{cycle} \times \eta_{Turbine} \times \eta_{Generator} \times \eta_{Auxiliary}}$$

Example: Suppose, for a modern steam power plant, $\eta_{Boiler} = 92\%$, $\eta_{cycle} = 44\%$, $\eta_{Turbine(Mech)} = 95\%$, $\eta_{Generator} = 93\%$, $\eta_{Aux} = 95\%$, then calculate $\eta_{overall}$ of plant.

$$\therefore \eta_{overall} = \eta_{Boiler} \times \eta_{cycle} \times \eta_{Turbine} \times \eta_{Generator} \times \eta_{Aux}$$

$$= 0.92 \times 0.44 \times 0.95 \times 0.93 \times 0.95$$

$$= 0.34$$

So, only 34 % of the energy in fuel is converted to electricity and 66 % of the energy is lost.

Q. In a power plant, the efficiencies of the electric generator, turbine (Mechanical), boiler, cycle and the overall plant are 0.97, 0.95, 0.92, 0.42 and 0.33 respectively. What %ge of the total electricity generated is consumed in running the auxiliaries?

Solution: η_{plant} or $\eta_{overall} = \eta_{Boiler} \times \eta_{cycle} \times \eta_{Turbine} \times \eta_{Generator} \times \eta_{Aux}$

$$\Rightarrow 0.33 = 0.92 \times 0.42 \times 0.95 \times 0.97 \times \eta_{Aux}$$

$$\Rightarrow \eta_{Aux} = 0.9268$$

$$\therefore 1 - 0.9268 = 0.0732 \text{ or } 7.32\%$$

or 7.32 % of total electricity generated is consumed by the auxiliaries.

Ans

Cogeneration Plant :

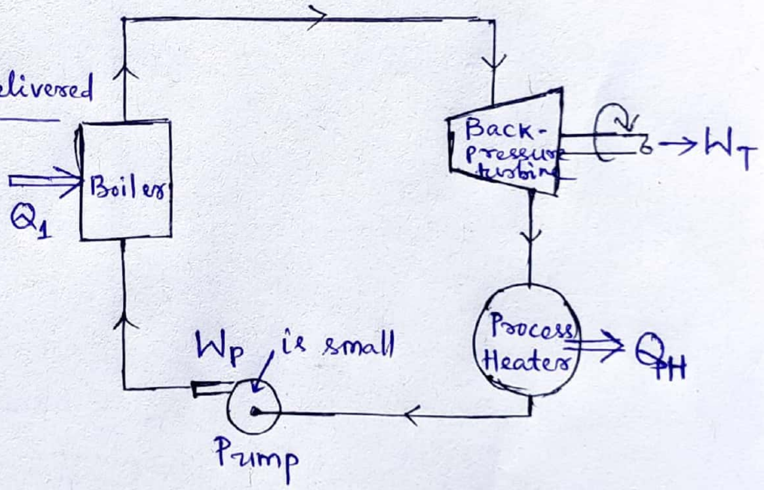
A plant producing both power (or Work O/P) and process heat is known as cogeneration plant.

- There are several industries such as paper mills, textile mills, chemical factories, jute mills, sugar factories, rice mills and so on where saturated steam at the desired temp. is required for heating, drying, etc. and the heat involved in these processes is called 'process heat'. In these industries, process heat is generally supplied by steam at about 5 atm. pressure and 150-200°c temp.
- Apart from the process heat, the plant produces some work o/p or power to drive various machineries, for lighting and for other purposes.
- Cogeneration plant produces more than one useful form of energy (i.e., here, power & process heat) from the same energy source.
- The power cycle in a cogeneration plant can use either a steam-turbine cycle or gas-turbine cycle or even a combined cycle.
- There is no condenser involved in a co-generation plant. So, there is no waste heat needs to be rejected.

Utilisation Factor =

$$= \frac{\text{Net Work O/P} + \text{Process heat delivered}}{\text{Total heat I/P}}$$

$$= \frac{W_{net} + Q_{PH}}{Q_{In}}$$



* In Top cycle cogeneration, high pressure heat is used for power generation and low pressure heat is used for process heating.

In Bottom cycle cogeneration, high pressure heat is used for process heating (glass furnaces) and low pressure heat is used for power generation.

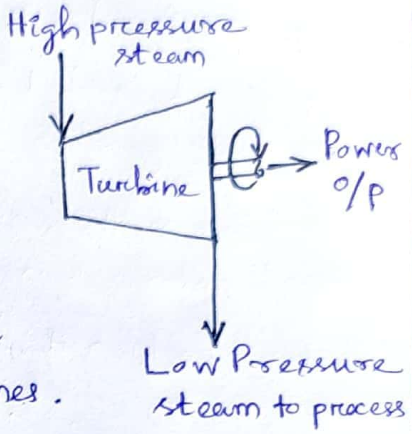
Back Pressure Turbine

Back pressure turbines are those steam turbines where the whole steam from the exit of these turbines is not condensed back into water, rather steam from the exit of turbine is used for other process works.

→ It is generally used in process plants/industrial processes, cogeneration plants or by-product cycles if power o/p is secondary and process heating by steam is primary factor.

→ In these turbines, there will be no condenser.

→ Back pressure steam turbine is also called as non-condensing steam turbine.



- Back pressure turbines are quite small with respect to their power output.
- They are usually single cylinder.
- They are inexpensive as compared to condensing steam turbines.
- It requires very less or no cooling water.
- Its efficiency is higher as it does not reject heat in the condensing process.

* The bigest disadvantage of this type of steam turbine is that it is highly inflexible. The o/p of the turbine can not be regulated as it does not allow changing the pressure and temp. of steam in the turbine. Therefore, it works best with the constant load.

\# Besides the use of back pressure turbines in process-industries and petrochemical installations, these are used for desalination of sea water, district heating and also for driving compressors and feed pumps.

Binary Vapour Cycle

In the binary (or two-fluid) cycle, two cycles with different working fluids are coupled in series, the heat rejected by one being utilized in the other.

* Although in the overall evaluation water is better than any other working fluid, however, in the high temp. range, there are a few better fluids and notable among them are

(a) diphenyl ether $(C_6H_5)_2O$

(b) aluminium bromide (Al_2Br_6)

(c) Mercury

(d) other liquid metal such as sodium potassium

* Mercury is a better fluid in the high temp range, because at high temp., its vapourisation pressure is relatively low.

But in the low temp range, Mercury is unsuitable, because its saturation pressure becomes exceedingly low and it would be impractical to maintain such a high vacuum in the condenser

Mercury - Steam Binary Cycle

→ In this type of binary vapour cycle, Mercury is used as a working substance in topping cycle whereas water is used for the bottoming cycle.

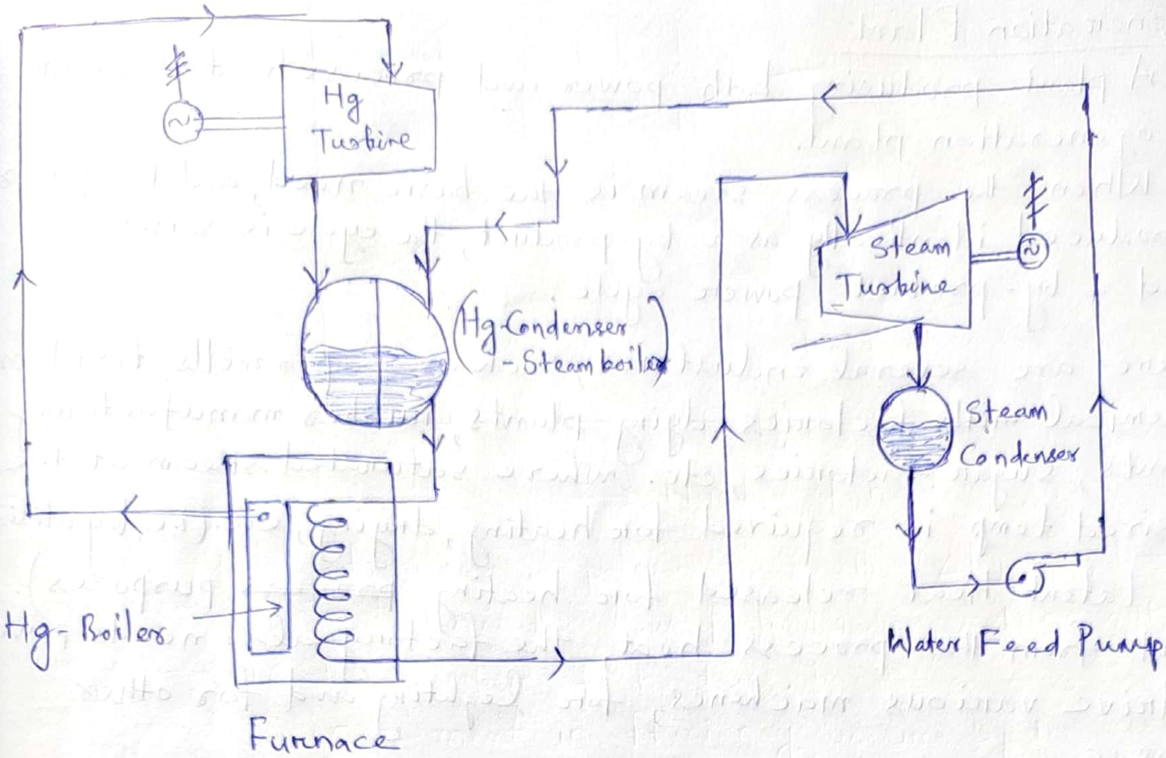
→ At 30°c, the saturation pressure of Mercury is only 2.7×10^{-4} cm Hg. So, in the low temp. range, mercury is unsuitable, because its saturation pressure becomes exceedingly low and there would be a high vacuum in the condenser.

For above reason, Mercury vapour leaving the Mercury turbine is ~~considered as~~ condensed at a higher temp, and the heat released during the condensation of Mercury is utilized in evaporating water to form steam to operate on a conventional turbine.

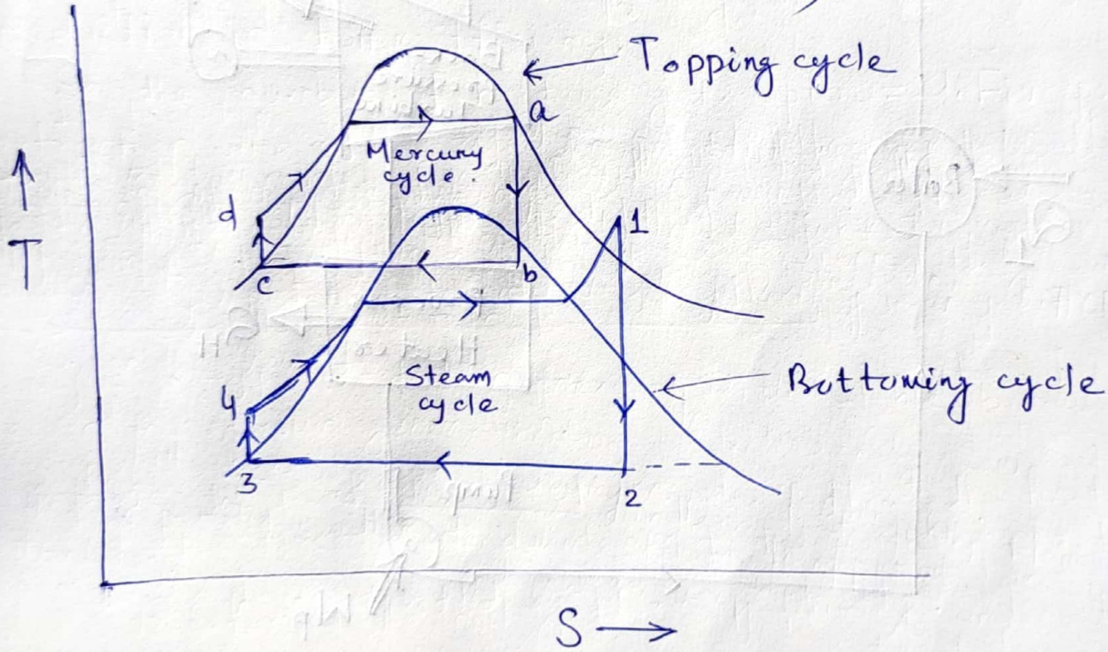
→ The heat rejected by Mercury during condensation is transferred to boil water and form saturated vapour.

→ The saturated vapour is heated by external source (furnace) in the superheater.

→ Superheated steam expands in the turbine and is then condensed and the condensate (feed water) is then pumped.



(Fig- Mercury-Steam Binary Cycle)



Efficiency of Binary Cycle

η_1 = efficiency of topping cycle

η_2 = efficiency of bottoming cycle

$$\eta_{overall} = 1 - (1-\eta_1)(1-\eta_2)$$
$$= \eta_1 + \eta_2 - \eta_1 \eta_2$$

Important Obj. Type Questions

Q.1. In Rankine cycle, regeneration results in higher efficiency because

(a) pressure inside the boiler increases

(b) heat is added before stream enters the Low pressure turbine

(c) average temperature of heat addition in the boiler increases.

(d) total work delivered by the turbine increases

Ans: c

Q.2. Reheat cycle in steam power plant is used to

(a) prevent excess of 10-20% moisture content in last stages of turbine.

(b) utilise heat of flue gas

(c) increase plant efficiency

(d) improve condenser performance

Ans: a

Q.3. The ideal cycle of steam power plant is the Rankine cycle instead of Carnot cycle because

a) the Rankine cycle has higher efficiency

b) the Rankine cycle efficiency is equal to Carnot cycle efficiency

c) the Rankine cycle has higher work ratio so it is easier to implement.

Ans: b

Q.4. Which one of the following cycle working within same temperature limits has the highest work ratio?

a) Carnot cycle
b) Joule cycle
c) Otto cycle
d) Rankine cycle

Ans: d

Q.5. Which combination of the following statements is correct?

The incorporation of reheater in a steam power plant:

1. always increases the thermal efficiency of the plant
2. always increases the dryness fraction of steam at condenser inlet
3. always increases the mean temp. of heat addition.
4. always increases the specific work output

a) 1 and 4
b) 2 and 4
c) 1, 3 and 4
d) 1, 2, 3 and 4

Ans: (b)

Q.6. Two vapour power cycle having cycle efficiencies 0.50 and 0.40 are coupled in series, then the efficiency of the coupled cycle will be

(a) 0.60 (b) 0.70 (c) 0.65 (d) 0.75

Soln: $\eta_{coupled} = \eta_1 + \eta_2 - \eta_1 \cdot \eta_2$

$= 0.50 + 0.40 - 0.50 \times 0.40$

$= 0.70$

Ans: (b)

Q.7. If power developed by a turbine in a certain steam power-plant is 1200 kW. Heat supplied to the boiler is 3360 KJ/kg. The heat rejected by the steam to cooling tower is 2520 KJ/kg. and feed pump work required to condensate back into boiler-pressure is 6 kW, then the mass rate of flow through the cycle is

a) 1.421 kg/s b) 14.21 kg/s

c) 0.1421 kg/s d) 0.01421 kg/s

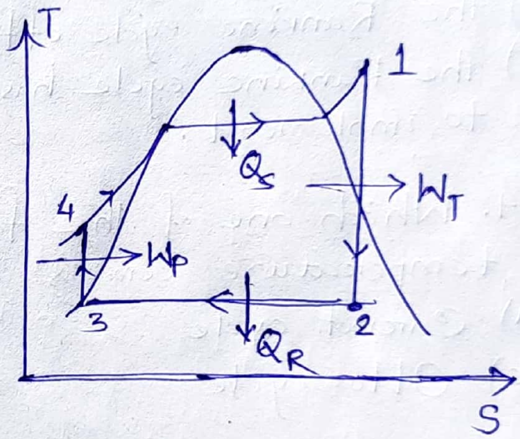
Soln: from 1st law of thermodynamic,

$W_{net} = \dot{m}(Q_s - Q_R)$

$\Rightarrow W_T - W_P = \dot{m}(3360 - 2520)$

$\Rightarrow 1200 - 6 = \dot{m} \times 840$

$\Rightarrow \dot{m} = \frac{1144}{840} = 1.421$ kg/s



Ans: (a)

Q.8. An electric power plant produces 10 MW of power, consuming 90×10^6 KJ/hr of fuel energy. The heat rejected by the power plant is

(a) 5 MW (b) 10 MW (c) 15 MW (d) 20 MW

Soln: Assuming no other losses,

Net power o/p = Heat supplied − Heat rejected

$\Rightarrow 10 \times 10^6 = \left(\frac{90 \times 10^6}{3600}\right) - Q_R$

$\Rightarrow Q_R = 15000$ kW or 15 MW

Ans: (C)

Q.9. Statement-1 : The higher the mean temp. of heat addition, the higher will be the cycle efficiency.

Statement-2 : The maximum temp. of steam that can be used is fixed from metallurgical considerations.

Ans: Both the statements 1 & 2 are TRUE.

Q.10. Assertion(A) : Thermal efficiency of a Rankine cycle using superheated steam is greater than the thermal efficiency of a corresponding Rankine cycle using steam without superheat, when both the cycles operate betn the same boiling and condensation pressure limits.

Reason(R) : Superheating increases the average temperature at which heat is supplied and accordingly the cycle efficiency improves.

Ans: Both A and R are TRUE and R is the correct explanation of A.

Q.11. The effect of turbine and pump efficiencies is to decrease the work ratio and thermal efficiency and to increase the specific steam consumption (SSC). (T/F)

Ans: TRUE

Q.12. Statement-1 : There is a considerable improvement in cycle efficiency with decrease of condenser pressure.

Statement-2 : A lower cooling water temp. gives lower condenser pressure and higher vacuum.

Ans: Both statement-1 & 2 are TRUE and statement-2 is the CORRECT explanation of statement-1.

Q.13. An ideal regenerative cycle for a steam power plant is not practicable because,

a) reversible heat transfer can not be realized in finite time.

b) heat exchanger in the turbine is mechanically impracticable

c) the moisture content of the steam in the turbine is high, which leads to excessive erosion of turbine blades.

d) All the above.

Ans: (d)

Example 2.1 Steam at 40 bar, 500 °C flowing at the rate of 5500 kg/h expands in a h.p. turbine to 2 bar with an isentropic efficiency of 83%. A continuous supply of steam at 2 bar, 0.87 quality and a flow rate of 2700 kg/h is available from a geothermal energy source. This steam is mixed adiabatically with the h.p. turbine exhaust steam and the combined flow then expands in a l.p. turbine to 0.1 bar with an isentropic efficiency of 78%. Determine the power output and the thermal efficiency of the plant. Assume that 5500 kg/h of steam is generated in the boiler at 40 bar, 500 °C from the saturated feedwater at 0.1 bar.

Had the geothermal steam not been added, what would have been the power output and efficiency of the plant? Neglect pump work.

Solution With reference to Fig. E2.1

$$h_1 = 3445.3 \text{ kJ/kg}, s_1 = 7.0901 \text{ kJ/kg } K = 1.5301 + x_{2s} \times 5.5970$$

$$x_{2s} = \frac{5.5600}{5.5970} = 0.9934$$

$$h_{2s} = 504.7 + 0.9934 \times 2201.9 = 2692.04 \text{ kJ/kg K}$$

$$h_1 - h_2 = 0.83(3445.3 - 2692.04) = 625.21 \text{ kJ/kg}$$

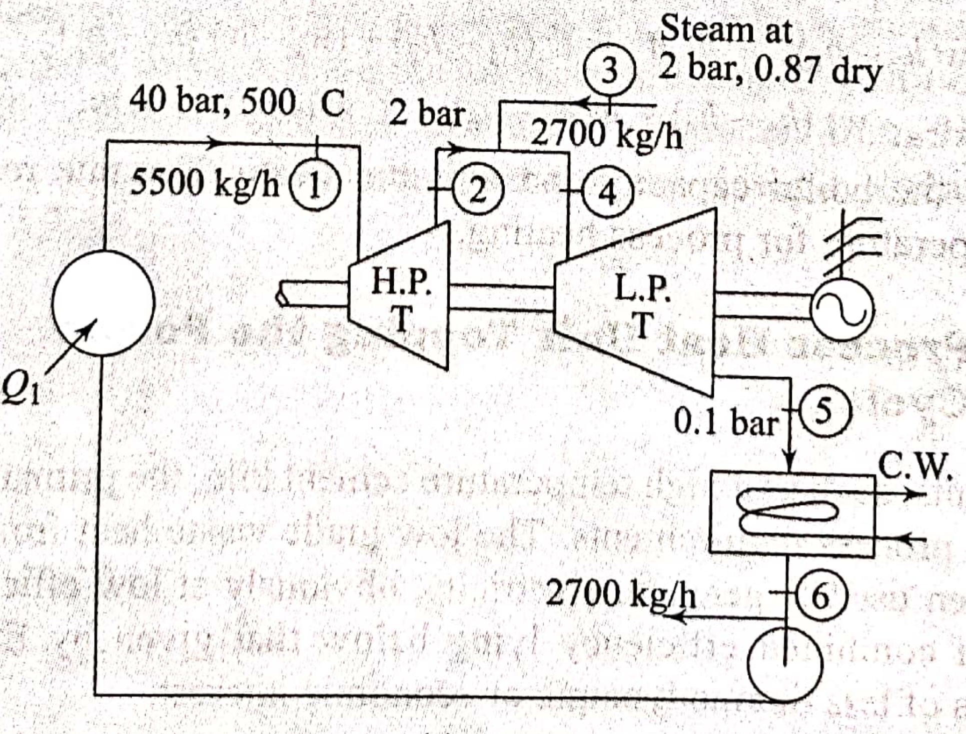
$$h_2 = 3445.3 - 625.21 = 2820.09 \text{ kJ/kg}$$

$$h_3 = 504.7 + 0.87 \times 2201.9 = 2420.4 \text{ kJ/kg}$$

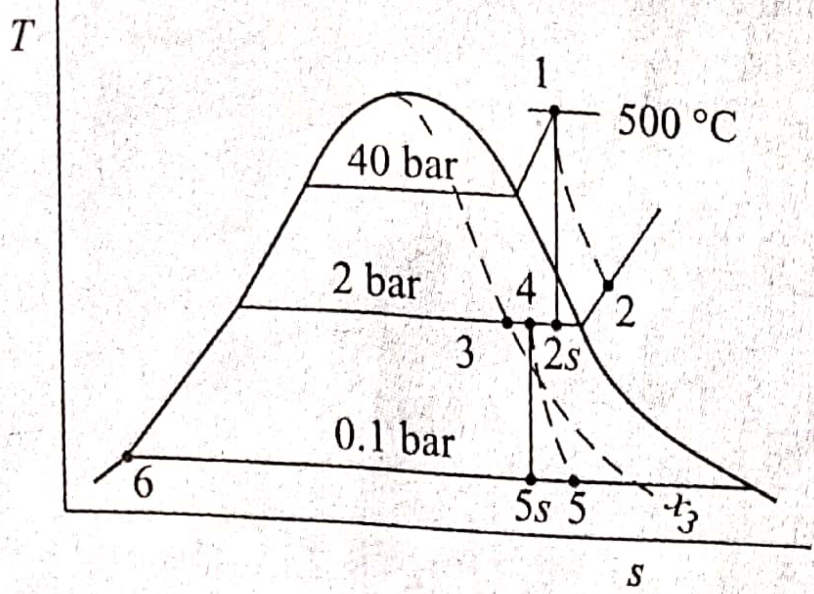
$$2700h_3 + 5500h_2 = (2700 + 5500)h_4$$

$$h_4 = \frac{2700 \times 2420.4 + 5500 \times 2820.09}{8200} = 796.96 + 1891.52$$

$$= 2688.48 \text{ kJ/kg}$$



(a)



(b)

Fig. E2.1

$$h_4 = 504.7 + x_4 \times 2201.9 = 2688.48;\ x_4 = \frac{2183.78}{2201.9} = 0.9917$$

$$s_4 = 1.5301 + 0.9917 \times 5.5970 = 7.0806 \text{ kJ/kg–K}$$

$$= s_{5s} = 0.6493 + x_{5s} \times 7.5009$$

$$x_{5s} = 0.8574; \quad h_{5s} = 191.84 + 0.8574 \times 2392.8 = 2243.44 \text{ kJ/kg}$$

$$h_4 - h_5 = 0.78(2688.48 - 2243.44) = 347.1 \text{ kJ/kg}$$

$$h_6 = 191.83 \text{ kJ/kg}$$

$$\dot{W} = 5500(h_1 - h_2) + 8200\,(h_4 - h_5) = 5500 \times 625.21 + 8200 \times 347.1$$

$$= 6284875 \text{ kJ/h} = 1745.8 \text{ kW} \qquad (Ans.)$$

$$Q_1 = 5500(h_1 - h_6) = 5500\,(3445.3 - 191.8) \times \frac{1}{3600} = 4970.63 \text{ kW}$$

$$\eta_{cycle} = \frac{1745.8}{4970.63} = 0.353 \quad \text{or} \quad 35.3\%$$

Without geothermal heat supply:

$$W_T = 5500\,(h_1 - h_2) = 955.18 \text{ kW} \qquad (Ans.)$$

$$Q_1 = 5500\,(h_1 - h_6) = 4970.63 \text{ kW}$$

$$\eta_{cycle} = \frac{955.18}{4970.63} = 0.1922 \quad \text{or} \quad 19.22\% \qquad (Ans.)$$

Eample 2.8 In a cogeneration plant, the power load is 5.6 MW and the heating load is 1.163 MW. Steam is generated at 40 bar and 500 °C and is expanded isentropically through a turbine to a condenser at 0.06 bar. The heating load is supplied by extracting steam from the turbine at 2 bar, which condensed in the process heater to saturated liquid at 2 bar and then pumped back to the boiler. Compute (a) the steam generation capacity of the boiler in t/h, (b) the heat input to the boiler in kW, (c) the fuel burning rate of the boiler in t/h if a coal of calorific value 25 MJ/kg is burned and the boiler efficiency is 88%, (d) the heat rejected to the condenser, (e) the rate of flow of cooling water in the condenser if the temperature rise of water is 6°C. Neglect pump work.

Solution With reference to Fig. E2.8,

$$h_1 = 3445.3 \text{ kJ/kg}, \quad s_1 = 7.0901 = s_2 = s_3$$

$$7.0901 = 1.5301 + x_2 \times 5.5970 \quad \text{or} \quad x_2 = \frac{5.56}{5.597} = 1.0$$

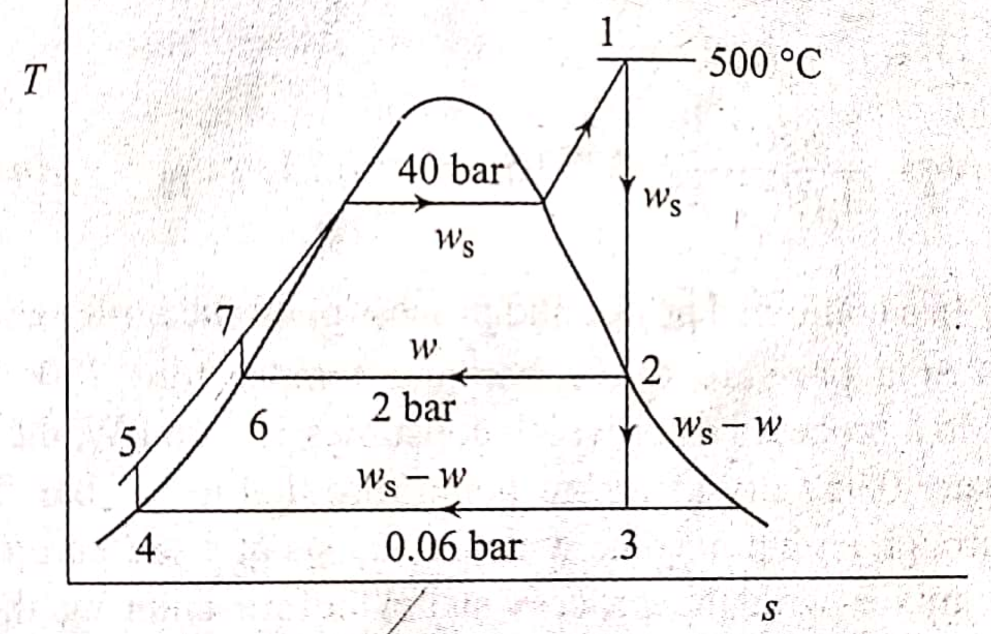


Fig. E2.8

$$\therefore \quad h_2 = h_g = 2706.7 \text{ kJ/kg}, \; h_2 - h_6 = h_{fg} = 2201.9 \text{ kJ/kg}$$

If w is the rate of steam extraction for process heating,

$$w(h_2 - h_6) = 1.163 \times 10^3$$

$$w = \frac{1.163 \times 10^3}{2201.9} = 0.528 \text{ kg/s} = 1901.4 \text{ kg/h}$$

$$s_1 = 7.0901 = s_f + x_3 s_{fg} = 0.52 + x_3 \times 7.815$$

$$x_3 = 0.84$$

$$h_3 = 149.79 + 0.84 \times 2416 = 2180.59 \text{ kJ/kg}$$

Total work output, $W_T = w_s(h_1 - h_2) + (w_s - w)(h_2 - h_3)$

$$5.6 \times 10^3 = w_s \times 738.6 + w_s \times 526.11 - 277.8$$

$$w_s = \frac{5877.8}{1264.7} = 4.648 \text{ kg/s} = 16731 \text{ kg/h} = 16.73 \text{ t/h} \quad \textit{Ans.}\text{(a)}$$

$$h_7 = 504.7 + 1.061 \times 10^{-3}(40 - 2) \times 100 = 508.73 \text{ kJ/kg}$$

$$h_5 = 149.79 + 1.006 \times 100 \times 40 \times 10^{-3} = 153.8 \text{ kJ/kg}$$

$$Q_1 = (w_s - w)(h_1 - h_5) + w(h_1 - h_7)$$

$$= (4.648 - 0.528)(3445.3 - 153.8) + 0.528(3445.3 - 508.73)$$

$$= 4.120 \times 3291.5 + 0.528 \times 2936.57 = 15111.5 \text{ kJ/s}$$

$$= 15.111 \text{ MW} \quad \textit{Ans.}\text{(b)}$$

$$h_{boiler} = \frac{Q_1}{w_f \times \text{C.V.}} = \frac{15.111}{w_f \times 25} = 0.88$$

$$w_f = 0.687 \text{ kg/s} = 2473.2 \text{ kg/h} = 2.473 \text{ t/h} \quad \textit{Ans.}\text{(c)}$$

$$Q_2 = (w_s - w)(h_3 - h_4) = 4.12 \times 2030.8 = 8367 \text{ kW}$$

$$= 8.367 \text{ MW} \quad \textit{Ans.}\text{ (d)}$$

If w_c = water flow rate in the condenser,

$$Q_2 = w_c c_p(t_2 - t_1)$$

$$\therefore \quad w_c = \frac{8367}{4.187 \times 6} = 333.05 \text{ kg/s} = 0.333 \text{ m}^3\text{/s} \quad \textit{Ans.}\text{ (e)}$$