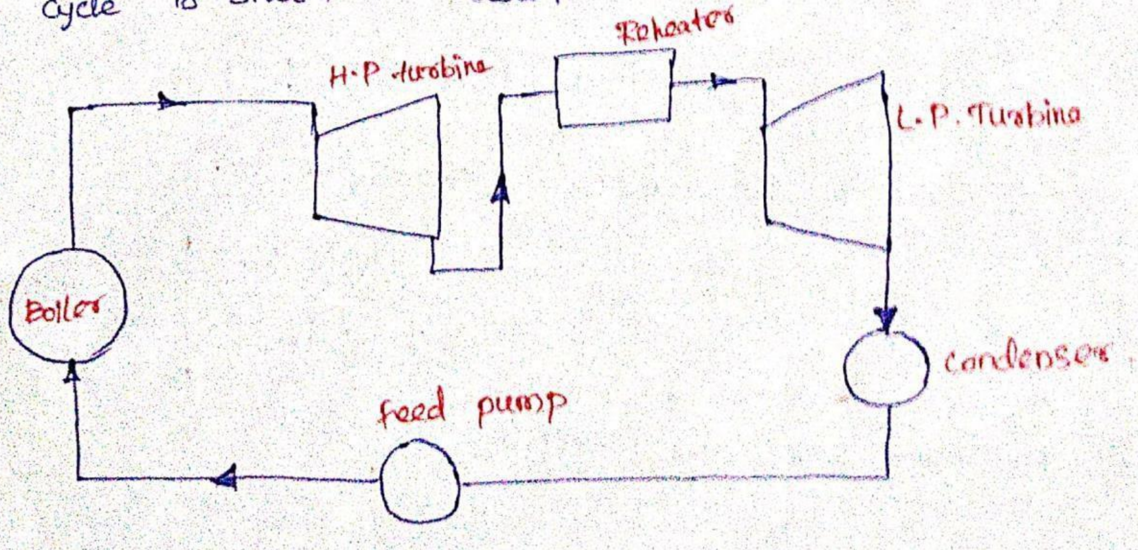
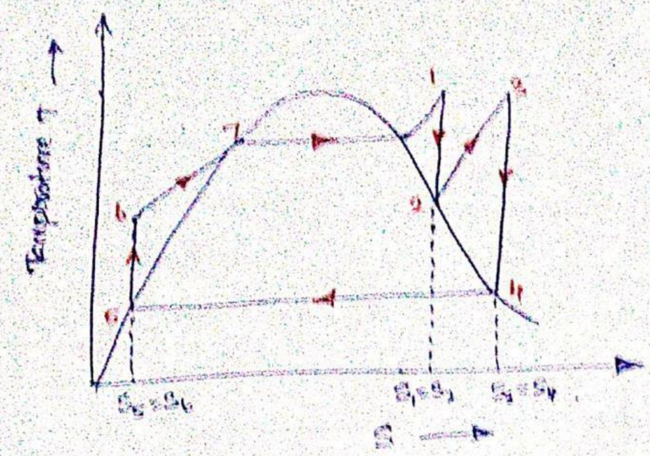
Reheat Rankine cycle :-

It is desirable to increase the average temperature and pressure of the steam at which the heat is supplied to it and also to keep the steam as dry as possible at the end of the turbine. If the pressure increases, the expansion ratio in the turbine will also be increased and the steam becomes wet at the end of expansion. Increasing the moisture of the steam will cause the erosion of the turbine blades and also increase the losses.

In reheat cycle, the expansion is being carried out in two stages. The steam is initially expanded in H.P turbine to some pressure and then it is reheated with the help of flue gases in the boiler. Then the steam is expanded in L.P turbine to the condenser pressure. The main purpose of reheating is to increase the dryness fraction of the steam passing through turbine should never fall below 0.8. The thermal efficiency is increased with reheat cycle and also the specific steam consumption is decreased. But, the thermal efficiency of the reheat cycle may be decreased, if it is used at low pressures. T-s diagram for reheat cycle is shown in below.





The process 1-2 represent isentropic expansion in high-pressure turbine, and 3-4 represent isentropic expansion in low-pressure turbine. The steam is reheated at constant pressure 2-3. The reheat can be carried out by returning the steam to the boiler and passing it through a heat exchanger placed in the boiler at constant pressure.

Heat supplied, $Q_s = Q_{s_{1-6}} + Q_{s_{2-3}}$

$$= (h_1 - h_6) + (h_3 - h_2)$$

Work output $W = W_{1-2} + W_{3-4} - W_P$.

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

∴ The efficiency of the reheat rankine cycle is:

$$\eta_{reheat} = \frac{(h_1 - h_2) + (h_3 - h_4) - W_P}{h_1 - (h_{f_4} - W_P) + (h_3 - h_2)}$$

∴ $W_P = V_{f_4}(P_1 - P_4)$

If the pump work is neglected.

$$\eta = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f_4}) + (h_3 - h_2)}$$

where, h_1 = enthalpy of super heated steam $= h_g + C_{pg}(T_{sup} - T_{sat})$

h_2 = enthalpy of steam at intermediate pressure P_2.

Note:-

The steam at this stage may be super heated, wet & dry, it is found by comparing s_1 & s_2.

$s_2 = s_1 \Rightarrow$ Dry, $h_2 = h_{g_2}$.

$s_2 < s_1 \Rightarrow$ Superheated, $h_2 = h_{g_2} + C_{p_g}(T_{sup} - T_{sat})$

$s_2 > s_1 \Rightarrow$ Wet, $h_2 = h_{f_2} + x_2 h_{fg_2}$.

$h_3 \Rightarrow$ enthalpy of superheated steam at pressure $P_3 = P_2$.

$h_4 \Rightarrow$ enthalpy of steam at pressure P_4 i.e. condenser pressure

$h_6 \Rightarrow$ enthalpy of steam at pump outlet.

$h_6 = h_5 + W_p$.

$W_p = (P_6 - P_5) \times V_5$. $\therefore P_1 = P_6$.

$W_p = (P_1 - P_4) \times V_{f_4}$. $P_4 = P_5$.

Problem:-

(1) Consider a steam power plant operating on an ideal reheat Rankine cycle. The steam enters the H.P turbine at 30 bar and 350°c. After expansion to 5 bar, the steam is reheated to 350°c and then expanded the L.P turbine to the condenser pressure of 0.075 bar. Determine the thermal efficiency of the cycle and the quality of the steam at the outlet of the L.P turbine

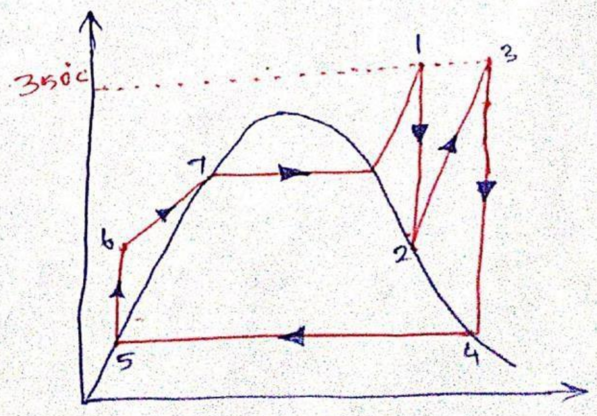
Given:-

$P_1 = 30$ bar

$T_1 = 350°C$

$P_2 = 5$ bar.

$P_3 = 0.075$ bar.



To find:-

i) Thermal efficiency of cycle.

ii) Quality of the steam at the outlet of L.P turbine.

Solution :-

i) Thermal efficiency of cycle :-

$$\eta_{RE} = \frac{(h_1 - h_2) + (h_3 - h_4) - W_P}{h_1 - (h_5 + W_P) + (h_3 - h_2)}$$

To find h_1,

at $P_1 = 30$ bar $T = 350°c$.

$h_1 = 3117.5$ KJ/kg. $S_1 = 6.747$ kg/kg.k.

To find h_2

Find the steam condition with the help of S_1 & $S_2 \Rightarrow S_1 = S_2$.

at 5 bar. $S_2 = S_{g_2} = 6.819$ KJ/kg.

S_2 & $S_{g_2} > S_1$, so the steam is in wet condition.

$\therefore h_2 = h_{f_2} + x_2 h_{fg_2}$.

@ 5 bar.

$S_1 = S_2 = S_{f_2} + x_2 S_{fg_2}$.

$6.747 = 1.860 + x_2 (4.959)$

$\boxed{x_2 = 0.98}$

@ 5 bar,

$h_{f_2} = 640.1$ KJ/kg.

$h_{fg_2} = 2107.4$ KJ/kg.

$h_2 = 640.1 + (0.98)(2107.4)$

$h_2 = 2705.35$ KJ/kg.

To find h_3.

The stage 3 is in Superheated condition.

So, $P_3 = 5$ bar $T_1 = 350°c$.

$h_3 = 3168.1$ KJ/kg. $S_3 = 7.634$ KJ/kg K

To find h_4

At the end of stage 4, the steam will be in wet steam condition.

$$h_{4} = h_{f4} + x_4 h_{fg4}.$$

To find x_4 $\quad S_3 = S_4$.

$$S_3 = S_4 = S_{f4} + x_4 S_{fg4}.$$

At $P_4 = 0.075$ bar.

$S_{f4} = 0.576$ KJ/kg.K, $h_{f4} = 168.65$ KJ/kg.

$S_{fg4} = 7.677$ KJ/kg.K, $h_{fg4} = 2406.2$ KJ/kg.

$$S_4 = S_{f4} + x_4 S_{fg4}.$$

$$7.634 = 0.576 + x_4 (7.677)$$

$$\boxed{x_4 = 0.919}$$

$$h_4 = h_{f4} + x_4 h_{fg4}.$$

$$= 168.65 + 0.919 (2406.2)$$

$$h_4 = 2379.94 \text{ KJ/kg}.$$

$$h_5 = h_{f4} = 168.65 \text{ KJ/kg}.$$

$$W_P = V_{f4} (P_1 - P_4)$$

@ $P_4 = 0.075$.

$$V_{f4} = 0.0010075$$

$$W_P = 0.0010075 (30 - 0.075)$$

$$=$$

$$\eta_{RE} = \frac{(h_1 - h_2) + (h_3 - h_4) - W_P}{h_1 - (h_{f4} + W_P) + (h_3 - h_2)}.$$

$$= \frac{(3117.5 - 2705.35) + (3168.1 - 2379.94) - 3.0149}{3117.5 - (168.65 + 3.0149) + (3168.1 - 2705.35)}$$

$$= \frac{412.15 + 788.16 - 3.0149}{3117.5 - 171.6649 + 462.75}.$$

$$\eta_{RE} = \frac{1197.29}{2483.08} = 0.48.$$

$$\boxed{\eta_{R.E} = 48\ \%}$$

Result :-

i) Thermal efficiency of the cycle $\eta_{RE} = 48\ \%$.

ii) Quality of the steam at L.P turbine $x_4 = 0.919$.

(2) In the reheat cycle the steam is at $6\ MN/m^2$ and $450°c$. The first reheat is done at $1\ MN/m^2$ to $370°c$. The second reheat is done at $0.2\ MN/m^2$ to $320°c$. The exhaust pressure is $0.02\ MN/m^2$. Determine the thermal efficiency and power developed at a steam rate of 1 kg/s.

Given :-

$P_1 = 6\ MN/m^2 = 60$ bar

$P_2 = 1\ MN/m^2 = 10$ bar.

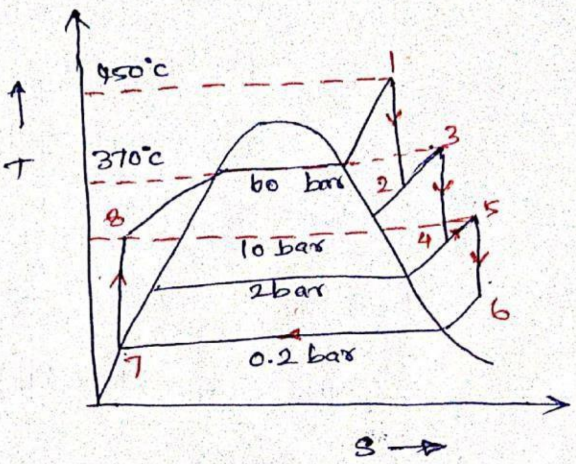
$P_4 = 0.2\ MN/m^2 = 2$ bar

$P_6 = 0.02\ MN/m^2 = 0.2$ bar.

$T_1 = 450°c$

$T_3 = 370°c$

$T_5 = 320°c$, $m_s = 1$ kg/s.



To find :-

i) Thermal efficiency (η)

ii) Power developed (P).

Solution :-

At 60 bar and 450°C.

$h_1 = 3301.15$ kJ/kg.

$s_1 = 6.714$ kJ/kg·k.

To find h_2.

Find the state of steam.

$S_1 = S_2 = 6.714$ kJ/kg.

At 10 bar,
$S_{g_2} = 6.583$ KJ/kg.

$S_2 > S_{g_2}$ (The steam is Super heated)

$T_2 = 205°c$ By using mollier chart.

$h_2 = 2830$ KJ/kg.

To find h_3:-

At 10 bar, $T_3 = 370°c$.

$h_3 = 3200.86$ KJ/kg.

$S_3 = 7.3686$ KJ/kg.k

To find h_4.

Find the state of steam.

$S_3 = S_4 = 7.3686$ KJ/kg.k.

At 2 bar. $S_{g_4} = 7.127$ KJ/kg k.

$S_4 > S_{g_4}$ (The steam is in superheated condition)

$T_4 = 170°c$ (By using mollier chart)

$h_4 = 2800$ KJ/kg.

To find h_5.

At 2 bar, $T_5 = 320°c$.

$h_5 = 3112.78$ KJ/kg $S_5 = 7.962$ KJ/kg.k

To find h_6.

Find the state of steam.

$S_5 = S_6 = 7.962$ KJ/kg.K

At 0.2 bar, $S_{g_6} = 7.909$ KJ/kg.k.

$S_6 > S_{g_6}$ (The steam state is superheated)

$T_6 = 61°c$ (By using mollier chart)

$h_6 = 2600$ KJ/kg.

$h_{f_6} = 251.5$ KJ/kg.

(16)

$$\eta = \frac{(h_1-h_2)+(h_3-h_4)+(h_5-h_6)}{(h_1-h_{f6})+(h_3-h_2)+(h_5-h_4)}$$

$$= \frac{(3301.5-2838.42)+(3200.86-2809.3)+(3112.08-2613.72)}{(3301.5-2151.5)+(3200.86-2838.42)+(3112.08-2809.3)}$$

$\eta = 0.3642$

$\boxed{\eta = 36.42\ \%}$

$$P = m\left[(h_1-h_2)+(h_3-h_4)+(h_5-h_6)\right]$$

$$= 1\left[(3301.5-2838.42)+(3200.86-2809.3)+(3112.08-2613.72)\right]$$

$\boxed{P = 1353\ kW}$

$$P = m\left[(h_1-h_2)+(h_3-h_4)+(h_5-h_6)\right]$$

$$= 1\left[(3301.5-2838.42)+(3200.86-2809.3)+(3112.08-2613.72)\right]$$

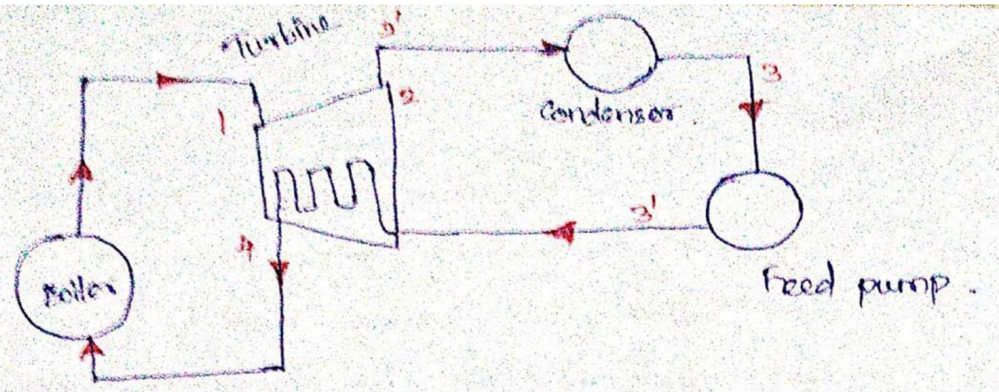
$$\boxed{P = 1353 \text{ kW}}$$

REGENERATIVE RANKINE CYCLE :-

a) Ideal :- The rankine cycle efficiency is less than carnot cycle for the same temperature limit because heating of feed water taken places with a large temperature difference. If the temperature of feed water is raised to the saturation temperature corresponding to the boiler pressure before it enters into the boilers, the cycle efficiency will be as close as to carnot cycle efficiency.

The working fluid leaving the feed pump circulates around the turbine casing where the heat transfer takes places between the incoming steam and the fluid in the liquid state inside the casing.

(17)

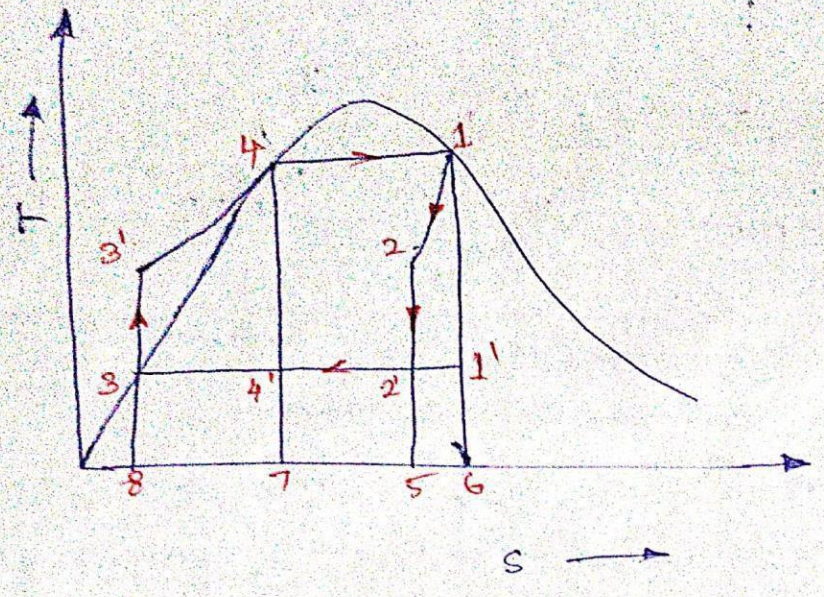


1-2 - heat loss by the steam in the turbine

3-4 - heat gained by the working fluid flows through the turbine casing.

4-1 - heat transfer from the boiler to the working fluid.

2'-3' - amount of heat transferred from the working fluid to the coolant.

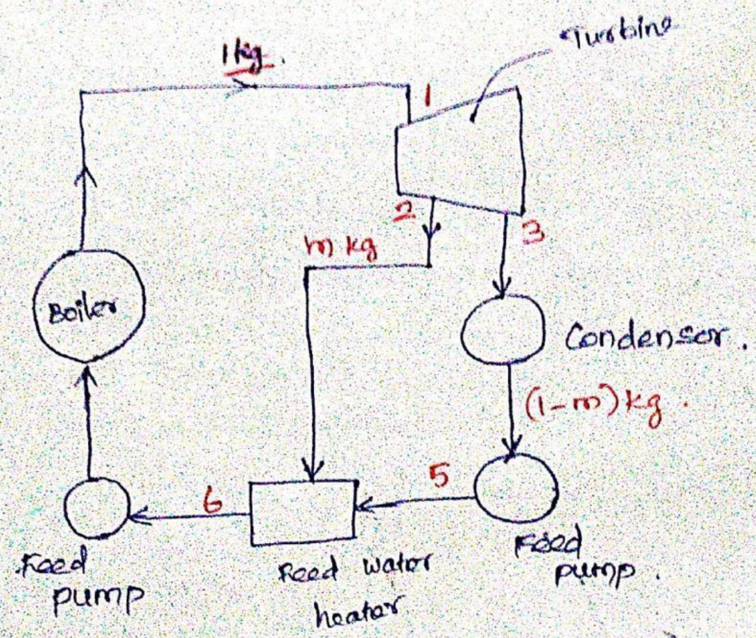


⇒ The area under the curve 1-2 and 3-4 are equal.

1) Practical Regenerative Rankine cycle :-

i) Single stage Regenerative Rankine cycle :-

The above cycle is clearly not a practical proportion because the turbine operates with wet steam of low dryness fraction which will affect the turbine blades severely. However the rankine cycle efficiency can be improved upon in practice by bleeding off some of the steam at an intermediate pressure during expansion and it is used to heat the feed water in separate feed water heater.



The steam expands from condition 1 through the turbine. At the pressure corresponding to point 2, a quantity of steam with m kg per kg of steam supplied from boiler is bled off for heating feed water. The rest of steam (1-m) kg completes the expansion and is exhausted to the condenser pressure P_3. The amount of steam is then condensed and pumped to the same pressure as the bleed steam. The bleed steam of m kg and feed water are mixed in the feed water under ideal adiabatic conditions, the state of the condensed mass m kg and the feed water (1-m) kg leaving the heater will be same and is represented by the state 7. The feed water is then pumped by the second feed pump to the boiler pressure where it is heated to state 1 and cycle is repeated.

Work done by the turbine per kg of steam

$$W_T = (h_1 - h_2) + (1-m)(h_2 - h_3)$$

pump work,

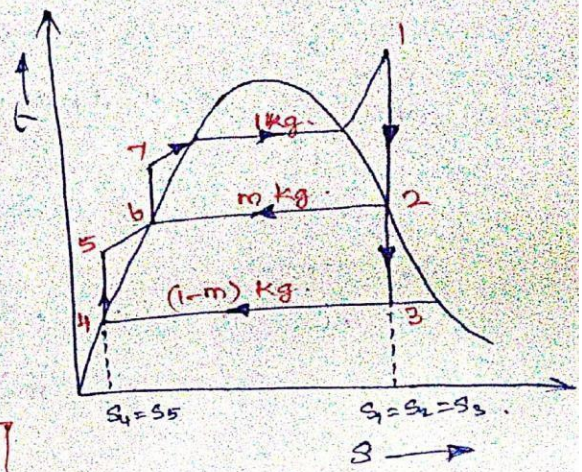
$$W_P = (1-m)(h_5 - h_4) + (h_7 - h_6)$$

$$= (1-m) \times v_4 (P_5 - P_4) + v_6 (P_7 - P_6)$$

$$W_P = (1-m)\, v_{f3} (P_2 - P_3) + v_{f2} (P_1 - P_2)$$

Net work output,

$$W = W_T - W_P$$



Heat supplied in the boiler,

$$Q_S = (h_1 - h_7)$$

Heat rejected by the condenser,

$$Q_R = (1-m)(h_3 - h_4)$$

$$Q_R = (1-m)(h_3 - h_{f3})$$

Thermal efficiency,

$$\eta_{Regenerative} = \frac{W}{Q_S} = \frac{Q_S - Q_R}{Q_S}$$

$$\eta = \frac{(h_1 - h_7) - (1-m)(h_3 - h_{f3})}{h_1 - h_7}$$

The amount of steam extracted (m) is determined from the heat balance in the feed water heater.

(60)

Heat lost by the steam = Heat gained by the water,

$$m \times (h_2 - h_6) = (1-m)(h_6 - h_5)$$

$$mh_2 - mh_6 = h_6 - h_5 - mh_6 + mh_5$$

$$mh_2 - mh_5 = h_6 - h_5$$

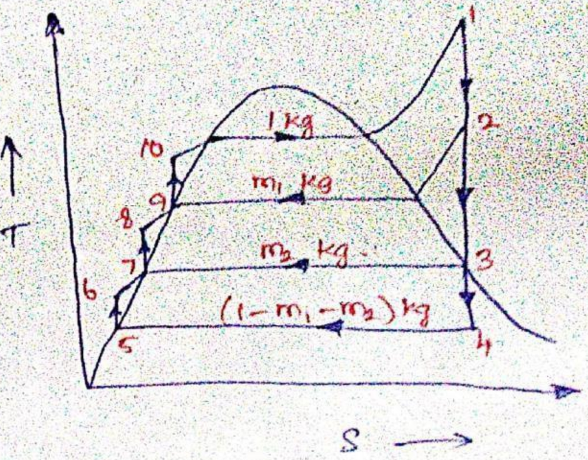
$$m(h_2 - h_5) = h_6 - h_5$$

$$m = \frac{h_6 - h_5}{h_2 - h_5} \qquad \because h_6 = h_{f2}$$

$$\boxed{m_1 = \frac{h_{f2} - h_5}{h_2 - h_5}}$$

ii) Two Stage Regenerative Rankine cycle :-

If a regenerative cycle employs two feed water heaters, i.e. steam is bleed from two place of the turbine.



Work done per kg of steam supplied to the turbine.

$$W_T = (h_1 - h_2) + (1-m_1)(h_2 - h_3) + (1-m_1-m_2)(h_3 - h_4)$$

Pump work,

$$W_P = W_{P_1} + W_{P_2} + W_{P_3}.$$

$$W_P = (1-m_1-m_2)(P_6 - P_5) + (1-m_1)(h_8 - h_7) + (h_{10} - h_9)$$

$$W_P = (1-m_1-m_2) V_{f4}(P_3 - P_4) + (1-m_1) V_{f3}(P_2 - P_3) + V_{f2}(P_1 - P_2)$$

Heat supplied by the boiler per kg of steam generated,

$$Q_s = (h_1 - h_{10})$$

Thermal efficiency,

$$\eta = \frac{W}{Q_s} = \frac{W_T - W_P}{Q_s} = \frac{W_T - W_P}{h_1 - h_{10}}.$$

The amount of steam bleed from turbine in two stages m_1 and m_2 can be determined from energy balance equation

For first heater,

$$m_1 h_2 + (1-m_1) h_8 = h_9$$

$$m_1 h_2 + h_8 - m_1 h_8 = h_9$$

$$m_1 (h_2 - h_8) = h_9 - h_8$$

$$m_1 = \frac{h_9 - h_8}{h_2 - h_8} \qquad \because h_9 = h_{f2}$$

$$\boxed{m_1 = \frac{h_{f2} - h_8}{h_2 - h_8}}$$

For second heater,

$$m_2 h_3 + (1 - m_1 - m_2) h_6 = (1-m_1) h_7$$

$$m_2 h_3 + h_6 - h_6 m_1 - h_6 m_2 = h_7 - m_1 h_7$$

$$m_2 h_3 - m_2 h_6 + h_6 = h_7 - m_1 h_7 - m_1 h_6$$

$$m_2 (h_3 - h_6) + h_6 = h_7 - m_1 (h_7 - h_6)$$

$$m_2 = \frac{h_7 - h_6 - m_1 (h_7 - h_6)}{h_3 - h_6}$$

$$\boxed{m_2 = \frac{(1-m_1)(h_7 - h_6)}{h_3 - h_6}}$$

Problems :-

(1) A regenerative cycle utilize steam as working fluid steam is supplied to the turbine at 40 bar and 450°c and the condenser pressure is 0.03 bar. After expansion in the turbine to 3 bar. Some of the steam is extracted from the turbine for heating the feed water from the condenser in an open heater. The pressure in the boiler is 40 bar and the state of the fluid leaving the heater is saturated liquid water at 3 bar. Assuming isentropic heat drop in the turbine & pump. Compute the efficiency of the cycle.

Given :-

$P_1 = 40$ bar

$T_1 = 450°c$

$P_2 = 3$ bar

$P_3 = 0.03$ bar.

To find :-

Efficiency of the cycle (η_{Reg}).

Solution :-

The state 1 is superheated steam

$P_1 = 40$ bar $\quad T_1 = 450°c$.

$h_1 = 3330.35$ KJ/kg.

$S_1 = 6.9363$ KJ/kg.K.

The state 2 is in wet steam

$S_1 = S_2$ (isentropic process)

$S_1 = S_2 = 6.9363$ KJ/kg.K.

At 3 bar,

$S_{f_2} = 1.672$ KJ/kg.K. $\quad h_{f_2} = 561.5$ KJ/kg.

$S_{fg_2} = 5.319$ KJ/kg.K. $\quad h_{fg_2} = 2163.2$ KJ/kg.

$$S_2 = S_{f_2} + x_2 S_{fg_2}.$$

$$6.9363 = 1.672 + x_2(5.319)$$

$$\boxed{x_2 = 0.98}.$$

$$h_2 = h_{f_2} + x_2 h_{fg_2}$$

$$= 561.5 + (0.98)(2163.9)$$

$$\boxed{h_2 = 2681.48 \text{ kJ/kg}}$$

The state 3 is also wet steam

$$S_3 = S_2 = 6.9362 \text{ kJ/kg.K}$$

At $P_3 = 0.03$ bar

$S_{f_3} = 0.3541$ kJ/kg.K, $h_{f_3} = 101.0$ kJ/kg.

$S_{fg_3} = 8.2241$ kJ/kg.K $h_{fg_3} = 2444.6$ kJ/kg.

$$S_3 = S_{f_3} + x_3 S_{fg_3}$$

$$6.9363 = 0.354 + x_3 (8.224)$$

$$\boxed{x_3 = 0.8}$$

$$h_3 = h_{f_3} + x_3 h_{fg_3}$$

$$= 101.0 + (0.8)(2444.6)$$

$$\boxed{h_3 = 2056.68 \text{ kJ/kg}}$$

Pump work during 4-5 process

$$W_P = (1-m)(h_5 - h_4)$$

$$= (1-m)\left[V_{f_3}(P_2 - P_3)\right]$$

$$h_5 - h_4 = V_{f_3}(P_2 - P_3)$$

$V_{f_3} = 0.001003$ $P_2 = 300$ kN/m^2

$P_3 = 3$ kN/m^2

$$h_5 - h_4 = 0.001003(300 - 3)$$

$h_5 - h_4 = 0.2978$ kJ/kg. $\because h_4 = h_{f_3} = 101.05$ kJ/kg.

$$h_5 - 101.05 = 0.2978$$

$$h_5 = 0.2978 + 101.05$$

$$\boxed{h_5 = 101.34 \text{ kJ/kg}}$$

Amount of Steam bleed,

$$m = \frac{h_{f2} - h_5}{h_2 - h_5}$$

$$= \frac{561.5 - 101.34}{2681.43 - 101.34} = \frac{460.16}{2580.06}$$

$$\boxed{m = 0.1783 \text{ kg}}$$

To find h_7 (Feed pump)

$W_p = h_7 - h_6$.

$W_p = V_{f2}(P_1 - P_2)$

$V_{f2} = 0.001071$ $P_1 = 4000$ kN/m²

$P_2 = 300$ kN/m²

$W_p = 0.001071 (4000 - 300)$

$W_p = 3.9973$ kJ/kg.

$h_7 - h_6 = 3.973$ $\because h_6 = h_{f2}$

$h_7 - 561.47 = 3.973$ $h_{f2} = 561.47$

$h_7 = 3.973 + 561.47$

$$\boxed{h_7 = 565.44 \text{ kJ/kg}}$$

$$\eta_{REG} = \frac{(h_1 - h_7) - (1-m)(h_3 - h_{f3})}{(h_1 - h_7)}$$

$$= \frac{(3330.35 - 565.44) - (1 - 0.1783)(2056.68 - 101.0)}{(3330.35 - 565.44)}$$

$$= \frac{(2764.91) - (0.8217)(1955.68)}{2764.91}$$

$$= \frac{791.23}{2764.91}$$

$$\boxed{\eta_{REG} = 28.6\ \%}$$

Problem on Two Stage Regenerative cycle :-

(13). In a regenerative steam cycle employing two open feed water heater, the steam is supplied to the turbine at 30 bar and 500°c and is exhausted to the condenser pressure 0.04 bar. The extraction points for two heaters are at 3.5 bar and 0.75 bar respectively. calculate the thermal efficiency of the plant.

Given :-

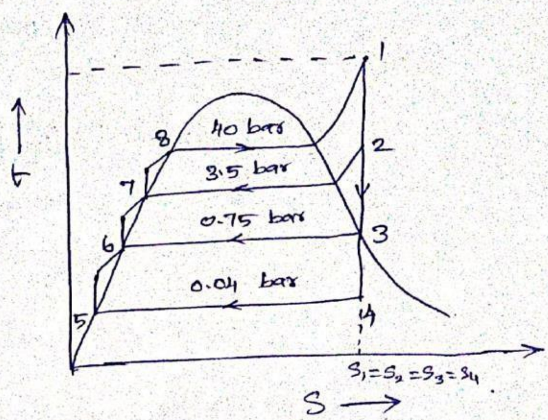
$P_1 = 30$ bar

$T_1 = 500°C$

$P_2 = 3.5$ bar

$P_3 = 0.75$ bar

$P_4 = 0.04$ bar.



To find :-

Thermal efficiency (η_{REG})

Solution :-

$$\eta = \frac{W}{Q_s} = \frac{W_T - W_P}{Q_s}.$$

$$W_T = (h_1 - h_2) + (1-m_1)(h_2 - h_3) + (1-m_1-m_2)(h_3 - h_4)$$

$$W_P = (1-m_1-m_2) + (1-m_1)(h_8 - h_7) + (h_{10} - h_9).$$

$$Q_s = h_1 - h_{10}.$$

To find h_1.

The steam is superheated in state (1).

At $P_1 = 30$ bar $T_1 = 500°C$.

$h_1 = 3456.2$ KJ/kg.

$S_1 = 7.235$ KJ/kg·k.

To find h_2.

Find the state of steam.

$S_1 = S_2 = 7.235$ KJ/kg·k.

At 3.5 bar, $S_{g_2} = 6.939$ KJ/kg·k.

$S_2 > S_{g_2}$.

The steam is superheated.

From the mollier chart, through the point.

$P_2 = 3.5$ bar, $S_2 = 7.235$ KJ/kg.K.

$h_2 = 2850$ KJ/kg.

To find h_3,

$P_3 = 0.75$ bar.

Find the state of steam.

$S_2 = S_3 = 7.235$ KJ/kg.K

At $P_3 = 0.75$ bar

$S_{g_3} = 7.457$ KJ/kg.K, $S_{f_3} = 1.213$ KJ/kg.K, $S_{fg_3} = 6.243$ KJ/kg.K.

$S_{g_3} > S_3$ (steam is wet). $h_{f_3} = 384.3$ KJ/kg.

$h_{fg_3} = 2278.6$ KJ/kg.

$S_3 = S_{f_3} + x_3 S_{fg_3}$.

$7.235 = 1.213 + x_3 (6.243)$

$x_3 = 0.96$

$h_3 = h_{f_3} + x_3 h_{fg_3}$.

$= 384.3 + (0.96)(2278.6)$

$h_3 = 2581.75$ KJ/kg

To find h_4.

The steam is wet condition

$h_4 = h_{f_4} + x_4 h_{fg_4}$.

$S_1 = S_4 = 7.235$ KJ/kg.K.

At 0.04 bar

$S_{f_4} = 0.423$ KJ/kg.K $h_{f_4} = 121.46$ KJ/kg.

$S_{fg_4} = 8.053$ KJ/kg.K. $h_{fg_4} = 2433.1$ KJ/kg

$V_{f_4} = 0.001004$ m^3/kg

$S_4 = S_{f_4} + x_4 S_{fg_4}$.

$7.235 = 0.423 + x_4 (8.053)$

$x_4 = 0.845$

$h_{f_4} = h_{f_4} + x_4 h_{fg_4}$.

$= 121.4 + (0.845)(2433.1)$

$h_4 = 2179.54$ KJ/kg

Pump work (5-6)

$$W_p = (1-m_1-m_2)(h_6-h_5)$$

$$W_p = (1-m_1-m_2)\left[V_{f4}(P_3-P_4)\right]$$

$$h_6-h_5 = V_{f4}(P_3-P_4)$$

$$h_6-h_5 = 0.001004\,(75-4)$$

$$h_6-h_5 = 0.071284$$

$\because h_5 = h_{f4}$.

$h_{f4} = 121.4$ KJ/kg.

$$h_6-121.4 = 0.071284$$

$$\boxed{h_6 = 121.53 \text{ KJ/kg}}$$

Pump work (7-8)

$$W_p = (1-m_1)(h_8-h_7)$$

$$W_p = (1-m_1)\,V_{f3}(P_2-P_3)$$

$$h_8-h_7 = V_{f3}(P_2-P_3)$$

At 0.75 bar.

$$V_{f3} = 0.001037 \text{ m}^3/\text{kg}.$$

$$h_8-h_7 = 0.001037\,(350-75)$$

$\because h_7 = h_{f3}$

$h_{f3} = 384.4$.

$$h_8-h_7 = 0.285$$

$$h_8 = 0.285 + h_7$$

$$= 0.285 + h_{f3}$$

$$= 0.285 + 384.4$$

$$\boxed{h_8 = 384.68 \text{ KJ/kg}}$$

Pump work (9-10)

$$W_p = h_{10}-h_9$$

$$W_p = V_{f1}(P_1-P_2)$$

At 30 bar $V_{f1} = 0.001079$ m^3/kg.

$$h_{10}-h_9 = V_{f1}(P_1-P_2)$$

$$h_{10}-h_9 = 0.001079\,(3000-350)$$

$$h_{10}-h_9 = 2.859$$

$$h_{10} = 2.859 + h_9.$$

$h_{10} = 2.859 + h_{f_2}$ $\quad \because h_9 = h_{f_2}$

$= 2.859 + 584.33$ $\quad h_{f_2} = 584.33$ KJ/kg.

$$\boxed{h_{10} = 587.19 \text{ KJ/kg}}$$

$$m_1 = \frac{h_7 - h_8}{h_2 - h_8} = \frac{h_{f_2} - h_{f_3}}{h_2 - h_{f_3}} = \frac{584.33 - 384.6}{2850 - 384.6}$$

$$\boxed{m_1 = 0.081 \text{ kg}}$$

$$m_2 = \frac{(1-m_1)(h_7 - h_6)}{h_3 - h_6} = \frac{(1-m_1)(h_{f_3} - h_6)}{h_3 - h_6}.$$

$$= \frac{(1-0.8)[384.39 - 121.53]}{2581.75 - 121.53}$$

$$= \frac{(0.918)(262.8)}{2460.22}$$

$$\boxed{m_2 = 0.098 \text{ kg}}.$$

$$W_T = (h_1 - h_2) + (1-m_1)(h_2 - h_3) + (1 - m_1 - m_2)(h_3 - h_4)$$

$$= (3456.2 - 2850) + (1 - 0.081)(2850 - 2581.75) + (1 - 0.081 - 0.098)(2581.75 - 2179.54)$$

$$\boxed{W_T = 1183.09 \text{ KJ/kg}}.$$

$$W_P = (1 - m_1 - m_2) + (1 - m_1)(h_8 - h_7) + (h_{10} - h_9)$$

$$= (1 - 0.081 - 0.098) + (1 - 0.081)(384.67 - 384.39) + (587.19 - 584.33)$$

$$\boxed{W_P = 3.18 \text{ KJ/kg}}$$

$$W = W_T - W_P = 1183.09 - 3.18.$$

$$\boxed{W = 1199.9 \text{ KJ/kg}}$$

$$Q_S = h_1 - h_{10}. = 3456.5 - 587.19.$$

$$\boxed{Q_S = 2869.31 \text{ KJ/kg}}.$$

$$\eta = \frac{W}{Q_S} = \frac{1179.9}{2869.31} = 0.4112.$$

$$\boxed{\eta = 41.12\ \%}.$$

(2). A reheat cycle operating between 30 bar and 0.04 bar has a superheat and reheat temperature of 450°c. The first expansion take place till the steam is dry saturated and then reheat is given. Neglecting feed pump work determine the ideal cycle efficiency.

Given :-

$P_1 = 30$ bar.

$P_4 = 0.04$ bar.

$T_1 = 450°c$

$T_3 = 450°c$.

$x_2 = 1$

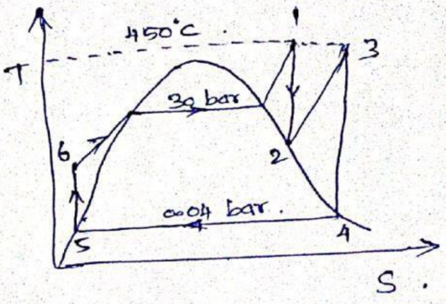
To find :-

Thermal efficiency of cycle $(\eta_{cycle}) = \dfrac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f4}) + (h_3 - h_2)}$

Solution :-

The state 1 is superheat steam.

@ P = 30 bar, T = 450°c.



$h_1 = 3344.35$ KJ/kg.

$S_1 = 7.080$ KJ/kg.k.

At 0.04 bar,

$h_{f4} = 121.4$ KJ/kg. $\quad S_{f4} = 0.423$ KJ/kg.k.

$h_{fg4} = 2433.1$ KJ/kg. $\quad S_{fg4} = 8.053$ KJ/kg.k.

$S_1 = S_2 = 7.080$ KJ/kg.k.

In dry saturated steam condition.

$S_2 = S_g$. $\Rightarrow$ similarly $h_2 = h_g$.

(from steam table) $P_2 = 2.3$ bar.

At 2.3 bar.

$h_g = h_2 = 2712.6$ KJ/kg.

At 2.3 bar and 450°c.

$h_3 = 3381.46$ KJ/kg.

$S_3 = 8.3061$ KJ/kg.k.

Process 3-4

$S_3 = S_4 = 8.3061$ KJ/kg.k.

$S_4 = S_{f4} + x_4 S_{fg4}$

at 0.01 bar $s_{f4} = 0.423$ kJ/kg·K. $\quad h_{f4} = 121.4$ kJ/kg.

$s_{fg4} = 8.052$ kJ/kg·K. $\quad h_{fg4} = 2433.1$ kJ/kg.

$$8.3061 = 0.423 + x_4 (8.053)$$

$$\boxed{x_4 = 0.98}$$

$$h_4 = h_{f4} + x_4 h_{fg4}$$

$$= 121.4 + (0.98 \times 2433.1)$$

$$h_4 = 2505.84 \text{ kJ/kg}$$

The cycle efficiency. $\eta = \dfrac{(h_1 - h_2) + (h_3 - h_4) - W_p}{(h_1 - (h_{f4} + W_p)) + (h_3 - h_2)}$

$\Rightarrow W_p = 0$.

$$\eta = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f4}) + (h_3 - h_2)}$$

$$\eta = \frac{(3344.35 - 2712.6) + (3381.46 - 2505.84)}{(3344.35 - 121.4) + (3381.46 - 2712.6)}$$

$$\eta = 0.3873.$$

$$\boxed{\eta = 38.73\ \%}$$

UNIT - 4

Problem :-

1) In a Rankine cycle, the steam at inlet to turbine is saturated at a pressure of 20 bar superheated at 300°C. The exhaust pressure is 0.07 bar and expansion take place isentropically. Determine, i) pump work ii) Work turbine. iii) Rankine efficiency iv) Work done v) Specific steam consumption (Steam Rate)

Given :-

$P_1 = 20$ bar.

$T_1 = 300°C$.

$P_2 = 0.07$ bar.

To find :-

i) pump work.
ii) Turbine work.
iii) Rankine efficiency
iv) Work done.
v) Specific steam consumption (SSC)

Solution :-

At $P_1 = 20$ bar $T_1 = 300°C$.

$h_1 = 3025.0$ KJ/kg.

$S_1 = 6.770$ KJ/kg.K.

At 0.07 bar.

$S_1 = S_2 = 6.770$ KJ/kg.k

$S_{f_2} = 0.559$ KJ/kg.k. $h_{f_2} = 163.4$ KJ/kg. $V_{f_2} = 0.001007$ m³/kg.

$S_{fg_2} = 7.718$ KJ/kg.k. $h_{fg_2} = 2409.2$ KJ/kg.

$S_2 = S_{f_2} + x_2 S_{fg_2}$.

$6.770 = 0.559 + x_2 (7.718)$

$x_2 = \frac{6.211}{7.718}$

$\boxed{x_2 = 0.80}$

$h_2 = h_{f_2} + x_2 h_{fg_2}$.

$= 163.4 + (0.80)(2409.2)$

$h_2 = 2090.76$ KJ/kg.

$$\eta = \frac{(h_1 - h_2) - w_p}{h_1 - (h_{f2} + w_p)} = \frac{(3025 - 2090.76) - 2.0069}{3025 - (163.4 + 2.0069)}$$

$$= \frac{932.34}{2859.59}$$

$$= 0.3260$$

$$\eta = 32.6\%$$

Turbine Work $W_T = h_1 - h_2$

$= 3025 - 2090.76$

$= 934.24$

Pump Work $W_p = V_{f2}(P_1 - P_2)$

$= 0.001007\,(2000 - 7)$

$= 2.0069$

Work done $W = q_s - q_R$

$= 2859.79 - 1927.36$

$= 932.34$ KJ/kg

$q_s = h_1 - (h_{f2} + W_p)$

$= 3025 - (163.4 + 2.0069)$

$= 2859.79$ KJ/kg

$q_R = h_2 - h_3 = h_2 - h_{f2}$

$= 2090.76 - 163.4$

$= 1927.36$

Specific steam consumption (SSC) $= \frac{3600}{W}$ KJ/kW.hr

$W = (h_1 - h_2) - W_p = 932.34$

$= \frac{3600}{932.34}$

$= 3.86$ KJ/kW.hr

Specific steam flow rate (SSF) $= \frac{1}{W}$ Kg/kW

$= \frac{1}{932.34}$

$= 1.072 \times 10^{-3}$ kg/kW

Work ratio $= \frac{W_T - W_p}{W_p}$

$= \frac{934.24 - 2.0069}{2.0069}$

$= 464.51$