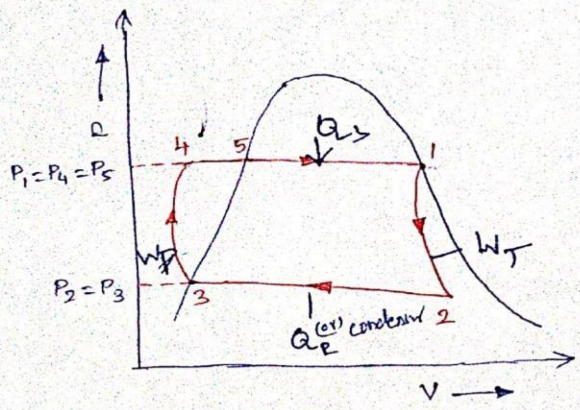
UNIT - IV.

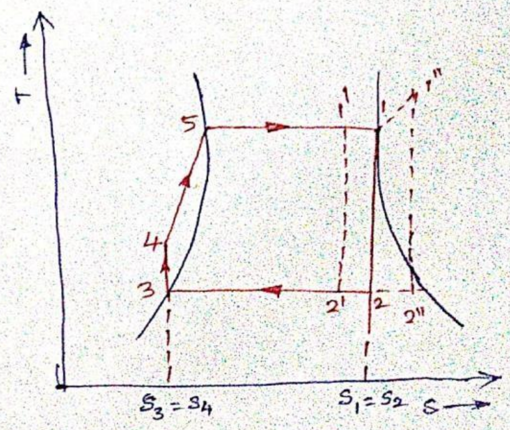
STEAM POWER CYCLES.

IDEAL RANKINE CYCLE :-

The Rankine cycle is an ideal cycle for vapour power cycles. The PV and Ts diagram are shown in fig.



P-V Diagram



T-s diagram.

Process 1-2 :-

The dry saturated steam from boiler is expanded in the turbine isentropically (upto point 2) for developing mechanical work and hence, the pressure of steam falls from P_1 to P_2. The temperature at the end of expansion is T_2 which is the saturated temperature at condenser pressure P_2. The steam after expansion is in wet condition with dryness fraction x_2.

Work done $W_T = h_1 - h_2$.

Process 2-3 :-

The wet steam is then condensed in a condenser isothermally and isobarically. The wet steam is converted into water in condenser. This process is a heat rejection process; the heat is rejected from wet steam to atmospere.

Heat rejected. $Q_R = h_2 - h_3 = h_2 - h_{f_2}$ $\quad \because h_3 = h_{f_2}$.

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Process 3-4 :-

The water from the condenser is pumped isentropically from pressure P_3 to the boiler pressure P_4. There is a slight rise in temperature from T_3 to T_4. The enthalpy of water increases due to the pump work.

Work done by pump $W_P = h_4 - h_3$.

$$W_P = V_3 (P_4 - P_3)$$

$$W_P = V_{f_4} (P_4 - P_3) = V_{f_2} (P_1 - P_2)$$

ie: $P_4 = P_1 \quad P_3 = P_2 \quad V_3 = V_{f_2}$.

Process 4-5 :-

The heat is supplied by the boiler to raise the temperature of water to saturated temperature at T_5 at pressure of P_5.

Heat supplied during 4-5, $Q_{S_{4-5}} = h_5 - h_4$.

Process 5-1 :-

The saturated water is then heated in the boiler to the initial dry saturated liquid condition at the pressure P_1. The enthalpy increases by a large value during evaporation.

Heat supplied during 5-1 $Q_{S_{5-1}} = h_1 - h_5$

Total heat supplied, $Q_S = Q_{S_{4-5}} + Q_{S_{5-1}}$

$$= h_5 - h_4 + h_1 - h_5$$

$$= h_1 - h_4$$

$$\boxed{Q_S = h_1 - h_{f_4}} \qquad \because h_4 = h_{f_4}.$$

(or)

$$\boxed{Q_S = h_1 - (h_3 + W_P)} \qquad \because h_4 = h_3 + W_P,\ h_3 = h_{f_2},\ h_4 = h_{f_2} + W_P$$

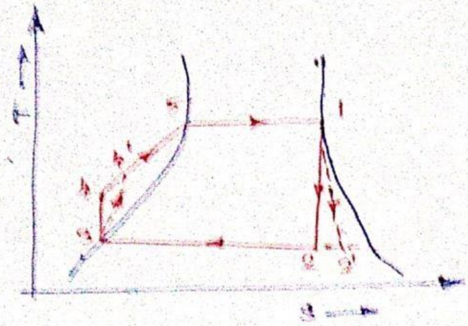
Net work output, $W = W_T - W_P$

$$= (h_1 - h_2) - W_P$$

$$\boxed{W = h_1 - (h_{f_2} + W_P)}$$

Actual Rankine cycle :-

The reversible adiabatic process is practically not possible because of frictional and other losses in turbine and pump.



The actual expansion is irreversible as shown by line 1-2'. Similarly the actual compression process is irreversible as indicated by line 3-4'. The isentropic efficiency is given by,

$$\text{Isentropic efficiency} = \frac{\text{actual work}}{\text{isentropic work}} \quad \text{for an expansion process}$$

$$\text{Turbine efficiency } \eta_T = \frac{h_1 - h_2'}{h_1 - h_2}.$$

$$\text{Isentropic efficiency} = \frac{\text{isentropic work input}}{\text{actual work input}} \quad \text{compression process.}$$

$$\text{Pump efficiency } \eta_P = \frac{h_4 - h_3}{h_4' - h_3}.$$

Efficiency ratio :-

The efficiency ratio of the cycle is the ratio of actual cycle efficiency to the ideal efficiency.

$$\text{Efficiency ratio} = \frac{\text{Actual cycle efficiency}}{\text{Rankine efficiency}}.$$

where,

$$\text{Actual cycle efficiency}, \eta = \frac{(h_1 - h_2') - W_p}{h_1 - (h_{f_3} + W_p)}$$

Efficiency of the cycle, $\eta = \frac{W}{Q_S} = \frac{(h_1 - h_2) - W_P}{h_1 - h_4}$

$$\eta = \frac{(h_1 - h_2) - W_P}{h_1 - (h_{f_2} + W_P)}$$

otherwise, $\eta = \frac{Q_S - Q_R}{Q_S} = \frac{(h_1 - h_4) - (h_2 - h_3)}{h_1 - h_4} = \frac{h_1 - h_4 - h_2 + h_3}{h_1 - h_4}$

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

$$\boxed{\eta = \frac{(h_1 - h_2) - W_P}{h_1 - (h_{f_2} + W_P)}}$$

The pump work is very small, it is neglected.

$$\eta = \frac{h_1 - h_2}{h_1 - h_3} \quad \because h_3 = h_{f_2}$$

$$\boxed{\eta = \frac{h_1 - h_3}{h_1 - h_{f_2}}}$$

i) Specific steam Consumption (SSC) :-

It is defined as the mass flow of steam required to develop unit power output.

$$\boxed{SSC = \frac{3600}{W} \text{ kg/kW-hr}}$$

where,

$W = (h_1 - h_2) - W_P$ with pump work.

$W = h_1 - h_2$ without pump work. } output.

ii) Specific Steam flow rate (SSF)

It is defined as the steam flow in kg required to develop unit power output,

$$\boxed{SSF = \frac{1}{W} \text{ kg/kW}}$$

iii) Work ratio,

It is defined as the ratio of network to the gross work.

$$\text{Work ratio} = \frac{\text{Network}}{\text{Gross work}} = \frac{W_T - W_P}{W_T}$$

Problems :-

1. Dry saturated steam is supplied to a steam turbine at 12 bar and after the expansion its condenser pressure is 1 bar. Find the Rankine cycle efficiency. Specific steam consumption. Neglect feed pump work.

Given :-

$P_1 = 12$ bar

$P_2 = 1$ bar.

To find :-

i) Rankine cycle efficiency (η).

ii) SSC.

Solution :-

$$\eta = \frac{h_1 - h_2}{h_1 - h_{f_2}}$$

$P_1 = 12$ bar. dry saturated steam. ($x=1$)

$$h_1 = h_f + h_{fg} = h_g.$$

$$\boxed{h_1 = 2782.7 \text{ KJ/kg}} = h_g$$

$$s_g = S_1 = 6.519 \text{ KJ/kg.K}.$$

$$T_s = 188°C.$$

At 1 bar.

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

$h_{f_2} = 417.5$ KJ/kg. $s_f =$

$h_{fg} = 2256.9$ KJ/kg. $s_{fg} =$

Since the expansion is isentropic

$$S_1 = S_2.$$

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

$$6.519 = 1.303 + x_2(6.057)$$

$$\boxed{x_2 = 0.86}$$

$$h_2 = 417.5 + 0.86(2256.9)$$

$$\boxed{h_2 = 2358.48 \text{ KJ/kg}}.$$

$$\eta = \frac{h_1 - h_2}{h_1 - h_{f2}} = \frac{2782.7 - 2358.43}{2782.7 - 417.5}$$

$$= \frac{424.27}{2365.2}$$

$$\eta = 0.1798.$$

$$\boxed{\eta = 17.98\ \%}$$

ii) Specific Steam Consumption.

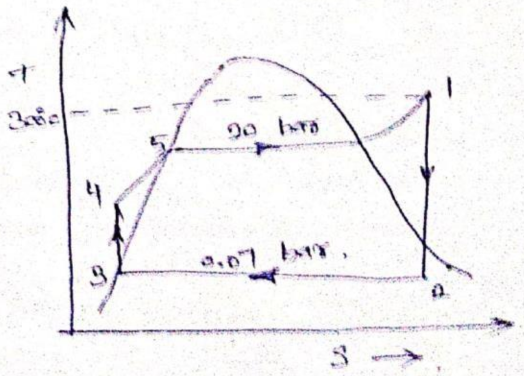
$$SSC = \frac{3600}{W} = \frac{3600}{h_1 - h_2}$$

$$= \frac{3600}{2782.7 - 2358.43}$$

$$\boxed{SSC = 8.48\ kg/kW\text{-}hr}$$

Q: Steam turbine receives steam at a pressure of 20 bar superheated at 300°c. The exhaust pressure is 0.07 bar and expansion takes place isentropically. Using steam table calculate the following.

a) Heat supplied assuming that the feed pump supplies water to the boiler at 20 bar.
b) Heat rejected.
c) Work done
d) Thermal Efficiency.
e). Theoretical Steam consumption.



Given:-

$P_1 = 20$ bar

$T_1 = T_{sup} = 300°c$

$P_2 = 0.07$ bar.

To find:-

Q_s, Q_s, W, η and SSC.

Solution :-

From Superheat Steam table at 20 bar and 300°c.

$h_1 = 3025$ KJ/kg.

$S_1 = 6.77$ KJ/kgK

From Steam table at 0.07 bar.

$h_{f_2} = 163.4$ KJ/kg. $S_{f_2} = 0.559$ KJ/kg.K.

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

$v_{f_2} = 0.001007$ m³/kg.

isentropically,

$S_1 = S_2 = 6.77$ KJ/kgK.

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

$6.77 = 0.559 + x_2 (7.718)$

$x_2 = 0.8$

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

$h_2 = 163.4 + 0.8 (2409.2)$

$h_2 = 2090.76$ KJ/kg

pump work, $W_P = h_4 - h_3 = V_3 (P_4 - P_3)$ $h = pv$

$= V_{f_2} (P_1 - P_2)$ $\Rightarrow$ KN/m²

$= 0.001007 (2000 - 7)$

$W_P = 2.0069$ KJ/kg

Heat supplied, $Q_s = h_1 - (h_{f_2} + W_P)$

$= 3025 - (163.4 + 2.0069)$

$Q_s = 2859.79$ KJ/kg.

Heat rejected, $Q_R = h_2 - h_3 = h_2 - h_{f_2}$

$= 2090.76 - 163.4$.

$Q_R = 1927.36$ KJ/kg

Work done $W = Q_S - Q_R$.

$= 2859.7 - 1927.36$.

$W = 932.34$ KJ/kg.

Thermal efficiency $= \frac{W}{Q_S} = \frac{932.34}{2859.79}$

$= 0.326$. $\eta = 32.6\ \%$

Theoretical Steam Consumption.

$SSC = \frac{3600}{W} = \frac{3600}{932.34}$

$SSC = 3.86$ KJ/kWhr.