Thermodynamics

3 E's → Energy, Entropy, Equilibrium

Heat transfer:

Transfer of energy (heat) is transit due to temp. diff.

Prop. of pure substance:

Steam table, Mollien diag, p-h chart

Work is high grade energy
Heat is low ——

* Properties:

Identified / Observed characteristics of a system

Measured properties: Pressure, temperature, mass, specific vol.
Calculated properties: Gas constant, Thermal conductivity, Avogadro No.

Extrinsic prop. (Mass dep.): volume, length

Intrinsic prop. (mass indep.): pressure, temperature

* State:

It consists of some properties

Minimum number of independent prop. to define the state of a syst. is governed by Gibb's phase rule

$f = C - \phi + 2$

f - no. of indep. prop.

C - no. of components

ϕ - no. of phases

ice

component = C = 1 (water only)

$\phi = 1$ (only solid phase is present)

↳ that means below 0°C

$f = 2$

say P & V or P & T or V & T

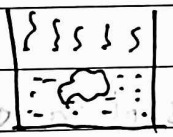
ice & water at 0°C

$C = 1$

$\phi = 2$

$f = 1$

Either of the P or T is needed to define state



ice water steam

$C = 1$

$\phi = 3$

$f = 0$

State is already defined and called as tripple point

* Process :

When system moves from one state to another it undergoes something called process

Isothermal is very slow process

Adiabatic process is very fast process

* Cyclic process :

A system when undergoes several processes & returns back to the initial state to retrace its path, is called cyclic process

Atleast 2 processes are req. for cyclic process

* Pure substance :

Substance having homogeneous chemical composition (const.)

i.e. vol. increases during freezing.

* P-V diagram of pure substances whose volume reduces during melting at P = 1 atm

Imp

1 $-20°C$ ice

$\downarrow Q_1$ $V\uparrow$

2 $0°C$ ice

$\downarrow Q_2 = L_{fusion}$ $V\downarrow$

3 $0°C$ water ~~$V\uparrow$~~

$\downarrow Q_3$ $V\uparrow$

4 $100°C$ water ~~$V\uparrow$~~

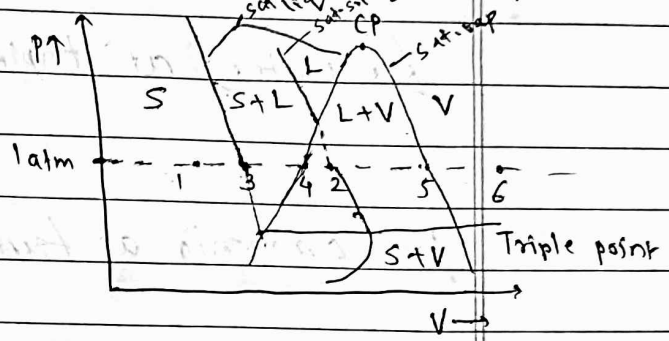
$\downarrow Q_4 = L_{vap}$ $V\uparrow$

5 $100°C$ steam

$\downarrow Q_5$ $V\uparrow$

6 $250°C$ steam (superheated)

S - solid L - liq V - vapour



CP - critical point

for P = 1atm points for diff. phases are plotted similarly for other values of pressure, the graph for all phases is drawn there.

at P = 1atm dist. in 4 & 5 i.e. ~~phase~~ state changing moment, is higher i.e as we go on increasing pressure, that dist. will go on decreasing thereby decrease in Latent heat.

$P\uparrow \Rightarrow L\downarrow$

at CP, $L = 0$

VIMP

Critical pressure = 221.26 bar
Critical temp = 374.15 °C = 101 K

Subcritical power plant :

Boiler pressure is below critical pressure. (general value 150 bar)

Supercritical power plant :

Boiler pressure is above critical pressure. (general value 250 bar)

$1 \text{ bar} = 10^5 \text{ Pa}$

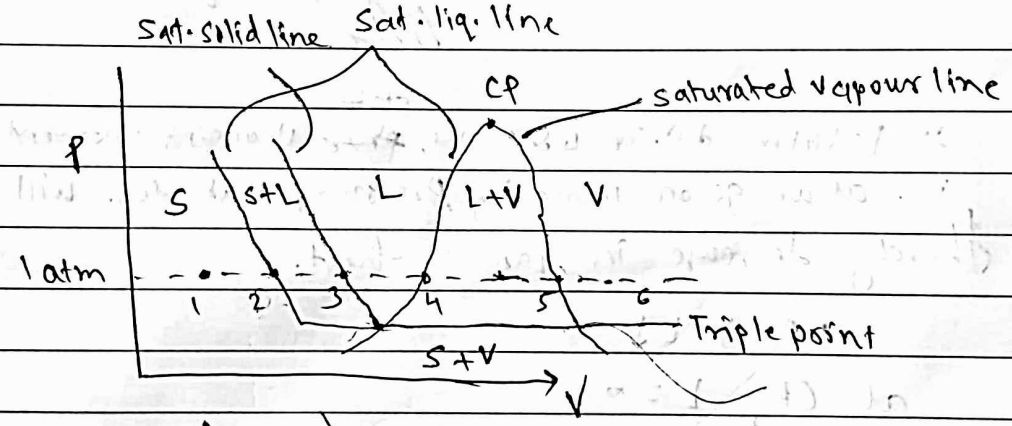
Imp supercritical power plants have greater amount of efficiency

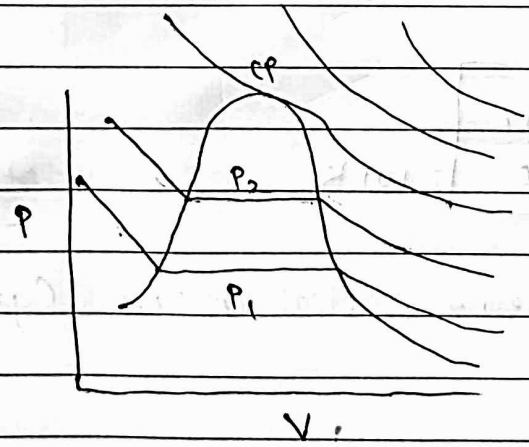
Imp for increasing pressure latent heat decreases & saturat^n temp increases
& for decreasing pressure latent heat increases & sat. temp decreases

for water, at triple point, temp = 0.01°C
pressure = 0.0061 bar

for ammonia at triple point, temp = −78°C
pressure = 0.061 bar

* Majority for fluids except water

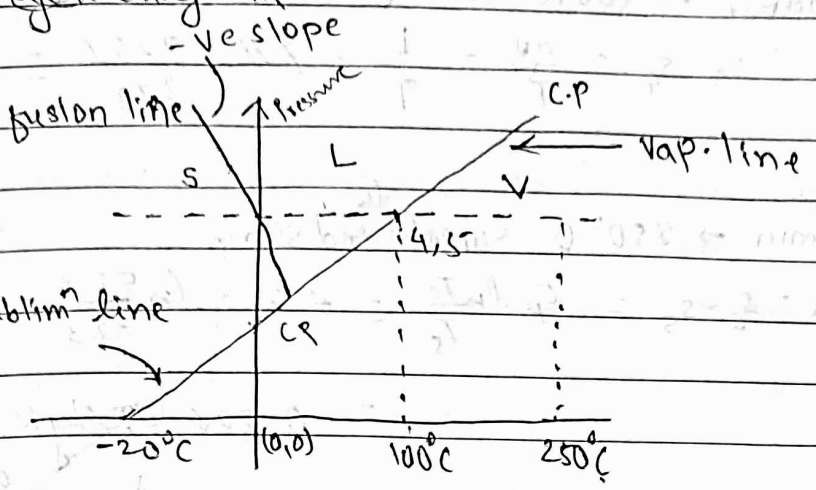




$CP > P_2 > P_1$

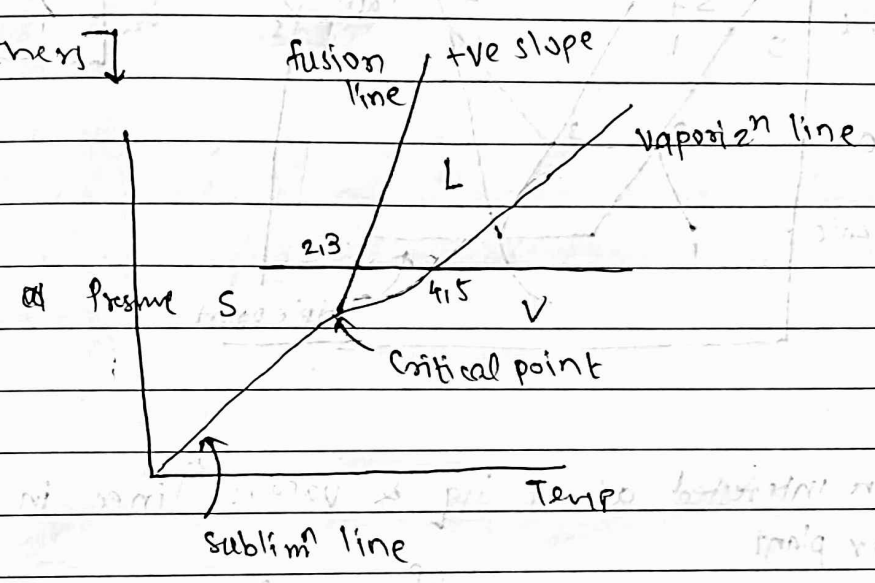
this graph is drawn only considering L & V state

* P-T cycle diagram



for water only

for others



$$ds = S_2 - S_1 = \int_1^2 \frac{dQ}{T} = C_p \int_1^2 \frac{dT}{T} = C_p \ln \frac{T_2}{T_1}$$

① -20°C ice to ② 0°C ice

$$ds = C_p \ln \frac{T_2}{T_1} = 2.093 \ln \frac{273}{253} = 0.16 \text{ kJ/kgK}$$

② 0°C ice to ③ 0° Water

$$ds = \frac{dQ}{T} = \frac{L}{T_2} = \frac{334.96}{273} = 1.23 \text{ kJ/kgK}$$

③ 0°C water to ④ 100°C water

$$ds = C_p \ln \frac{T_4}{T_3} = 4.187 \ln \frac{373}{273} = 1.3 \text{ kJ/kg K}$$

$\frac{dT}{ds}$

$100^\circ C$ water (4) $\rightarrow$ $100^\circ C$ steam (5)

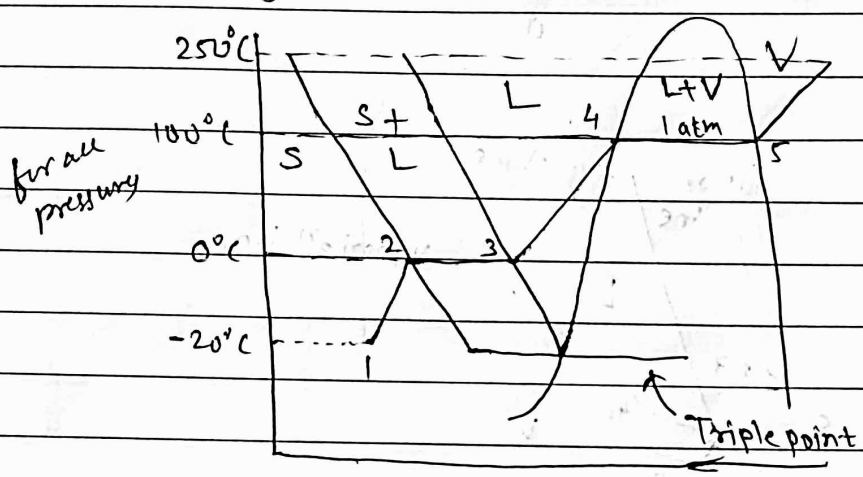
$$ds = s_5 - s_4 = \frac{dQ}{T} = \frac{L}{T} = \frac{2257}{373} = 6.05 \text{ kJ/kgK}$$

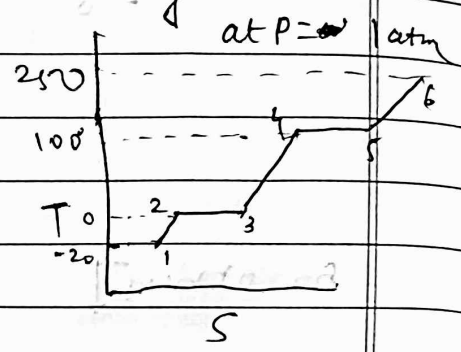
$100^\circ C$ steam (5) $\rightarrow$ $250^\circ C$ superheated steam (6)

$$ds = s_6 - s_5 = C_p \ln\frac{T_6}{T_5} = 2.093 \ln\frac{523}{373}$$

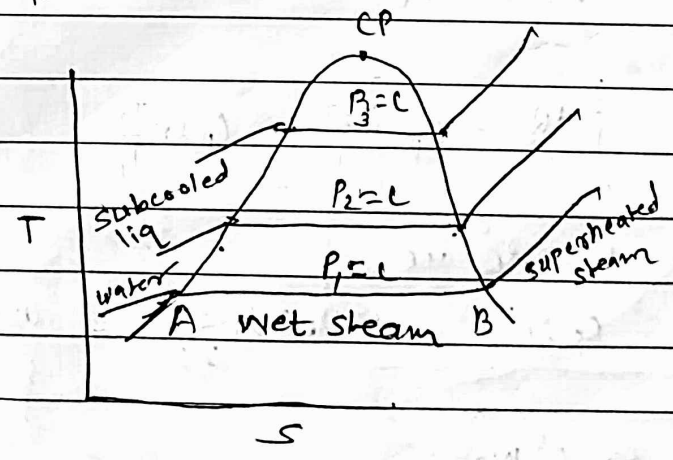
$$= 0.706 \text{ kJ/kgK}$$

T-S diagram





* We are interested about liq & vapour lines in case of vapour power plant



AB contains wet steam

wet steam = mixture of water & vapour

* Quality of steam/dryness fract^n of steam (x)

$x = 0.75$ → 75 % dry steam, 25 % water

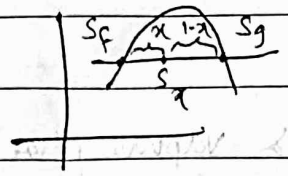
$x = 0.25$ → 25 % dry steam, 75 % water

$$x = \frac{\text{Wt. of dry steam}}{\text{Total wt of wet steam}}$$

S_f = specific entropy of water (complete water)

S_g = ——— " ——— dry steam (complete gas)

S_x = ——— " ——— wet steam with dryness fract^n x



$$\boxed{S_x = x S_g + (1-x) S_f}$$

$$\boxed{\begin{aligned} S_x &= S_f + x(S_g - S_f) \\ &= S_f + x S_{fg} \end{aligned}}$$

1] At 5 bar, specific entropy of water is 1.86 kJ/kgK while that of steam is 6.819 kJ/kgK where steam quality is 75%. Find sp. entropy of wet steam

$S_f = 1.86$ $\quad S_g = 6.819$ $\quad x = 75\% = 0.75$ $\quad S_x = ?$

$$S_x = S_f + (S_g - S_f)x$$

$$S_x = 5.57 \text{ kJ/kgK}$$

* Mollier diagram

$$dQ = dU + PdV$$

$$TdS = dU + PdV$$

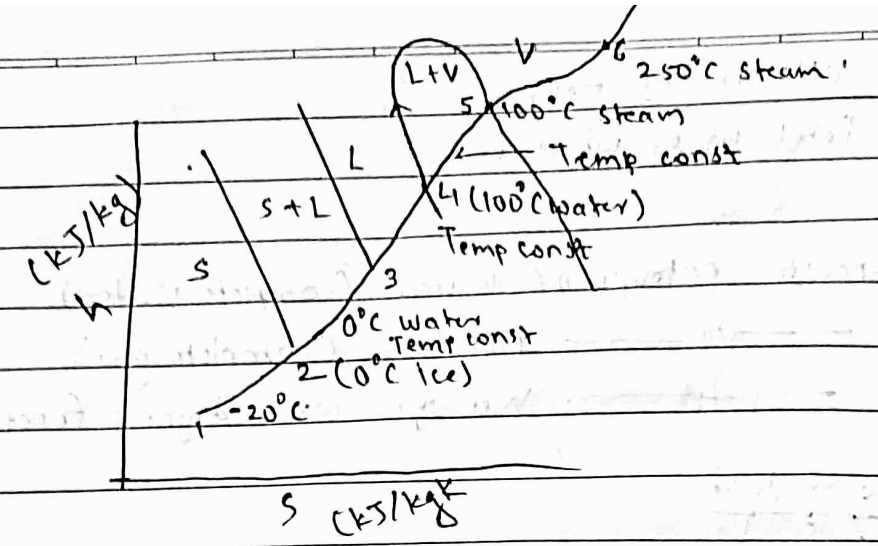
$$h = u + Pv$$

$$dh = du + Pdv + vdP$$

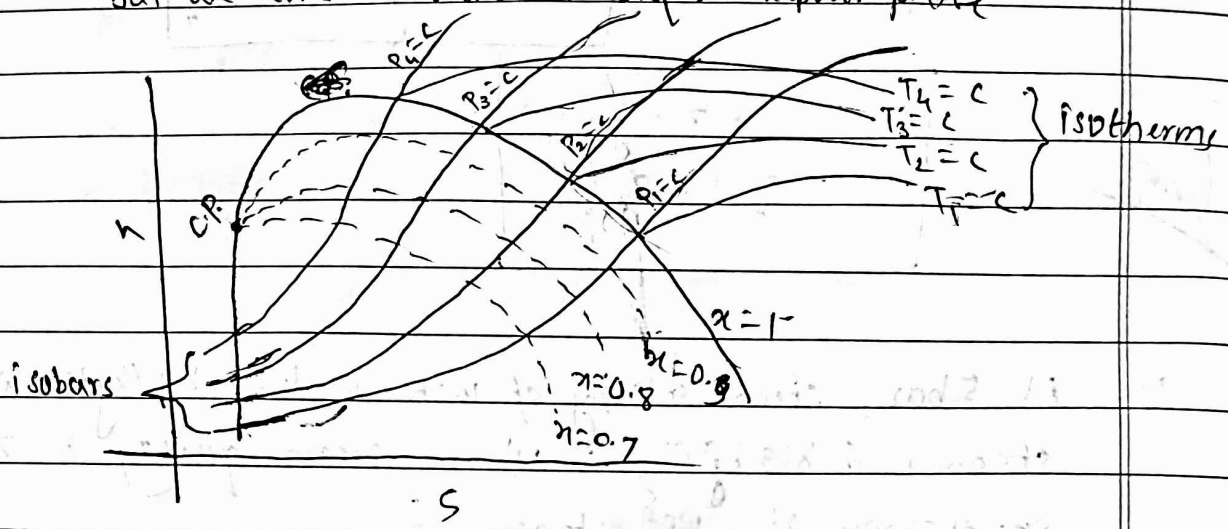
$$dh = Tds + vdP$$

when $P = \text{const}$, $dP = 0$

$$\frac{dh}{ds} = T$$



but we are interested in liq & vapour phase



* Heat engine

Engine: Device that converts any form of energy into mechanical energy

Heat engine: heat energy → mechanical energy.

* Kelvin-Plank statement

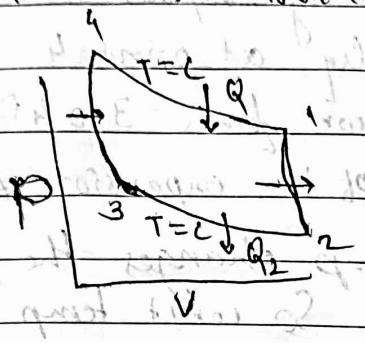
It is impossible to construct a device operating in a cycle & produce no effect other than work by extracting heat from a single heat reservoir

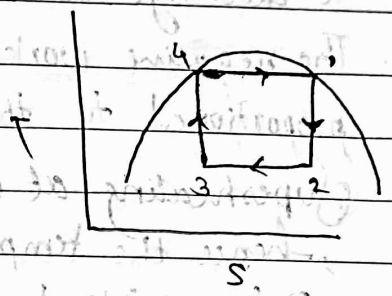
* Clausius statement

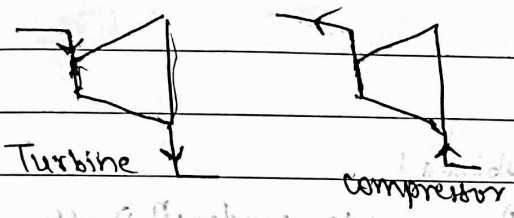
It is impossible to construct a device which extracts heat from lower temp. to higher without appliⁿ of external work

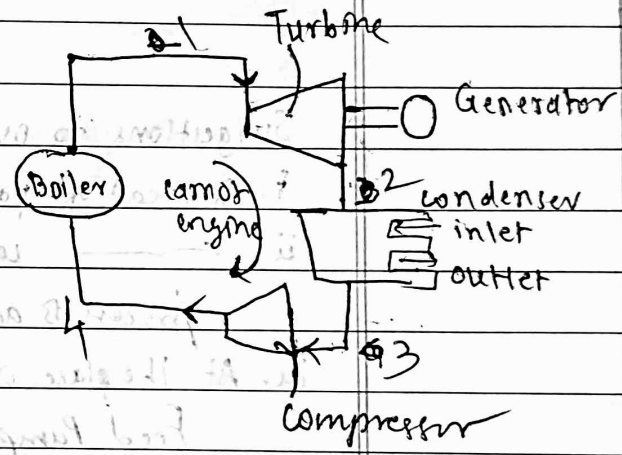
Heat engine comprises of 4 processes. → 2 reversible isothermal
2 reversible adiabatic

1→2 rev. adia expansion in turbine
2→3 rev isothermal heat rejectⁿ in condensor
3→4 rev adia compression in compressor
4→1 rev Isoth. heat addition in boiler









1] A carnot cycle is working with steam as working fluid betⁿ pressures 50bar & 5bar What's its efficiency?

for 5 bar, saturated temp = 151.8 °C
T_2 = 424.8 °K

for 50 bar, saturated temp = 263.9 °C
T_1 = 536.9 K

$$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{424.8}{536.9} = 0.2087$$
$$= 20.87\%$$

Drawbacks of Carnot Cycle

i. To Design & control a partial condensor that could terminate condensation at point 3 is difficult.

ii. It is difficult to design a compressor to handle a mixture of largely liq & partly vapour at point 3 & to discharge it as saturated liq at point 4

iii. The negative work of compressor from 3 to 4 is very large proportioned to the +ve work of the expansion from 1 to 2

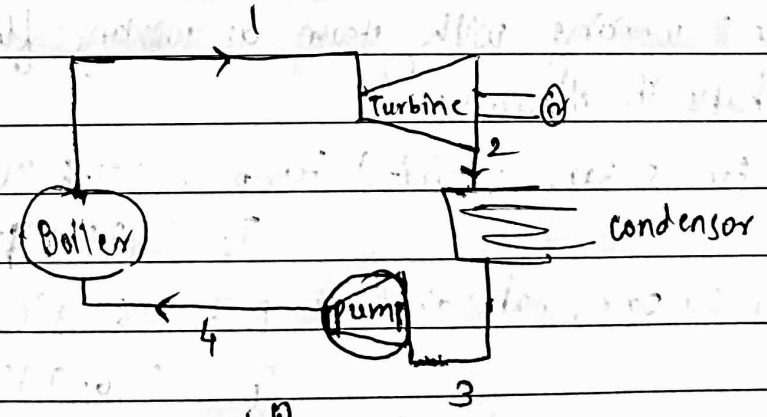
iv. Superheating at constant temp changes the pressure, hence the temperature also. So const temp heat addn is impossible for superheated steam

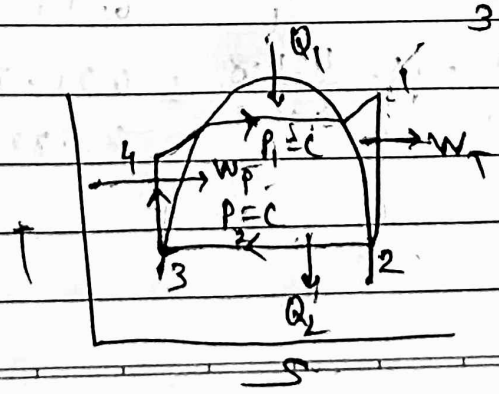
Suggestions to overcome drawbacks:

i: Instead of partial condensn, complete condensn is allowed

ii: ← const. temp heat addn & heat rejectn, constant pressure process is adopted

iii: At the place of compressor, use a pump (BFP) i.e Boiler Feed Pump



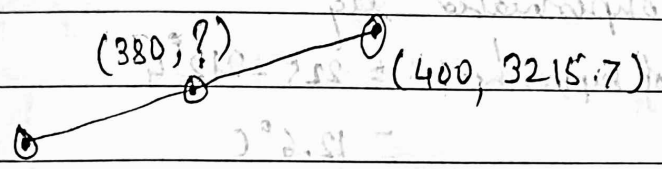


1] Find ~~Stop~~ Specific enthalpy of superheated steam at 40 bar & 380°C

From superheated steam - Specific enthalpy table,

Graph of ~~pressure~~ temp vs enthalpy is assumed to be a straight line

at 40 bar & 350°C, 3095.1 kJ/kg
40 bar & 400°C, 3215.7 kJ/kg



$$\frac{3215.7 - 3095.1}{400 - 350} = \frac{? - 3095.1}{380 - 350}$$

$\therefore ? = \cancel{3276}$ 3137 kJ/kg

2] ~~Gro~~ State the con^n of steam

at pressure = 10 bar, total heat is 2646 kJ/kg

From saturated water, steam pressure table,

heat is given to be 2646 kJ/kg
it is specific enthalpy i.e. $h_x < h_g$ & $h_x > h_f$
$\therefore$ wet steam

at 10 bar, $h_x = 2646$
$h_f = 762.6$ $h_g = 2776.2$

$h_x = h_f + x(h_g - h_f) \Rightarrow x = 0.935 = 93.5\%$

specific vol. $= V_x = V_f + x(V_g - V_f) = 0.18174 \ m^3/kg$

$\rho = \frac{1}{V_x} = 5.5022 \ kg/m^3$

3) At $p = 15$ bar, Temp $= 197.4°C$

Saturated temp at 15 bar $= T_s = 198.3°C$

as $T < T_s$

It is subcooled liq.

4) at $p = 20$ bar, $T = 225°C$ find h_g at $225°C$

$T_s = 212.4°C$

$T_s < T$

$\therefore$ Superheated liq

degree of superheat $= 225 - 212.4$

$= 12.6°C$

$x_1 = 212.4°C$ $\quad x_2 = 250$ $\quad x_3 = 225$

$h_{g_1} = 2797.2$ kJ/kg $\quad h_{g_2} = 29024$ $\quad h_{g_3} = ?$

equate slope $\quad h_{g_3} = 2833$ kJ/kg

5) 7 bar specific vol. $= 0.26$ m³/kg find quality of steam

$V_x = 0.26$

$V_x = V_f + x(V_g - V_f)$

$0.26 = 0.001108 + x(0.27268 - 0.001108)$

$x = 0.9533$

Thus we can find s_x, h_x also for same x

6) 5 bar $V_x = 0.45$ m³/kg

$V_x = V_f + x(V_g - V_f)$

$0.45 = 0.001093 + x(0.37466 - 0.001093)$ ⇒ here x will come out greater than 1

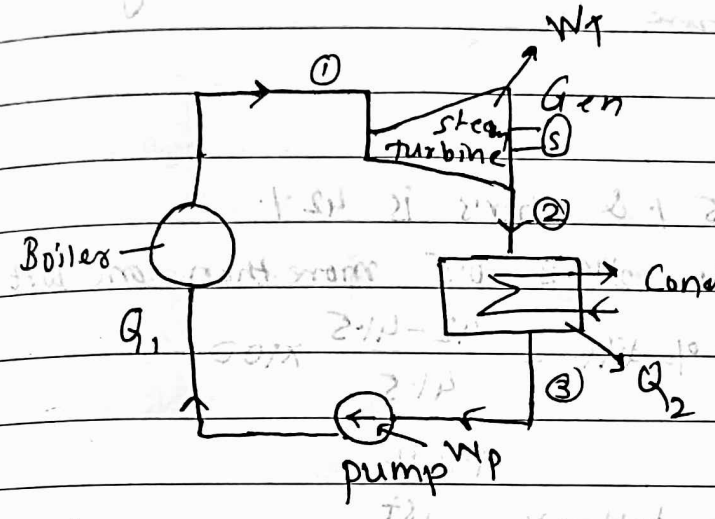
$V_x > V_g$ ⇒ Superheated steam

i) 8 bar total heat = 2805 kJ/kg

$h_f = 720.9$ kJ/kg $h_g = 2767.4$ kJ/kg

This is a superheated steam

* Rankine cycle



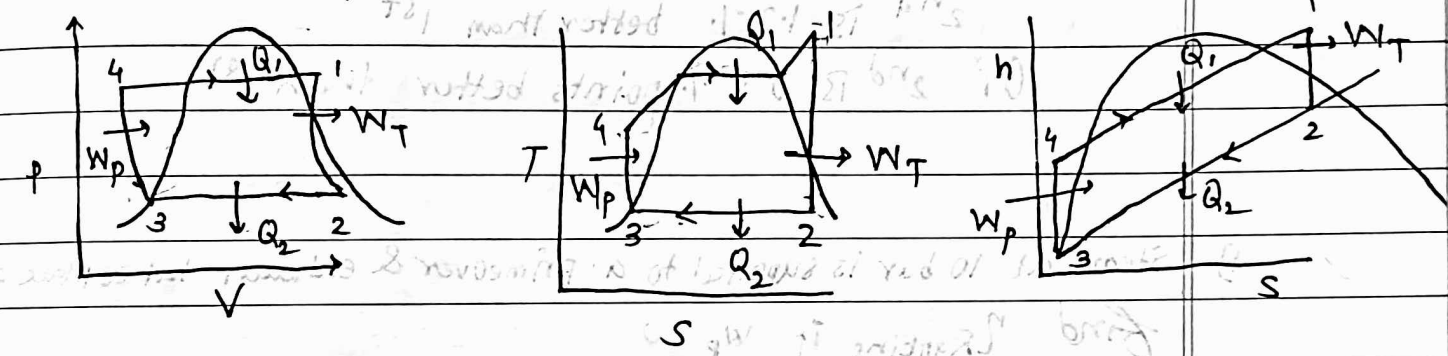
1-2 = rev. adiabatic (isentropic) expansion in turbine

2-3 isobaric heat reject^n in condensor reversible

3-4 rev. adiabatic (isentropic) compression in pump

4-1 rev isobaric heat addition in boiler

$Q_2 < 0$
$Q_1 > 0$
$W_p < 0$
$W_T > 0$



Assumptions:

i. Unit mass flow rate

ii. Neglecting changes in kinetic & potential energy

$Q_1 = h_1 - h_4$
$Q_2 = h_2 - h_3$
$W_p = h_4 - h_3$
$W_T = h_1 - h_2$

provide them with respective signs

$Q_1 > 0$
$Q_2 < 0$
$W_p < 0$
$W_T > 0$

$$\eta_{Rankine} = \frac{W_{net}}{Q_1} = \frac{W_T - W_p}{Q_1} = \frac{-(h_4 - h_3) + (h_1 - h_2)}{h_1 - h_4}$$

$$W_{net} = W_T - W_p = Q_1 - Q_2 = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_3) - (h_4 - h_3)} = \frac{h_1 - h_2 - W_p}{h_1 - h_3 - W_p}$$

$W_p << W_T \Rightarrow$ neglect W_p

$$\eta_{rankine} = \frac{h_1 - h_2}{h_1 - h_3}$$

P_1 = boiler pressure (main steam) (steam entering turbine)
P_2 = condenser pressure

One efficiency is 41.5 % & other's is 42 %.
this means 2nd is 0.5 more than one wrt 41.5

i.e % diff. $= \frac{42 - 41.5}{41.5} \times 100$

Imp

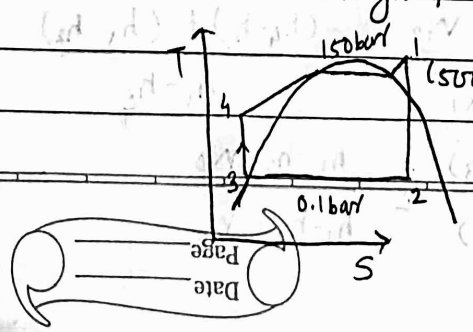
$= 1.2\%$

2nd is 1.2 % better than 1st
Or 2nd is 0.5 % points better than 1st

1] Steam at 10 bar is supplied to a primeover & exhaust takes place at 0.2bar
find $\eta_{Rankine}$ if $W_p = 0$
i. if steam is dry saturated at inlet.
ii. steam is 0.9 dry at inlet
iii. steam has 50°C superheat at inlet
Neglect pumpwork Also find η_{carnot} in each one

2] Find the efficiency of Rankine cycle having boiler pressure 150 bar at 500°C & ~~conduct~~ condenser pressure of 0.1 bar

Seeing in table, at 150 bar, saturated temp is 342.1°C
That means given temp is for saturated steam



1-2 is rev. adiabatic ⇒ isentropic

$S_1 = S_2$

Specific entropy at 150 bar & 500°C is 6.349

$\therefore S_x = 6.349$

$\therefore S_2 = 6.349$

$S_f = 0.649$ $S_g = 8.151$

$s_x = s_f + x(s_g - s_f)$

$x = 0.759$

$h_x = h_f + x(h_g - h_f)$

$h_x = h_2 = 2008.011$

h_3 will be h_f itself $x=0$ for that according to graph

$h_3 = 191.8$

$H = U + PV$

$\Delta Q = \Delta U + W$ $\quad \Delta H = \Delta U + PdV + VdP$

~~$Q = \Delta H - PV + PdV$~~

$\Delta Q = \Delta H - PdV - VdP + PdV$

$\Delta Q = \Delta H - VdP$

$\because$ adiabatic, $\Delta Q = 0$

$\therefore \Delta H = VdP$ $\quad P_1 = P_4,\ P_2 = P_3$

$\therefore h_4 - h_3 = V(P_1 - P_2)$ .... because the lines are ~~isentropic~~ ~~isobaric~~ isobaric

$h_4 - 191.8 = V_{f/0.1\,bar}(150 - 0.1)$

$h_4 - 191.8 = 0.00101 \times 149.9 \times 10^5 \times 10^{-3}$ kJ/kg

$h_4 = 206.94$ kJ/kg $\quad h_1 = h_{1/150\,bar,\ 500°C} = 3310.6$

$W_p = h_4 - h_3 = 2015.14$ kJ/kg

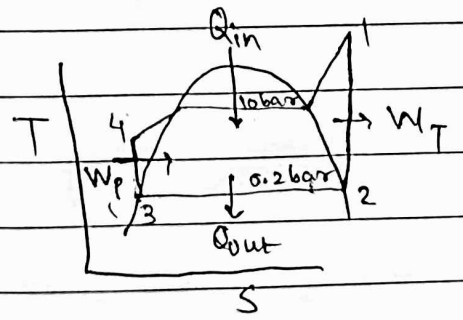
$W_T = h_1 - h_2 = 1300.65$ kJ/kg

$Q_2 = h_2 - h_3 = 1816.211$

$Q_1 = h_1 - h_4 = 3103.66$

$\eta_{rankine} = 1 - \frac{Q_2}{Q_1} = 41.48\%$

1] i.



$W_T = h_1 - h_2$

$W_p = h_4 - h_3$

$Q_{in} = h_1 - h_4$

$Q_{out} = h_2 - h_1$

for dry saturated steam, $h_2 = h_g|_{@0.2\,bar} = 2609.9$ kJ/kg

$h_3 = h_f|_{@0.2\,bar} = 251.5$ kJ/kg

$S_1 = S_2 = S_g|_{@0.2bar} = 7.909$ kJ/Kkg

S @ 500°C = 7.763

S @ 600°C = 8.029

We'll find temp for $S_1 = 7.909$

$$\frac{8.029 - 7.763}{600 - 500} = \frac{7.909 - 7.763}{T_1 - 500}$$

$$\frac{0.266}{14.6} = \frac{1}{T_1 - 500} \qquad T_1 = 554.88\,°C$$

now h @ 500°C = 3478.3

h @ 600°C = 3701.5

$$\frac{3701.5 - 3478.3}{100} = \frac{3701.5 - h_1}{600 - 554.88}$$

$h_1 = 3600.79$ kJ/kg

$W_p = h_4 - h_3 = 0$

$h_4 = h_3 \quad \therefore h_4 = 251.5$ kJ/kg

$$\eta_R = \frac{h_1 - h_2}{h_1 - h_3} = 29.58\%$$

$$\eta_{carnot} = 1 - \frac{T_2}{T_1}$$

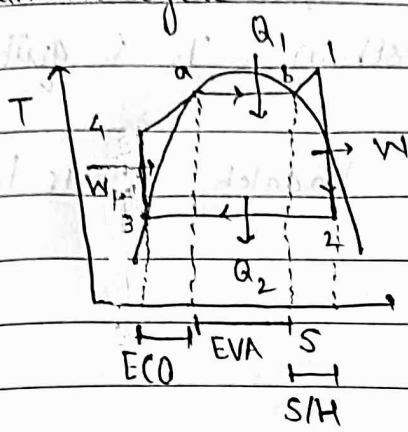
$\because$ Steam is dry saturated T_2 will be Saturated temp at 0.2bar

$\therefore T_2 = 60.1\,°C = 333.1K$

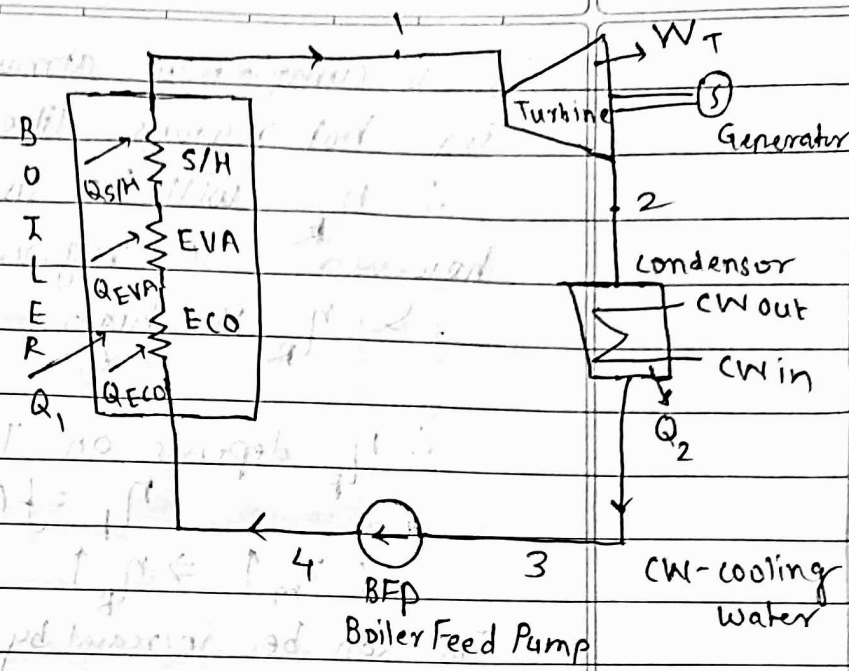
$T_1 = 554.88 + 273 = 827.88K$

$$\eta_{carnot} = 1 - \frac{T_2}{T_1} = 59.76\%$$

* Rankine cycle



Subcritical Steam Cycle



$(Temp)_{CW_{in}} < (Temp)_{CW_{out}}$

$Q_1 = Q_{ECO} + Q_{EVA} + Q_{S/H}$

ECO - ECOnomiser

EVA - EVAporator

S/H - Super Heater

4 → a is subcooled liq

a → b is wet steam, temp is constant it is called saturation ~~steam~~ temp.

b → 1 is superheated steam

* Mean temp. of heat addition (T_m)

It is theoritical constant temp. which gives same heat input as that of actual one

$Q_1 = h_1 - h_4 = T_m(S_1 - S_4)$

$$\boxed{T_m = \frac{h_1 - h_4}{S_1 - S_4}}$$

$Q_2 = h_2 - h_3 = T_2(S_2 - S_3)$

we know, $S_1 = S_2$ & $S_3 = S_4$

$$\eta_R = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2(S_2 - S_3)}{T_m(S_1 - S_4)}$$

$$\boxed{\eta_R = 1 - \frac{T_2}{T_m}}$$

Imp Ideally dryness fract^n at 2 is never less than 85 %.

if it is less than 0.85, there'll be more amount of water which will hamper the motion of blades of turbine & cause damage to it

~~Thill~~ This will have large economic loss & hence x is maintained always to be greater than 0.85

T_2 is completely atmosphere dependent
in hot regions like Rajasthan T_2 is quite high
$\therefore \eta_R$ will be low
however in regions like Ladakh, T_2 is low
& η_R is high

$\therefore \eta_R$ depends on T_m

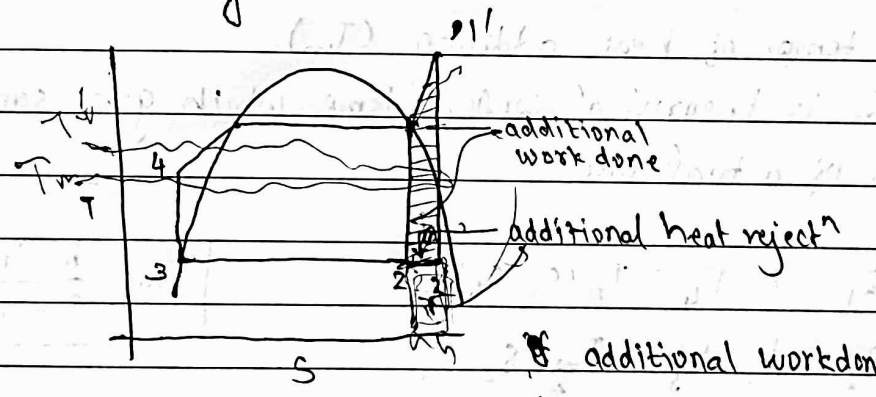
$$\eta_R = f(T_m)$$

if $T_m \uparrow \Rightarrow \eta_R \uparrow$

T_m can be increased by –

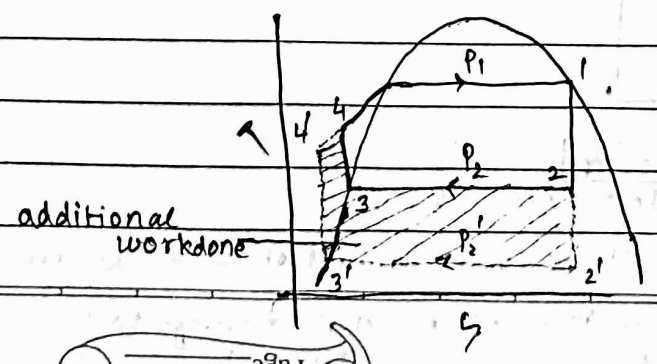
i. superheating
ii. increasing boiler pressure
iii. Reducing condenser pressure
iv. Reheating
v. Regenerating

i. Superheating



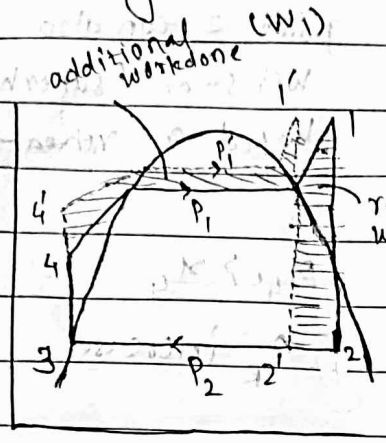
additional workdone > additional heat reject^n
η_R increases
dryness factor also increases

iii. Reducing condenser pressure



P_2 - condenser pressure
$P_2' < P_2$
additional workdone is present
here ~~satura~~ dryness factor decreases
$x_{2'} < x_2$
η_R increases

ii. Increasing boiler pressure



P_1 - boiler pressure

$P_1' > P_1$

$x_2' < x_2$

$W_1 > W_2$

η_R increases

$W_{P_1} = h_1 - h_2$

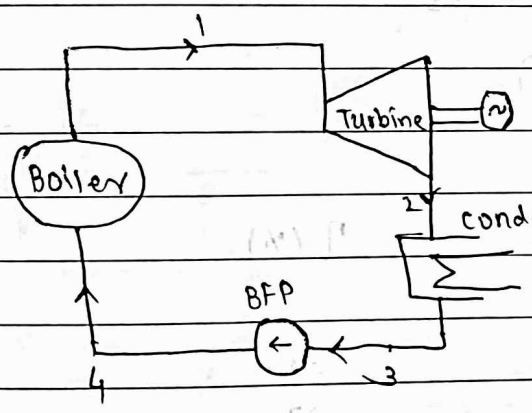
$W_{P_1'} = h_{1'} - h_2$

iv. Reheating

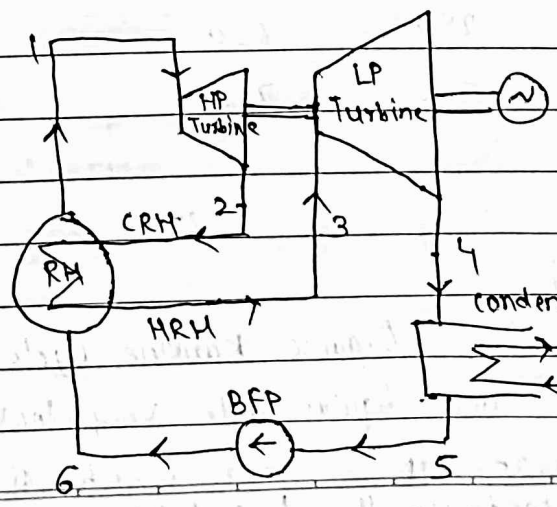
To improve the efficiency

To improve the quality of steam at the turbine exhaust

Modific^n in simple Rankine cycle ⇒ More than one stage turbines are used



modified



$P_2 < P_1$

HP - hot pressure

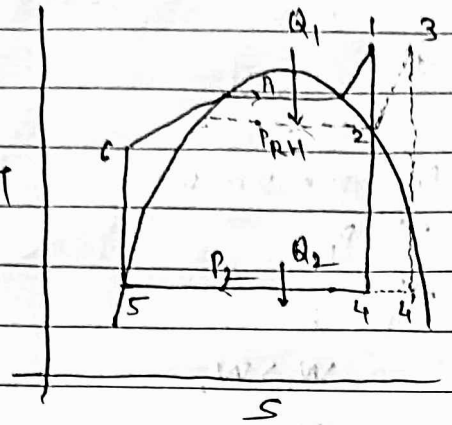
LP - low pressure

RH - reheater

CRH - cold ~~

HRH - hot ~~

T_1 & T_3 i.e. after reheating, temp is supposed to be same



point 2 can also be a wet steam / superheated steam based on reheating

$x_{4'} > x_4$

η_R increased.

$Q_1 = h_1 - h_6 + h_3 - h_2$

$Q_2 = \cancel{h_5 + h_4}\ h_4 - h_5$

$W_T = W_{HPT} + W_{LPT} = h_1 - h_2 + h_3 - h_4$

$\cancel{= h_2 - h_1 + h_4 - h_3}$

$W_p = h_6 - h_5$

$$\eta_{\text{Reheat rankine}} = \frac{Q_1 - Q_2}{Q_1} = \frac{h_1 - h_2 + h_3 - h_4 + h_5 - h_6}{h_1 - h_2 + h_3 - h_6}$$

$$= \frac{W_T - W_p}{Q_1}$$

$W_T - W_p = Q_1 - Q_2$

Imp → generally $\frac{1}{4} P_1 < P_{RH} < \frac{1}{3} P_1$

Type of power plant	Pressure (bar)	Temp (°C)	η (%)
subcritical	150	550	35
supercritical	250	600	37
ultrasupercritical	300	700	41

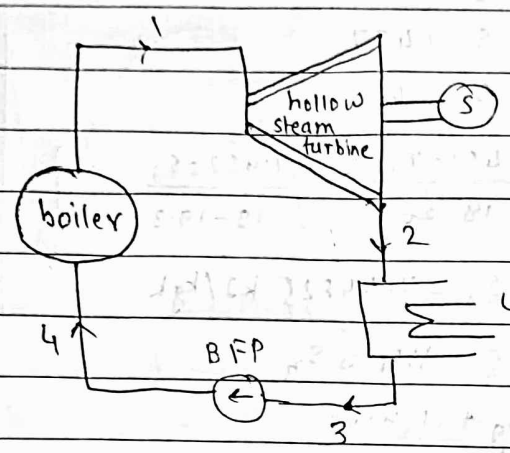
V. Regenerating

ORC - Organic Rankine Cycle

It uses liquids with very low boiling point. So that water in condenser which is at about 38°C easily condenses the low boiling point fluid thereby making lesser energy loss

This increases the efficiency of cycle

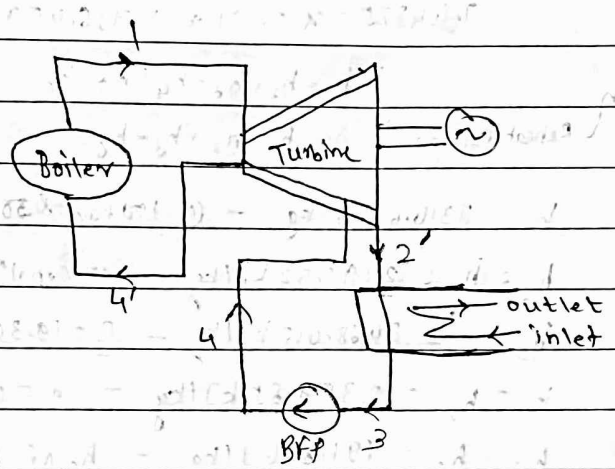
One more such cycle is Kalina cycle. It makes use of mixture of water & ammonia



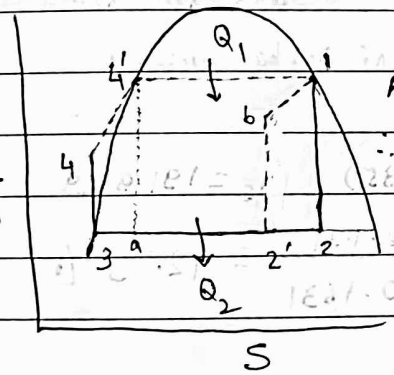
The turbine can't work both as workproducer & heat exchanger. dryness fracⁿ at the end of turbine exhaust reduces

modified

Regeneration is the attempt to convert the Rankine cycle ~~into Carnot~~ cycle.
Regeneration is Carnotizing the Rankine cycle



$x_{2'} < x_2$



Area(1b2'2) = Area(344'a)

$\therefore S_1 - S_{2'} = S_{4'} - S_3$

$\therefore S_{2'} - S_3 = S_1 - S_{4'}$

$Q_1 = h_1 - h_{4'}$ (boiler size increased)

$Q_2 = h_{2'} - h_3$ (condenser size decreased)

$$\eta_{Reg} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2(S_{2'} - S_3)}{T_1(S_1 - S_{4'})}$$

$W_p = h_4 - h_3$

$\therefore \boxed{\eta_{Reg} = 1 - \frac{T_2}{T_1}}$ ....like Carnot cycle

~~balancing energy at turbine,~~

$h_1 - h_{2'} + h_4 - h_{4'} - W_T = 0 \quad W_T = (h_1 - h_{2'}) - (h_{4'} - h_4)$

1] A power plant is running with subcritical steam condition (150 bar, 500°C) & expanded into the high pressure ~~taken~~ turbine so that the steam condition at the end of the turbine exhaust is dry saturated. The steam expanded into steam turbine & condensed at a pressure of 0.1 bar. find reheat pressure ~~(PR)~~ (P_{RH}) dryness fraction of LP turbine, find cycle efficiency

at the end of turbine means state 2 dry saturated means point 2 is on the curve. P_2 is P_{RH}

$P_1 = 150$ bar $T_1 = 500°C \Rightarrow$ from steam table, $S_1 = 6.349$ kJ/kgK

$S_1 = S_2 = 6.349$ $\because$ 2 is at dry saturated posⁿ, $S_2 = S_g = 6.349$

now we've to find P_2 at 19 bar, $S_g = 6.356$

at 19.5 bar, $S_g = 6.346$

using interpol^n, $\frac{6.356-6.346}{19-19.5} = \frac{6.356-6.349}{19-P_2}$

$\therefore P_2 = P_{Rh} = 19.35$ bar

now, $P_2 = P_3 = 19.35$ $T_3 = 500°C$ $S_3 = ?$

at 19 bar, $S = 7.457$

20 bar $S = 7.432$

using interpol^n, $\frac{7.457-7.432}{19-20} = \frac{7.457-S_3}{19-19.35}$

$S_3 = 7.44825$ kJ/kgK

now, $S_3 = S_4 = 7.44825 \rightarrow$ this is S_x

$S_x = x S_g + (1-x) S_f$

$7.44825 = x\, 8.151 + (1-x) 6.459 \Rightarrow x = 0.9063$

$$\eta_{\text{Reheat Rankine}} = \frac{h_1 - h_2 + h_3 - h_4 + h_5 - h_6}{h_1 - h_2 + h_3 - h_6}$$

$h_1 = 3310.6$ kJ/kg – @ 150 bar & 500°C from steam table

$h_2 = h_g = 2796.52$ kJ/kg – interpol^n from steam table

$h_3 = 3468.015$ kJ/kg – $P_3 = 19.35$ bar interpol^n

$h_4 = h_x = 2359.85$ kJ/kg – $x = 0.9063$ from formula

$h_5 = h_f = 191.8$ kJ/kg – h_f of 0.1 bar pressure

~~TMP~~ $\longrightarrow h_6 - h_5 = V_f (P_1 - P_2)$

$h_6 - 191.8 = 0.00101 (150 - 19.35)$, $h_6 = 191.9319$

$$\eta_{\text{Reheat}} = \frac{1622.1131}{3790.1631} = 42.79\%$$

* Regenerating Rankine cycle using Feed Water Heater

FWH

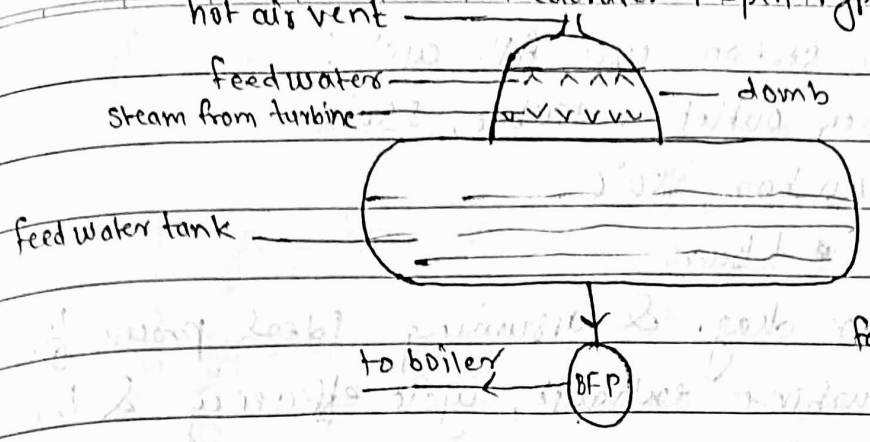
- open cycle — Direct contact type / Deaerator
- Closed type — Indirect type

Deaerator:

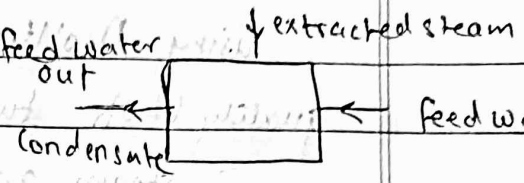
Removing air from feed water

Acting as heater to preheat the feed water

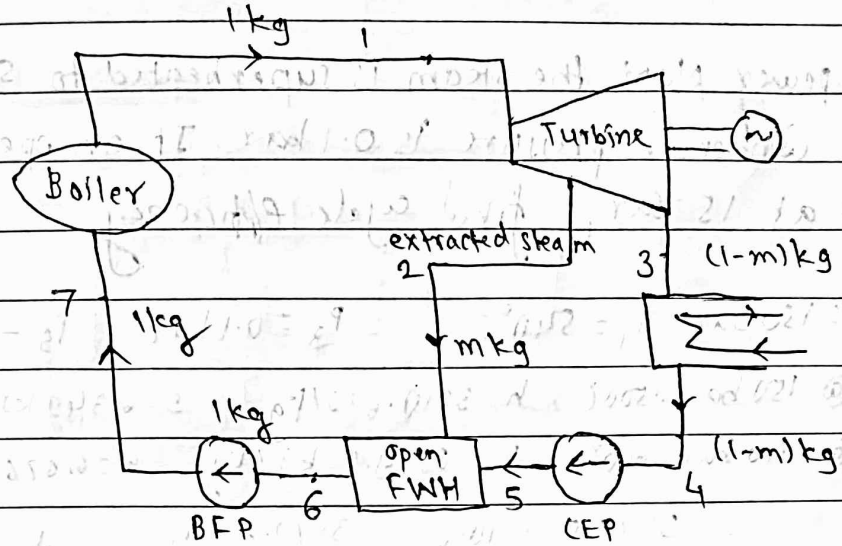
Deaerator / open type FWH



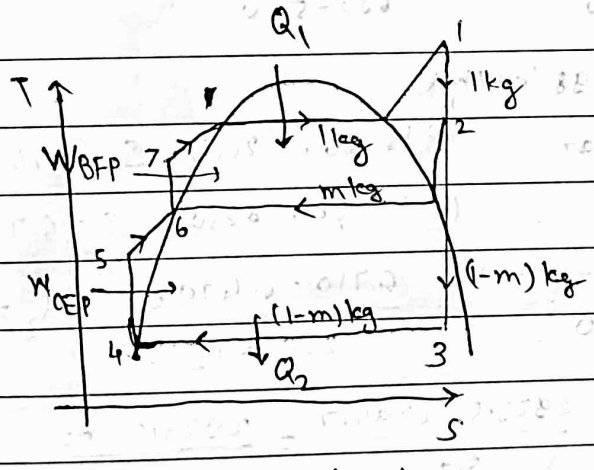
deaerator exchanges heat with feed water tank & and it gets heated the rest air expells through air vent



mixing of feed water & extracted steam takes place



extracted steam / bleed steam द्वारा m kg steam बाहर आता



$$Q_1 = 1 \times (h_1 - h_7)$$

$$Q_2 = (1-m)(h_3 - h_4)$$

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

$$W_p = W_{CEP} + W_{BFP}$$

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

for finding m, we've to do energy conservation across FWH

$$\Sigma \text{Energy}_{in} = \Sigma \text{Energy}_{out}$$

$$m h_2 + (1-m) h_5 = h_6$$

$$\therefore \boxed{m = \frac{h_6 - h_5}{h_2 - h_5}}$$

m is the fract^n of steam removed from 1 kg steam

VIMP

$$\boxed{\eta_{Reg} = 1 - \frac{Q_2}{Q_1} = \frac{W_T - W_p}{Q_1}}$$

1) A steam power station uses foll. cycle:
Steam at boiler outlet = 150 bar, 550°C
Reheat at 40 bar, 550°C
Condensor at 1 bar
Using Mollier diag. & assuming ideal process, find quality of turbine exhaust, cycle efficiency & the steam rate

2) In a power plant the steam is superheated to 540°C & 150 bar & the condenser pressure is 0.1 bar. If an open FWH is placed at 15 bar, find cycle efficiency

$P_1 = 150$ bar $T_1 = 540°C$ $P_3 = 0.1$ bar $P_5 = 15$ bar

@ 150 bar 500°C, $h = 3310.6$ kJ/kg $s = 6.349$ kJ/kgK

@ 150 bar 600°C, $h = 3579.8$ kJ/kg $s = 6.676$ kJ/kgK

$$\therefore \frac{3579.8 - 3310.6}{100} = \frac{3579.8 - h_1}{600 - 540} \qquad h_1 = 3418.28 \text{ kJ/kg}$$

$$\frac{6.676 - 6.349}{100} = \frac{6.676 - s_1}{600 - 540} \qquad s_1 = 6.4798 \text{ kJ/kgK}$$

$s_1 = s_2 = 6.4798$ kJ/kgK

$P_5 = P_2 = 15$ bar @ 15 bar 200°C $s = 6.451$ $h = 2794.7$

@ 15 bar 250°C $s = 6.710$ $h = 2923.5$

$$\therefore \frac{6.710 - 6.451}{50} = \frac{6.710 - 6.4798}{250 - T_2} \qquad T_2 = 205.5598°C$$

now @ 1 $$\frac{2923.5 - 2794.7}{50} = \frac{2923.5 - h_2}{250 - 205.5598}$$

$\therefore h_2 = 2809.022$ kJ/kg

$s_1 = s_2 = s_3 = 6.4798$ kJ/kgK

i.e $s_3 = s_x = 6.4798$

@ $P_3 = 0.1$ bar $s_f = 0.649$ $s_g = 8.151$ $h_f = 191.8$ $h_g = 2584.7$

$6.4798 = 0.649 + x(7.502)$ $x = 0.77723$

$h_x = 191.8 + 0.77723 \times 2392.9$

$h_x = h_3 = 2051.6402$ kJ/kg

$h_4 = h_f = 191.8$ kJ/kg

$h_5 - h_4 = v_f (P_5 - P_4)$

$h_5 - 191.8 = 0.001010 (15 - 0.1)$

$h_5 = 191.81505$ kJ/kg

$h_6 = h_f$ @ 15 bar $= 844.6$ kJ/kg

$h_7 - h_6 = v_f (P_7 - P_6)$

$h_7 - 844.6 = 0.001154 (150 - 15) = 844.7558$ kJ/kg

$$m = \frac{h_6 - h_5}{h_2 - h_5} = 0.24942$$

$Q_2 = (1-m)(h_3 - h_4) = 1395.958$

$Q_1 = 1(h_1 - h_7) = 2573.5242$

$$\eta_{Reg} = 1 - \frac{Q_2}{Q_1} = 0.457569$$

$\eta_{Reg} \approx 45.76\%$

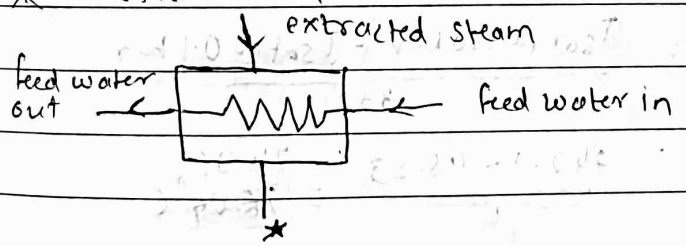
1) $P_1 = 150$ bar $T_1 = 550°C$

$P_3 = P_2 = 40$ bar $T_3 = 550°C$

$P_4 = 1$ bar

@150 bar, 550°

* Closed FWH



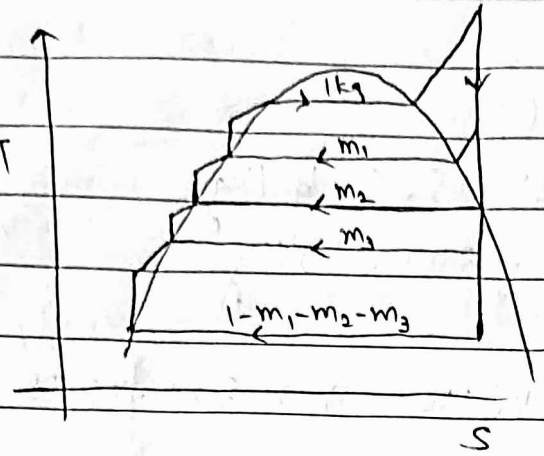
case ① if * goes in forward direct^n, it'll go to higher pressure for that purpose pump is needed ∴ feed forward goes to drift pump

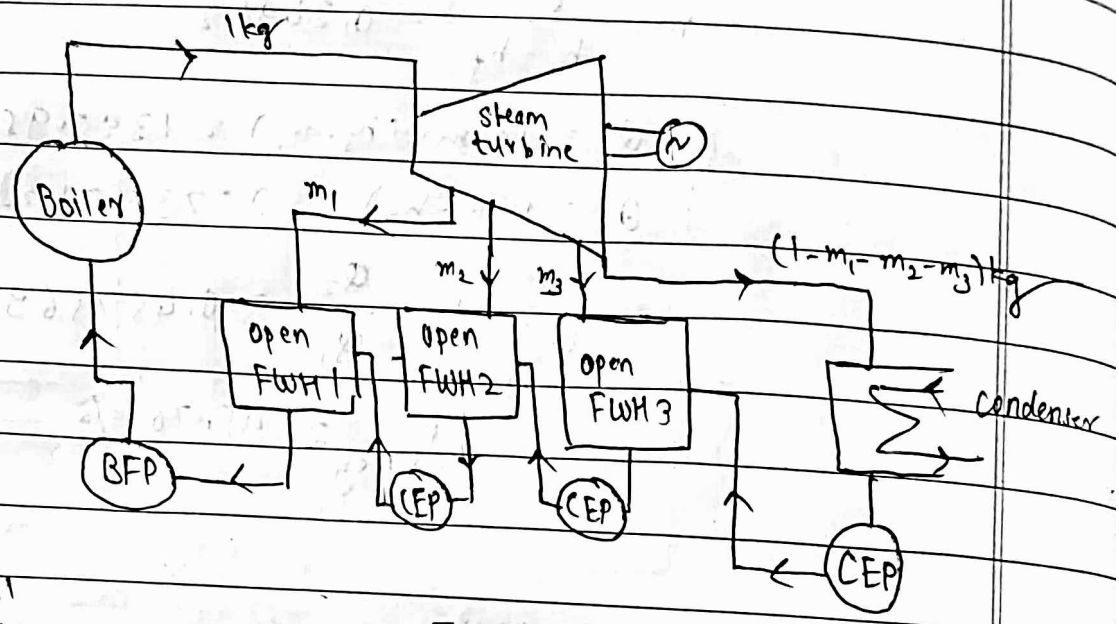
if * goes in backward direct^n, it'll go to condenser

In actual power plant, 1 open FWH is present & the rest are closed FWH

greater the no. of FWH, less amount of steam is going into the condenser

suppose 3 FWH are placed





Temp fall across each FWH $= \dfrac{T_{sat}\text{ @ boiler pressure} - T_{sat}\text{ @ condensor pressure}}{n+1}$

n = no. of FWH

suppose boiler pressure = 150 bar

condensor " = 0.1 bar

$\therefore$ Temp fall $= \dfrac{T_{sat}\text{ @ 150 bar} - T_{sat}\text{ @ 0.1 bar}}{3+1}$

$= \dfrac{342.1 - 45.83}{4} = 74.06$ °C

after passing through FWH1, temp will be $342.1 - 74.06$

$= 268.03$ °C

" " " FWH2, " " $= 268.03 - 74.06$

$= 193.97$ °C

" " FWH3 " " $= 193.97$ °C $- 74.06$ °C

$= 119.91$ °C

$= \frac{1}{W_{net}} \frac{kg}{kWs}$

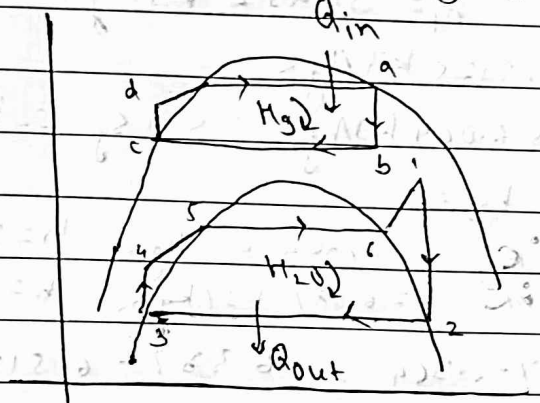
* Steam rate $= \frac{3600}{W_{net}}$ kg/kWhr — Amount of steam needed to produce 1 unit of shaft power

* Heat rate $= \frac{3600}{\eta} \frac{kJ}{kWh} = \frac{1}{\eta} \frac{kJ}{kWs}$ — $\eta = Q/W$, $\frac{1}{\eta} = W/Q$

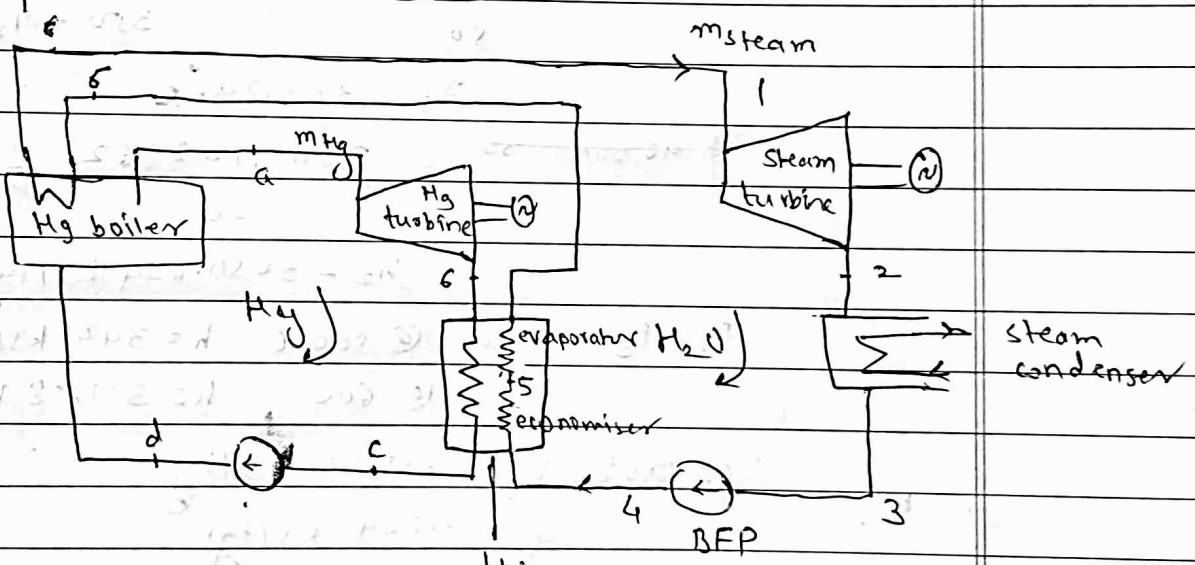
To produce 1 unit of shaft power, how much heat is req. is heat rate. 1 unit = 1 kWhr

* Binary vapour cycle

Mercury in topping cycle
Water in bottoming cycle } both are Rankine



heat released by Mercury at c to d = heat gained for evaporat^n of steam at 5-6



this is Hg ~~generator~~ condensor cum steam generator

~~$Q_{in} = m_{Hg}(h_a - h_d)$~~

$Q_{in} = m_{Hg}(h_a - h_d) + m_{H_2O}(h_5 - h_4 + h_1 - h_6)$

$Q_{out} = m_{H_2O}(h_2 - h_3)$

$W_T = m_{Hg}(h_a - h_b) + m_{H_2O}(h_1 - h_2)$

$W_P = m_{Hg}(h_d - h_c) + m_{H_2O}(h_4 - h_3)$

$m_{Hg}(h_b - h_c) = m_{H_2O}(h_c - h_5)$

$$\eta = 1 - \frac{Q_{out}}{Q_{in}}$$

1] $P_1 = 150$ bar $\quad T_1 = 550°C$

$P_{RH} = P_2 = 40$ bar $\quad T_3 = 550°C$

$P_4 = 1$ bar

@ 150 bar 500°C $\quad s = 6.349$ KJ/kgK $\quad h = 3310.6$ kJ/kg

@ 150 bar 600°C $\quad s = 6.676$ kJ/kgK $\quad h = 3579.8$ kJ/kg

∴ 150 bar 550°C, $s_1 = 6.5125$ kJ/kgK

$h_1 = 3445.2$ kJ/kg

$s_1 = s_2 = 6.5125$ kJ/kgK

∵ s_g @40 bar is 6.069 kJ/kgK $\quad s_2 > s_g$ ∴ it is superheated steam ∴ ~~$h_2 =$~~

@ 40 bar 300°K, $s = 6.364$ kJ/kgK $\quad h = 2962$ kJ/kg

—— 350°K $\quad s = 6.587$ kJ/kgK $\quad h = 3095.1$ kJ/kg

$$\therefore \frac{6.587 - 6.364}{50} = \frac{6.587 - 6.5125}{350 - T_2}$$

$T_2 = 333.296$°K

~~@ 40 bar 30~~

$$\frac{3095.1 - 2962}{50} = \frac{3095.1 - h_2}{16.704}$$

$h_2 = 3050.634$ kJ/kg

$P_2 = P_3 = 40$ bar @ 500°C $\quad h = 3445$ kJ/kg $\quad s = 7.091$ kJ/kgK

@ 600 $\quad h = 3712.8$ kJ/kg $\quad s = 7.368$ kJ/kgK

∴ @ 550°C, $h_3 = 3558.4$ kJ/kg

$s_3 = 7.2295$ kJ/kgK

$P_4 = 1 \quad s_3 = s_4 = s_x = 7.2295$ kJ/kgK

$= s_f + x(s_g - s_f) = 1.303 + x(6.057)$

quality of steam turbine $= x = 0.9784$

$h_x = h_4 = h_f + x(h_g - h_f)$

$= 417.5 + 0.9784(2257.9)$

$h_4 = 2626.753$ kJ/kg

$h_5 = h_f = 417.5$ kJ/kg

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$h_6 - h_5 = V_f (P_6 - P_5)$

$h_6 - 417.5 = 0.001043 (150 - 1)$ $\quad h_6 = 417.6554$ kJ/kg

$$\eta = \frac{h_1 - h_2 + h_3 - h_4 + h_5 - h_6}{h_1 - h_2 + h_3 - h_6} = \frac{1326.0576}{3535.3106}$$

$$= 0.3751$$

$$\text{heat rate} = \frac{1}{\eta} = 2.666 \ \frac{kJ}{kWs} = 9597.7 \ \frac{kJ}{kWHr}$$

$W_{net} = W_T - W_p = 1326.0576$

$$\text{steam rate} = \frac{1}{W_{net}} = 7.54 \times 10^{-4} \ \frac{kg}{kWs}$$

$$= 2.7144 \ kg/kWHr$$