Problem 1 Steam (dry and saturated) is supplied by the boiler at 15 bar and the condenser pressure is 0.4 bar. Calculate the Carnot and Rankine efficiencies of the cycle. Neglect the pump work.

Problem 2 The table below represents the steps of an idealised steam power plant:

Step	Location	Pressure (bar)	Temperature (°C)	Quality / State	Velocity m/s
1	Inlet to turbine	60	380	–	–
2	Exit from turbine and inlet to condenser	0.1	–	0.9	200
3	Exit from condenser and inlet to pump	0.09	–	Saturated Liquid	– –
4	Exit from pump and inlet to boiler	100	–	–	–
5	Exit from boiler	80	440	–	–

Assume that the steam mass flow rate leaving the boiler is 10^4 kg.h^{-1}. Sketch the cycle numbering each stage. Calculate:

(a) Specific enthalpies of all streams;

(b) Power output of the turbine;

(c) Heat transfer per hour in the boiler and condenser;

(d) Mass rate of cooling water circulated (kg/h) in the condenser assuming inlet and outlet fluid temperatures from the condenser of 20°C and 30°C. Assume the heat capacity at constant pressure of the cooling water (C_p) is 4.18 $\frac{\text{kJ}}{\text{kg.°C}}$;

(e) Diameter of the pipe connecting the turbine with the condenser;

(f) Sketch the Ts diagram, indicating each step of the cycle.

Problem 3 In the secondary cooling circuit of a nuclear power plant, the steam generator (boiler / reheater) produces superheated steam (SHS, Fig. 1) and is connected to two turbines operating as a reheat Rankine cycle. Isentropic efficiencies of the first (η_{T1}) and second (η_{T2}) turbines are 84%, 80%, respectively. The mass flow rate of water in the system is 1000 kg.s^{-1}.

- Determine *(a)-(t)* in Table 1;
- Calculate the produced by the turbines;
- Calculate the heat supplied by the boiler;
- Calculate the heat extracted from the condenser. Assume that the heat capacity at constant pressure (C_p) is 4.18 $\frac{\text{kJ}}{\text{kg.°C}}$;

Stage	P (bar)	T (°C)	State	Quality	h (kJ.kg^{-1})	s (kJ.(kg.K)$^{-1}$)
1	40	320	SHS	–	**(a)**	**(b)**
2	–	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**
3	7	370	SHS	–	**(h)**	**(i)**
4	0.10	**(j)**	**(k)**	**(l)**	**(m)**	**(n)**
5	0.10	**(o)**	**(p)**	–	**(q)**	**(r)**
6	40	–	**(s)**	–	**(t)**	–

Table 1: **Problem 3**.

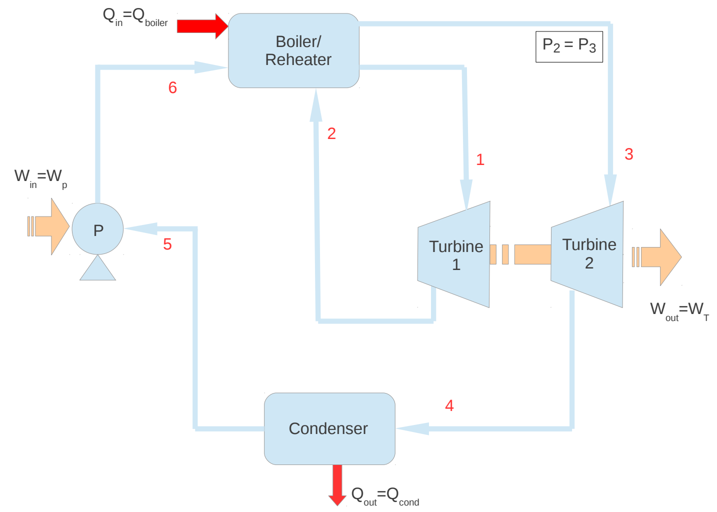


Figure 1: **Problem 3**

- Sketch the Ts diagram of the cycle.

Problem 4 A Carnot engine with water/steam (1 kg/s) as the working fluid operates on the cycle shown in Fig. 2. For $T_1 = 475\ K$ and $T_2 = 300\ K$, determine: (a) pressures at states 1, 2, 3, and 4; (b) quality x^{vapour} at states 2 and 3; (c) rate of heat addition; (d) rate of heat rejection; (e) mechanical power for each of the four steps; (f) thermal efficiency (η) of the cycle.

Problem 5 Water is the working fluid in an ideal Rankine cycle. Dry saturated vapour enters the turbine at 16 MPa, and the condenser pressure is 8 kPa. The mass flow rate of steam entering in the turbine is 120 kg/s. Calculate:

(a) the net power developed (in MW);

(b) rate of heat transfer to the steam passing through the boiler (in MW);

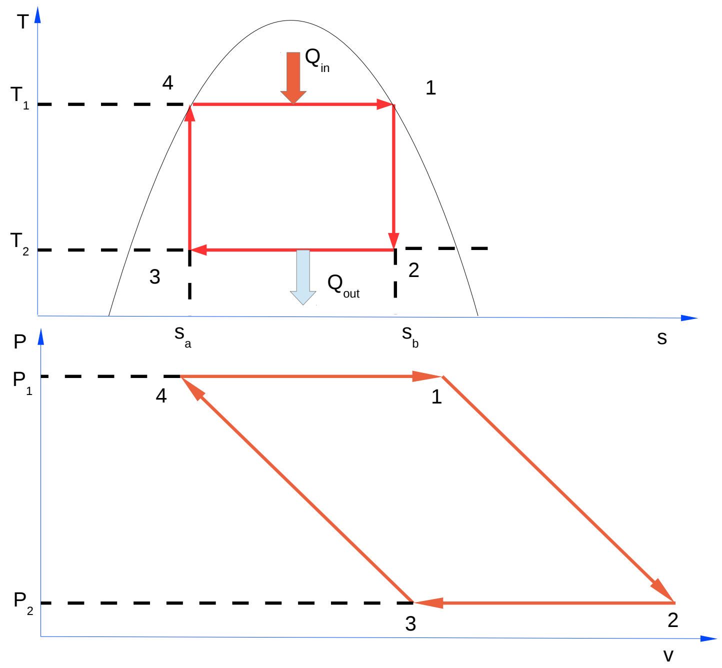


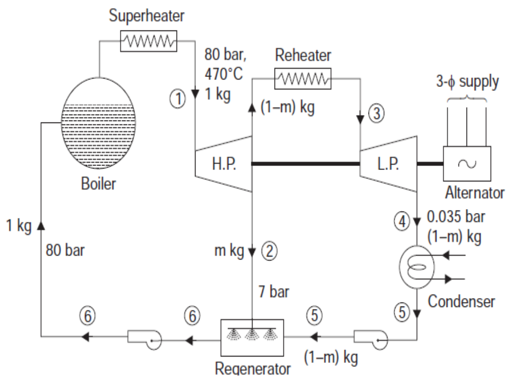
Figure 2: Ts and Pv diagrams for Carnot cycle (**Problem 4**).

(c) thermal efficiency;

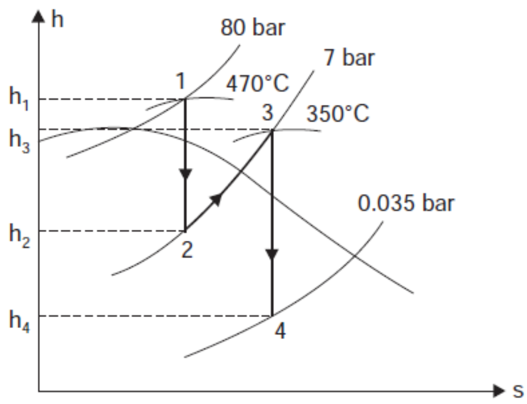
(d) mass flow rate of the condenser cooling water (in kg/s), if the cooling water undergoes a temperature increase of 18^{o}C with negligible pressure change in passing through the condenser. Assume that the heat capacity at constant pressure $\left(C_p\right)$ of the cooling water is 4.18 $\frac{\text{kJ}}{\text{kg.}^o\text{C}}$.

Problem 6 A steam power plant operates with with regenerative and reheat arrangement cycles. Steam is supplied to the H.P. turbine (Fig. 3a) at 80 bar and 470^{o}C. For feed heating, a part of steam is extracted at 7 bar and remainder of the steam is reheated to 350^{o}C in a reheater and then expanded in L.P. turbine down to 0.035 bar. Determine: (a) amount of steam bled-off for feed heating; (b) amount of steam supplied to L.P. turbine; (c) heat supplied to the boiler and reheater; (d) cycle efficiency, and (e) power developed by the system. The steam supplied by the boiler is 50 kg/s.

Problem 7 Steam power plant operating on a regenerative cycle, includes just one feedwater heater (FWH). Steam enters the turbine at 4000 kPa and 773.15 K and exhausts at 20 kPa. Steam for the FWH is extracted from the turbine at 70 kPa, and in condensing raises the temperature of the feedwater to within 7 K of its condensation temperature at 70 kPa. After fully condensed, the bled-off water the FWH is driven back to the condenser, where it mixes with the main wet vapour stream from the turbine. If the turbine and pump efficiencies are both 85%, what is the thermal efficiency of the cycle and what fraction of the steam entering the turbine is extracted for the feedwater heater?



(a)



(b)

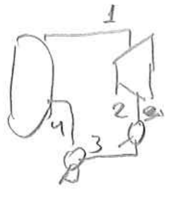
Figure 3: (a) Schematics and (b) hs diagram of a steam power cycle (**Problem 6**).

Assume that the enthalpy of the water fed into the boiler (h_i) is given by

$$h_i = h_{\text{liquid}}^{\text{sat}} + v_{\text{liquid}}^{\text{sat}} \left(1 - \beta T_i\right) \left(P_i - P^{\text{sat}}\right)$$

where v is the specific volume and $\beta = \dfrac{1}{v}\left(\dfrac{\partial v}{\partial T}\right)_P$ is the volume expansivity of the water.

P1 Water-Steam system



$$\left\{ \begin{array}{l} P_1 = 15 \text{ bar} \\ x_1 = 1 \text{ (dry \& saturated)} \end{array} \right. \Rightarrow \text{from saturated table} \left\{ \begin{array}{l} T_1 = T_{sat} = 198.3 °C \\ h_1 = h_g = 2792.2 \text{ KJ/Kg} \\ S_1 = S_g = 6.4448 \text{ KJ/Kg.K} \end{array} \right.$$

$$P_2 = 0.4 \text{ bar} \left\{ \begin{array}{l} T_2 = T_{sat} = 75.87 °C \\ h_g = 2636.8 \text{ KJ/Kg} \quad ; \; S_g = 7.6700 \text{ KJ/Kg.K} \\ h_f = 317.58 \text{ KJ/Kg} \quad ; \; S_f = 1.0259 \text{ KJ/Kg.K} \end{array} \right.$$

$$\eta_{Carnot} = 1 - \frac{T_2}{T_1} = 1 - \frac{(75.87 + 273.15)\,K}{(198.3 + 273.15)\,K} = 0.2597 \therefore \underline{\underline{25.97\%}}$$

$$\eta_{Rankine} = \frac{\text{Adiabatic or Isentropic Heat Drop}}{\text{Heat Supplied}} = \frac{h_1 - h_2}{h_1 - \underbrace{h_{f2}}}$$

assume $h_{f2} = h_{f4}$

$$h_2 ? \Rightarrow h_2 = h_{f2} + x_2 (h_{g2} - h_{f2})$$

$$x_2 : ?$$

Steam expands isentropically : $S_1 = S_2$

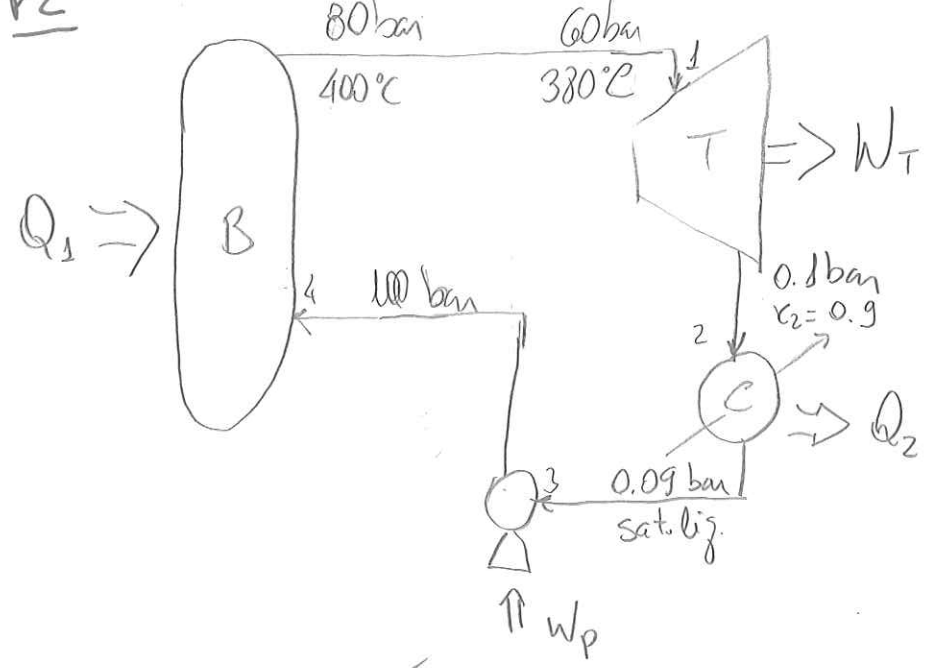
$$S_2 = S_{f2} + x_2 (S_{g2} - S_{f2}) = S_1 = 6.4448$$

$$x_2 = 0.8156 \therefore 81.56\%$$

$h_2 = 2209.14\ KJ/Kg$

$\eta_{Rankine} = 0.2356 \therefore \underline{23.56\%}$

P2



(a) Calculating $\underline{h}$ and $\underline{s}$ of all streams.

(1) Fluid entering the turbine $\begin{cases} P_1 = 60\,\text{bar} \\ T_1 = 380\,°C \end{cases}$

- superheated steam: $T_1 > T_{sat}\,(275.6\,°C)$
- through linear interpolation: $h_1 = 3124.15$ KJ/Kg ; $S_1 = 6.4595$ KJ/Kg.K

(2) Fluid leaving the turbine (isentropic expansion)

$S_2 = S_1$

and the fluid is 90% dry ($x_2 = 0.90$) at 0.1 bar

$$h_2 = h_{f_2} + x_2\,(h_{g_2} - h_{f_2})$$

$$h_2 = 191.83 + 0.90\,(2584.7 - 191.83) = 2345.41\ \text{KJ/Kg}$$

(3) Saturated liquid leaving the condenser:

$$h_3 = h_f\,(P = 0.09\,\text{bar}) = 182.86\ \text{KJ/Kg}$$

$S_3 = S_f(P = 0.09\,bar) = 0.6210\ KJ/Kg.K$

(4) $P_4 = 75\,bar$ (incompressible fluid)

$$\int_{h_3}^{h_4} dh = v \int_{P_3}^{P_4} dP$$ (isentropic compression)

$S_4 = S_3$

$$h_4 = h_3 + v_3 (P_4 - P_3)$$

$$v_3 = v_f(P_3 = 0.09\,bar) = 1.0093 \times 10^{-3}\ m^3/Kg$$

$$h_4 = 182.86\ \frac{KJ}{Kg} + 1.0093 \times 10^{-3}\ \frac{m^3}{Kg}\ (100 - 0.09)\,bar$$

$$h_4 = 192.94\ KJ/Kg$$

(b) Power from turbine

$$\dot{W}_T = \dot{m}_w (h_2 - h_1) = 10^4\ \frac{Kg}{h}\ (2345.41 - 3124.15)\ \frac{KJ}{Kg}$$

$$\dot{W}_T = -2163.17\ KJ/s = -2163.17\ KW$$

(c) HT (per hour)

- Boiler: $\left\{ \begin{array}{l} 80\ bar \\ 440°C \end{array} \right\}$

- superheated steam:
  $440°C > T_{sat} (= 295.06°C)$
  $h = 3246.1\ KJ/Kg$
  $S = 6.5190\ KJ/Kg.K$

$$\dot{Q}_1 = \dot{m}_\omega \left[h(P = 80\,\text{bar}) - h_4 \right]$$

$$\dot{Q}_1 = 10^4 \frac{Kg}{h} \left[3246.1 - 192.94 \right] KJ/Kg = 8481\ KJ/s$$

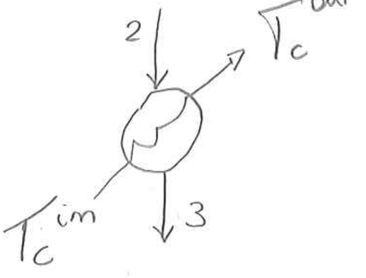
$$\dot{Q}_1 = 8481\ KW = 3.05 \times 10^7\ KJ/h$$

• Condenser:

$$\dot{Q}_2 = \dot{m}_\omega \left[h_3 - h_2 \right] = 10^4 \frac{Kg}{h} (182.86 - 2345.41) \frac{KJ}{Kg}$$

$$\dot{Q}_2 = -2.16 \times 10^7\ KJ/h = -6007.08\ KW$$

(d) $\dot{m}_c$: ? Heat lost from the steam is fully transferred to the cooling water



$$\dot{Q}_c = -\dot{Q}_2$$

$$\dot{Q}_c = -2.16 \times 10^7 \frac{KJ}{h}$$

$$\dot{Q}_c = \dot{m}_c Cp_c (T_c^{out} - T_c^{in})$$

$$\dot{m}_c \times 4.18 \frac{KJ}{Kg.°C} (30 - 20)°C = 2.16 \times 10^7 \frac{KJ}{h}$$

$$\dot{m}_c = 5.17 \times 10^5\ Kg/h$$

(e) diameter ϕ ?

$$\underbrace{\frac{\pi}{4}\phi^2}_{\text{cross-section area of the pipe}} \, u_2 = \dot{m}_w \, v_2$$

200 m/s

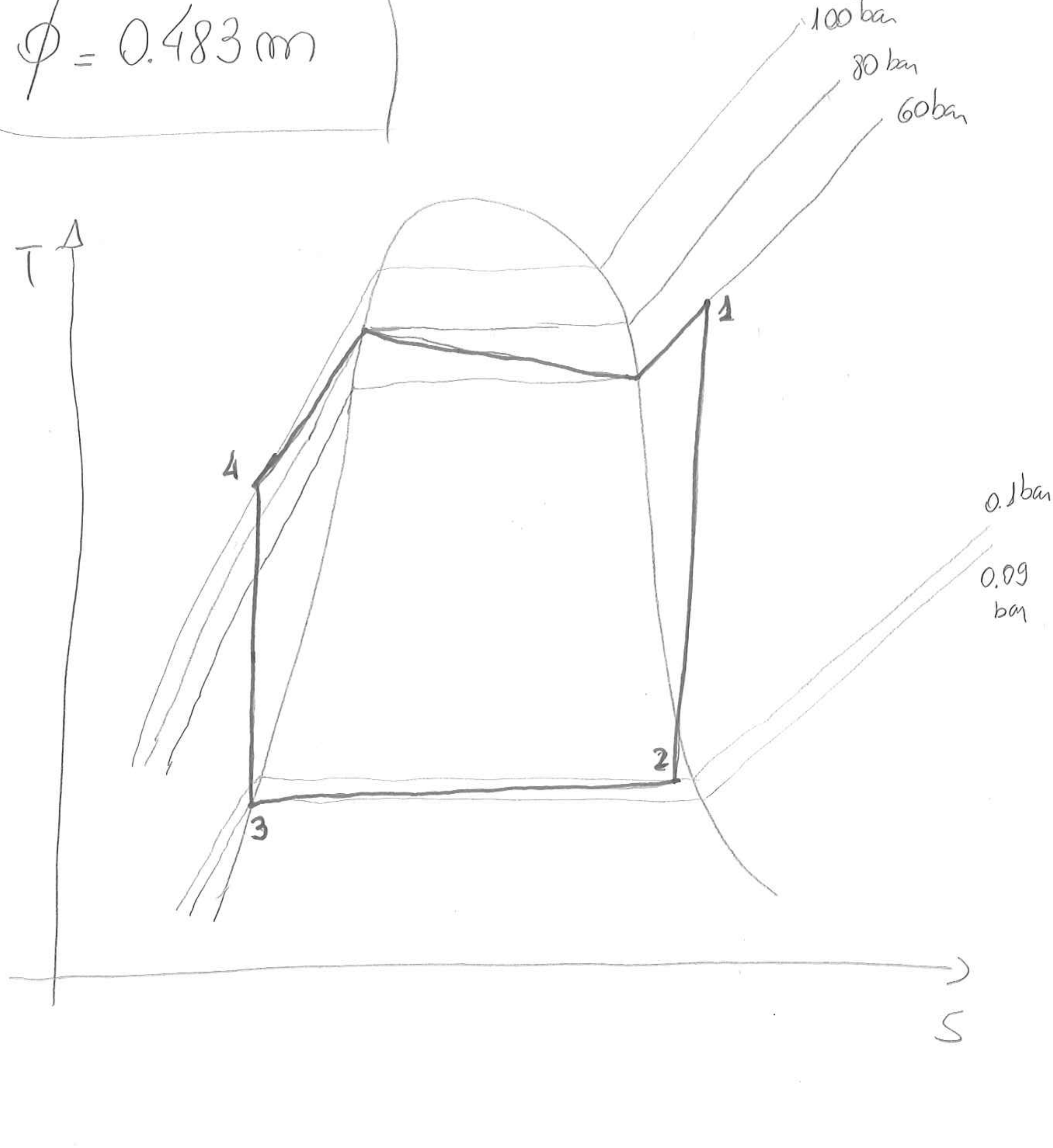
$P_2 = 0.1$ bar

$$v_2 = v_{f_2} + x_2 \left(v_{g_2} - v_{f_2} \right)$$

$$v_2 = 13.21 \text{ m}^3/\text{Kg}$$

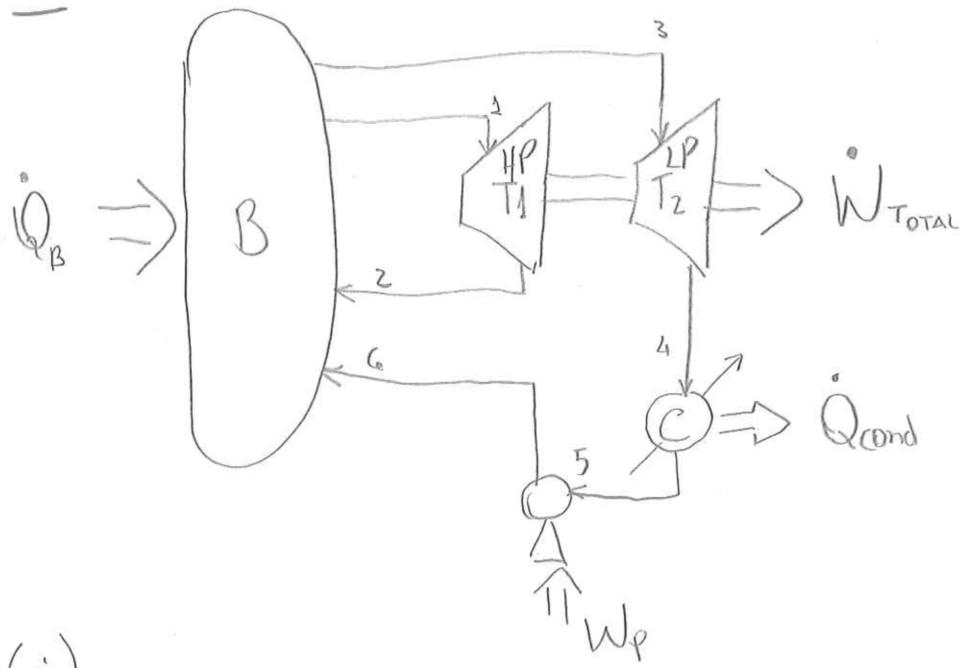
$$\boxed{\phi = 0.483 \text{ m}}$$

(f)



P3

$P_2 = P_3$



$\eta_{T_1} = 84\%$

$\eta_{T_2} = 80\%$

$\eta_P = 61\%$

(i)

(1) $P_1 = 40$ bar, $T_1 = 320°C$ $\left\{ \begin{array}{l} h_1 = 3015.4 \text{ KJ/Kg} \quad \text{(a)} \\ s_1 = 6.4553 \text{ KJ/Kg.K} \quad \text{(b)} \end{array} \right.$

(2) Ideal ; $S_{2S} = S_1$

$P_2 = P_3 = 7$ bar

$\hookrightarrow S_g(P = 7 \text{ bar}) = 6.7080 \text{ KJ/Kg.K} > S_{2S}$

(d)

(c) $\boxed{T_2 = T_{sat} = 165°C}$ $\Leftarrow$ $\boxed{\text{Saturated vapour}}$ (2 phase region)

Calculating how vaporised the water-steam system is:

$$S_{2S} = S_{f_2} + x_{2S}(S_{g_2} - S_{f_2})$$

$$6.4553 = 1.9922 + x_{2S}(6.7080 - 1.9922)$$

$$x_{2S} = 0.9464$$

$$h_{2s} = h_{f2} + x_{2s}(h_{g2} - h_{f2})$$

$$h_{2s} = 2652.75 \text{ KJ/Kg}$$

with the efficiency of the first turbine:

$$\eta_{T_1} = \frac{h_2 - h_1}{h_{2s} - h_1} = 0.84 \therefore \boxed{h_2 = 2710.77 \text{ KJ/Kg}} \ (f)$$

actual enthalpy

now calculating the actual quality:

$$h_2 = h_{f2} + x_2(h_{g2} - h_{f2})$$

$$\boxed{x_2 = 0.9745} \ (e)$$

and the actual entropy:

$$S_2 = S_{f2} + x_2(S_{g2} - S_{f2})$$

$$\boxed{S_2 = 6.5877 \text{ KJ/Kg.K}} \ (g)$$

(3) $P_3 = 7$ bar $\;$ $h_3 = 2932.2$ KJ/Kg $\quad$ (h)
$T_3 = 240°C$ $\;$ $S_3 = 7.0641$ KJ/Kg.K $\quad$ (i)

(4) Ideal: $S_{4s} = S_3$

$P_4 = 0.1$ bar $\therefore S_g(P = 0.1 \text{ bar}) = 8.1502 \text{ KJ/Kg.K} > S_{4s}$

(j) $\boxed{T_4 = T_{sat} = 45.81°C} \Leftarrow \boxed{\text{saturated vapour}}$ (K)

Calculating ideal quality:

$$S_{4s} = S_{f4} + x_{4s}(S_{g4} - S_{f4})$$

$$7.0641 = 0.6493 + x_{4s}(8.1502 - 0.6493)$$

$$x_{4s} = 0.8552$$

and ideal enthalpy

$$h_{4s} = h_{f4} + x_{4s}(h_{g4} - h_{f4})$$

$$h_{4s} = 2238.21 \text{ KJ/Kg}$$

With the efficiency of the second turbine:

$$\eta_{T_2} = \frac{h_4 - h_3}{h_{4s} - h_3} = 0.80 \therefore \boxed{h_4 = 2377.01 \text{ KJ/Kg}} \text{ (m)}$$

now calculating actual quality:

$$h_4 = h_{f4} + x_4(h_{g4} - h_{f4}) \therefore \boxed{x_4 = 0.9132} \text{ (l)}$$

and the actual entropy:

$$S_4 = S_{f4} + x_4(S_{g4} - S_{f4}) \therefore \boxed{S_4 = 7.4991 \text{ KJ/Kg.K}} \text{ (m)}$$

(5) Fluid leaving the condenser is $\boxed{\text{saturated liquid}}$ (p)

With $\boxed{T_5 = T_{sat}(P_5 = 0.1 \text{ bar}) = 45.81 °C}$ (o)

$$h_5 = h_f(P_5 = 0.1 \text{ bar}) = 191.83 \text{ KJ/Kg} \quad \text{(q)}$$

$$S_5 = S_f(P_5 = 0.1 \text{ bar}) = 0.6493 \text{ KJ/Kg.K} \quad \text{(r)}$$

(6) Fluid leaving the pump have undertaken an isentropic compression to $P_6 = 40$ bar. We can assume the fluid is incompressible, thus the fundamental thermodynamic relation

$$T ds = dh - v dP$$

is reduced ($ds = 0$) to $dh = v dP$. Integrating from state 5 to 6 and assuming incompressibility ($v_5 = v_6$):

$$h_6 = h_5 + v_5 (P_6 - P_5)$$

$$h_6 = 191.83 \frac{KJ}{Kg} + 1.0102 \times 10^{-3} \frac{m^3}{Kg} (40 - 0.10) \text{bar}$$

$$\boxed{h_6 = 195.86 \, KJ/Kg}$$

$$h_6 < h_g (P = 40 \text{ bar}) = 1087.3 \, KJ/Kg$$

$$\Downarrow$$

$\boxed{\text{subcooled liquid}}$ (S)

(ii) Total Power produced:

$$\dot{W}_{T1} = \dot{m}_w (h_2 - h_1) = 10^3 \frac{Kg}{s} (2710.77 - 3015.4) \frac{KJ}{Kg} = -3.05 \times 10^5 \, KJ/s$$

$$\dot{W}_{T_2} = \dot{m}_\omega (h_4 - h_3) = 10^3 \frac{Kg}{s} (2377.01 - 2932.2) \, KJ/Kg$$

$$\dot{W}_{T_2} = -5.55 \times 10^5 \, KJ/s$$

$$\dot{W}_{Total} = \dot{W}_{T_1} + \dot{W}_{T_2} = -8.60 \times 10^5 \frac{KJ}{s}$$

↳ The turbines produced 860 MW of power.

(iii) Heat supplied by the boiler:

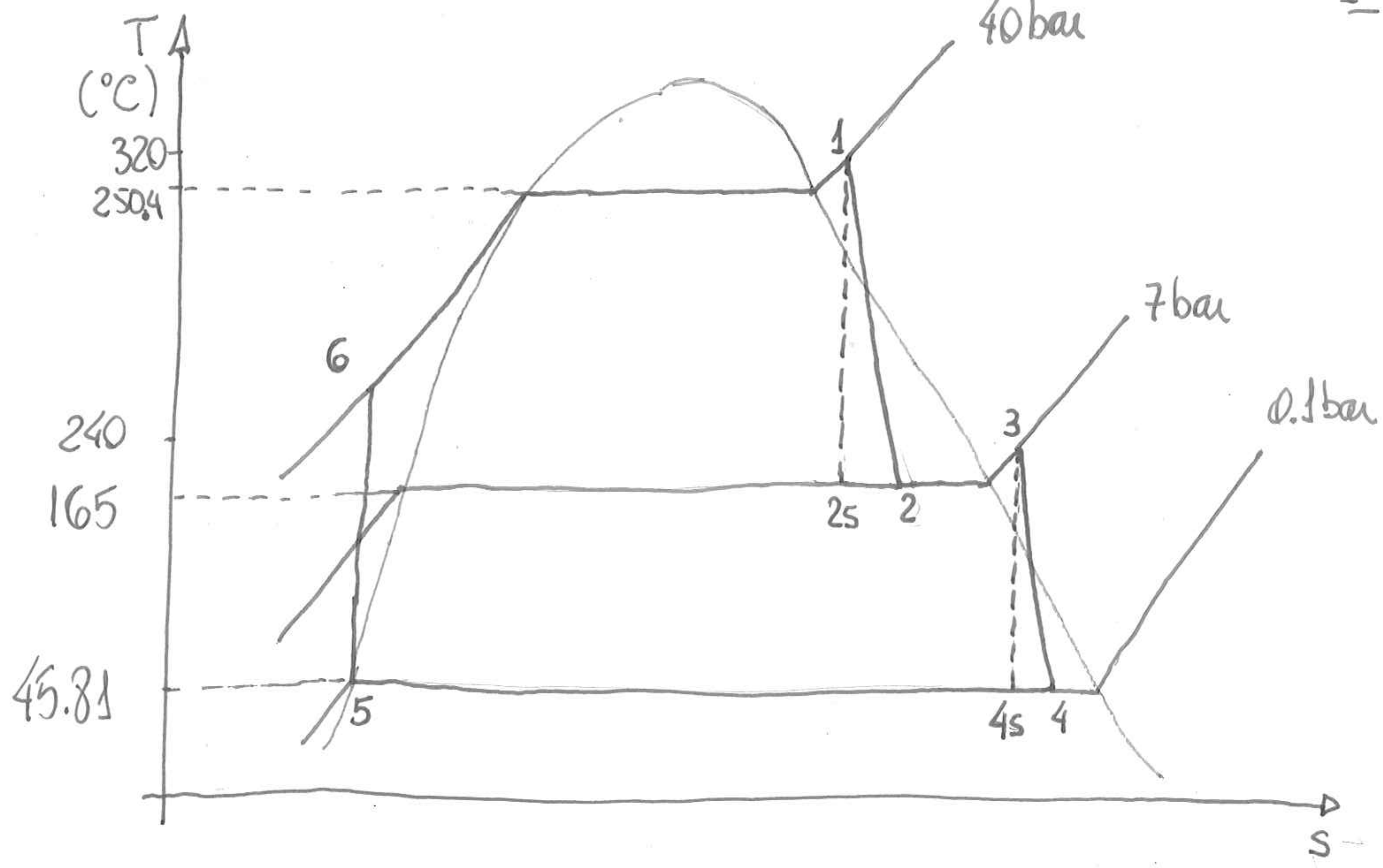
$$\dot{Q}_B = \dot{m}_\omega [(h_1 + h_3) - (h_2 + h_6)] = 3.04 \times 10^6 \, KJ/s$$

↳ The boiler supplied 3041 MW of heat to the system.

(iv) Heat extracted from the condenser

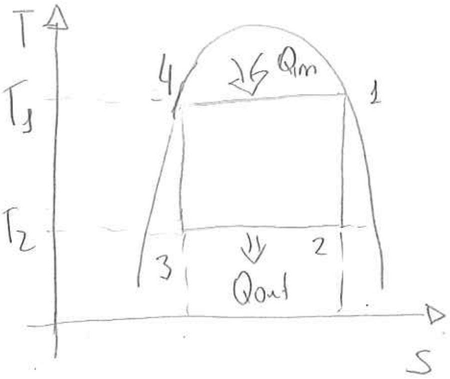
$$\dot{Q}_{cond} = \dot{m}_\omega (H_5 - H_4) = -2.19 \times 10^6 \frac{KJ}{s}$$

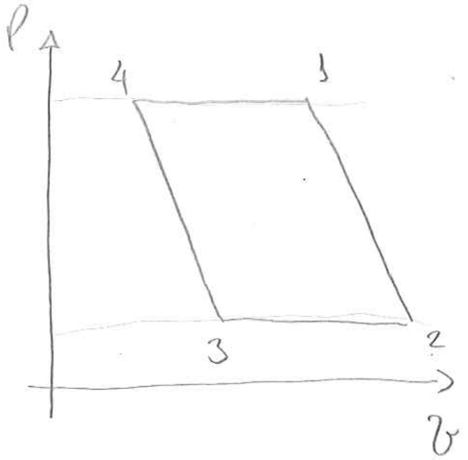
↳ 2185 MW of heat are extracted from the cycle.



T
(°C)
320
250.4
240
165
45.81
40 bar
7 bar
0.1 bar
1
2s
2
3
4s
4
5
6
s

P4: Carnot engine $\begin{cases} T_1 = 475K \\ T_2 = 300K \end{cases}$





(a) From the plot, at 1 the fluid is saturated vapour. From saturated water/steam table at 475K (= 201.85°C), through linear interpolation:

$$\boxed{\begin{aligned} P_1 &= 16.19 \text{ bar} = P_4 \\ h_1 &= 2794.18 \text{ KJ/Kg} \\ S_1 &= 6.4186 \text{ KJ/Kg.K} \end{aligned}}$$ (a)

(b) At 4, the fluid is a saturated liquid at 475K and through linear interpolation:

$$\boxed{\begin{aligned} P_4 &= 16.19 \text{ bar} \\ h_4 &= 860.83 \text{ KJ/Kg} \\ S_4 &= 2.3483 \text{ KJ/Kg.K} \end{aligned}}$$

(c) Fluid at 2 and 3 are wet vapour at 300K (= 26.85°C) and through linear interpolation:

$$\boxed{P_2 = P_3 = 0.0354 \text{ bar}}$$ (a)

1-2 and 3-4 are isentropic process, thus

$\begin{cases} S_2 = S_1 \\ S_3 = S_4 \end{cases} \Longrightarrow$ Calculating the quality of the vapour:

$$S_2 = S_{f2} + x_2 (S_{g2} - S_{f2}) \quad @ P_2$$

$$6.4186 = 0.3933 + x_2 (8.5188 - 0.3933)$$

$$\boxed{x_2 = 0.7415} \quad (b)$$

and the enthalpy

$$h_2 = h_{f2} + x_2 (h_{g2} - h_{f2})$$

$$h_2 = 112.62 + 0.7415 (2550.53 - 112.62)$$

$$\boxed{h_2 = 1920.33 \ KJ/Kg}$$

$$S_3 = S_{f3} + x_3 (S_{g3} - S_{f3}) \quad @ P_3$$

$$2.3483 = 0.3933 + x_3 (8.5188 - 0.3933)$$

$$\boxed{x_3 = 0.2406} \quad (b)$$

$$h_3 = h_{f3} + x_3 (h_{g3} - h_{f3})$$

$$h_3 = 112.62 + 0.2406 (2550.53 - 112.62)$$

$$\boxed{h_3 = 699.18 \ KJ/Kg}$$

Now calculating the heat addition:

$$\dot{Q}_{41} = \dot{m} (h_1 - h_4) = 1 \frac{Kg}{s} (2794.18 - 860.83) \frac{KJ}{Kg}$$

$$\boxed{\dot{Q}_{41} = 1933.35 \ KJ/s} \quad (c)$$

And the heat rejection:

$$\dot{Q}_{23} = \dot{m}\,(h_3 - h_2) = 1\,\text{Kg/s}\,(699.18 - 1920.33)\,\text{KJ/Kg}$$

$$\boxed{\dot{Q}_{23} = -1221.15\ \text{KJ/s}} \qquad \text{(d)}$$

Mechanical power for each stage of the cycle can be obtained through the Pv diagram. As there is no variation in pressure & temperature in 4-1 and 2-3:

$$\boxed{\dot{W}_{4\text{-}1} = \dot{W}_{2\text{-}3} = 0} \qquad \text{(e)}$$

For stages 3-4 and 1-2:

$$\dot{W}_{3\text{-}4} = \dot{m}\,(h_4 - h_3) = \boxed{161.65\ \text{KJ/s}} \qquad \text{(e)}$$

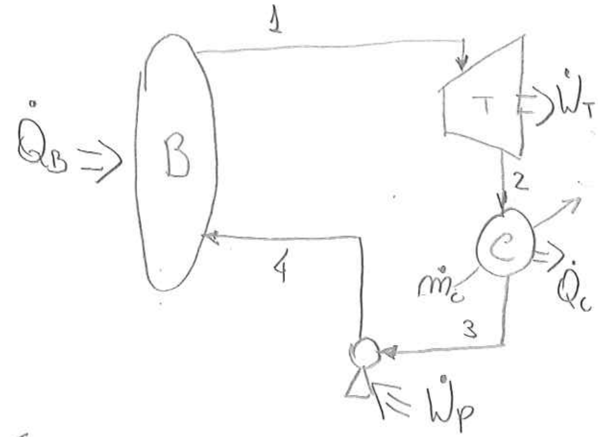
$$\dot{W}_{1\text{-}2} = \dot{m}\,(h_2 - h_1) = \boxed{-873.85\ \text{KJ/s}} \qquad \text{(e)}$$

Thermal efficiency,

$$\eta_{Carnot} = \frac{\text{Net work}}{\text{Added Heat}} = \frac{|\sum \dot{W}|}{\dot{Q}_{41}} = \frac{|-873.85 + 0 + 161.65 + 0|}{1933.35}$$

$$\eta_{Carnot} = 0.3684 \therefore \boxed{36.84\%} \qquad \text{(f)}$$

P5: Ideal Rankine



$P_1 = 16\ MPa = 160\ bar$ (dry saturated vapour)

$P_3 = 8\ KPa = 0.08\ bar$

$\dot{m}_\omega = 120\ Kg/s$

$\dot{W}_{cycle} = ?\quad \dot{Q}_B = ?\quad \eta = ?$

$\dot{m}_c\ (\Delta T_c = 18°C) = ?$

First, let's obtain specific enthalpies of all fluid streams:

(1) dry saturated vapour @ 160 bar $\begin{cases} h_1 = 2580.6\ KJ/Kg \\ S_1 = 5.2455 \\ T_1 = 347.4°C \end{cases}$

(2) Isentropic expansion ($S_2 = S_1$) with quality,

$$S_2 = S_{f_2} + x_2 (S_{g_2} - S_{f_2}) \quad @\ P_3 = P_2$$

$$5.2455 = 0.5926 + x_2 (8.2287 - 0.5926)$$

$$x_2 = 0.6093$$

$$h_2 = h_{f_2} + x_2 (h_{g_2} - h_{f_2})$$

$$h_2 = 1638.10\ KJ/Kg$$

(3) $P_3 = 0.08$ bar (saturated liquid)

$$h_3 = h_{f_3} (P = 0.08\ bar) = 173.88\ KJ/Kg$$

(4) $P_4 = 160$ bar (isentropic compression of a incompressible fluid):

$$dh = v\,dP \therefore h_4 = h_3 + v_3 (P_4 - P_3)$$

$$h_4 = 173.88 \frac{KJ}{Kg} + 1.0084 \times 10^{-3} \frac{m^3}{Kg} (160 - 0.08)\,bar = 190.01\ KJ/Kg$$

(a) $\dot{W}_{cycle}$: ?

$$\dot{W}_{cycle} = \dot{W}_T - \dot{W}_P = \dot{m}_\omega \left[(h_2 - h_1) - (h_4 - h_3)\right] = -1.15 \times 10^5 \, KJ/s$$

Net power of 115 MW

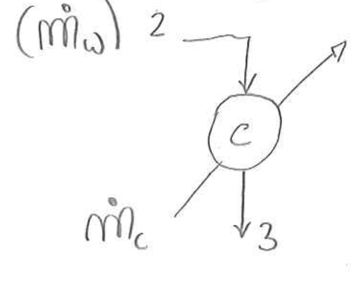
(b) $\dot{Q}_B$: ?

$$\dot{Q}_B = \dot{m}_\omega (h_1 - h_4) = 2.87 \times 10^5 \, KJ/s$$

↳ 287 MW of heat is supplied by the boiler.

(c) $$\eta = \frac{|\dot{W}_{cycle}|}{\dot{Q}_B} = \frac{115035.6}{286870.8} = 0.4010 \therefore 40.10\%$$

(d) Defining a control volume around the condenser, assuming no heat losses:



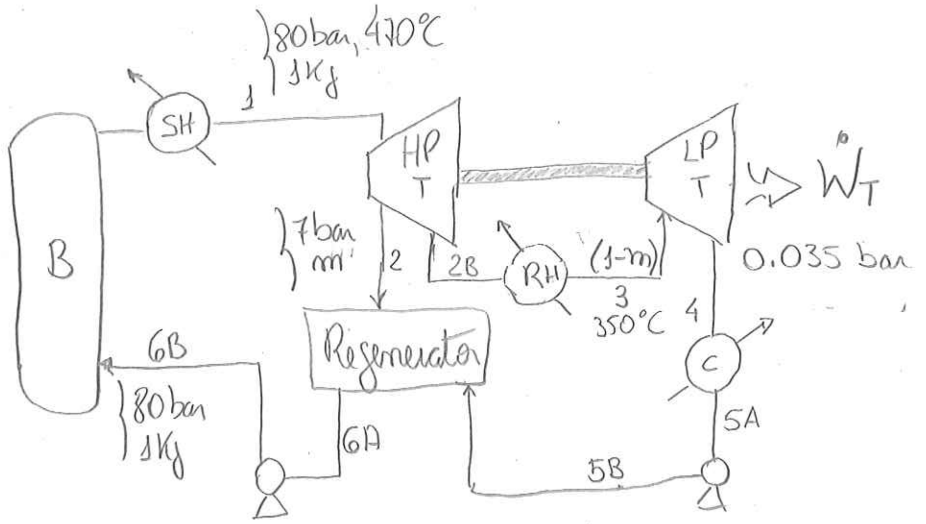
$$\dot{m}_\omega (h_3 - h_2) + \dot{m}_c \underbrace{\Delta h_c} = 0$$

$$\Delta h_c = C_{p_c} \Delta T_c$$

$$120 \frac{Kg}{s} (173.88 - 1638.10) \frac{KJ}{Kg} + \dot{m}_c \times 4.18 \frac{KJ}{Kg \cdot °C} \times 18°C = 0$$

$$\dot{m}_c = 2335.28 \, Kg/s$$

P6



Calculating specific enthalpies for all fluid streams:

(1) $P_1 = 80$ bar
$T_1 = 470°C > T_{sat}(80 \text{ bar})$ } superheated vapour

$h_1 = 3322.83$ KJ/Kg
$S_1 = 6.6237$ KJ/Kg.K

(2) Isentropic expansion ($S_2 = S_1$) to 7 bar

$S_f < S_2 < S_g$ @ 7 bar ⇒ saturated vapour

quality of the steam:

$$S_2 = S_{f_2} + x_2 (S_{g_2} - S_{f_2})$$

$$x_2 = 0.9821$$

and the enthalpy

$$h_2 = h_{f_2} + x_2 (h_{g_2} - h_{f_2}) \therefore h_2 = 2726.53 \text{ KJ/Kg}$$

(3) Isentropic expansion to 7 bar, but the temperature of the fluid was raised to 350°C in the reheater:

$T_3 > T_{sat}$ (@ 7 bar) $\Rightarrow$ superheated vapour

$$\begin{cases} h_3 = 3163.75 \ KJ/Kg \\ S_3 = 7.4722 \ KJ/Kg.K \end{cases}$$

(4) Isentropic expansion to 0.035 bar

$$S_4 = S_3$$

But the minimum pressure at the pressure table is $P = 0.04 \text{ bar} < P_4$. We can use the temperature table (A2) instead and operate a linear interpolation:

$$P_4 = 0.035 \text{ bar} \begin{cases} h_f = 111.88 \\ h_g = 2550.21 \end{cases} KJ/Kg; \quad \begin{cases} S_f = 0.3908 \\ S_g = 8.5225 \end{cases} KJ/Kg.K \qquad T_4 = 26.67°C$$

quality of the vapour

$$S_4 = S_{f4} + x_4 (S_{g4} - S_{f4})$$

$$7.4722 = 0.3908 + x_4 (8.5225 - 0.3908)$$

$$x_4 = 0.8708$$

$$h_4 = h_{f4} + x_4 (h_{g4} - h_{f4}) = 2235.18 \ KJ/Kg$$

(5A) Flow leaving the condenser is saturated liquid at $P_{5A} = P_4$:

$$h_{5A} = h_f (@ P_{5A}) = 111.88 \ KJ/Kg$$

(5B) Liquid leaving the pump. Assuming incompressible fluid being driven towards the regenerator, which is at $P_2 = 7\,bar = P_{5B}$, $(dh = v\,dP)$

$$h_{5B} = h_{5A} + v_{5A}\,(P_{5B} - P_{5A})$$

$$\hookrightarrow v_{5A} = v_f\,(@\ 0.035\,bar)$$
$$= 1.0034 \times 10^{-3}\,m^3/Kg$$

$$h_{5B} = 111.88\,\frac{KJ}{Kg} + 1.0034 \times 10^{-3}\,\frac{m^3}{Kg}\,(7 - 0.035)\,bar$$

$$h_{5B} = 112.58\,KJ/Kg \quad (< h_f\,(@7\,bar)\text{: subcooled liquid})$$

(6A) Saturated liquid at 7 bar

$$h_{6A} = h_f\,(@7\,bar) = 697.22\,KJ/Kg$$

(6B) Liquid leaving the pump,

$$h_{6B} = h_{6A} + v_{6A}\,(P_{6B} - P_{6A})$$

$$h_{6B} = 697.22\,\frac{KJ}{Kg} + 1.1080 \times 10^{-3}\,\frac{m^3}{Kg}\,(80 - 7)\,bar$$

$$h_{6B} = 705.31\,KJ/Kg$$

(a) Amount of "bled-off" steam for feed heating: $\underline{m}$?

↳ energy balance in the regenerator

$$m_T\, h_{6A} = (1-m)\, h_{5B} + m\, h_2 \quad (\text{where } m_T = 1\,\text{Kg})$$

$$\boxed{m = 0.2237\ \text{Kg}}$$

Thus 22.37% of the steam from the boiler is diverted (bled-off) to the regenerator whereas 77.63% of the steam is supplied to the LP turbine.

(b) Heat supplied to the LP turbine (i.e., boiler + reheater):

- boiler (assuming 1 Kg of steam)

$$Q_B = h_1 - h_{6B} = \boxed{2617.52\ \text{KJ/Kg}}$$

- reheater (per Kg of steam generated)

$$Q_{RH} = (1-m)(h_3 - h_{2B}) \quad \text{but } h_{2B} = h_2$$

$$\boxed{Q_{RH} = 339.41\ \text{KJ/Kg}}$$

(c) Therefore the total heat supplied by the boiler & reheater is (per Kg of steam)

$$Q = Q_B + Q_{RH} = \boxed{2956.93\ \text{KJ/Kg}}$$

(d) Thermal Efficiency

$$\eta = \frac{|W_{Total}|}{Q}$$

- Work done (per Kg of steam)
  - HP turbine: $W_{T_{HP}} = [m h_2 + (1-m) h_{2B}] - m_T h_1$

    $W_{T_{HP}} = -596.30$ KJ/Kg
  - LP turbine: $W_{T_{LP}} = (1-m) h_4 - (1-m) h_3$

    $W_{T_{LP}} = -720.85$ KJ/Kg
  - Pump 1: $W_{P_1} = (1-m)(h_{5B} - h_{5A})$

    $W_{P_1} = 0.5434$ KJ/Kg
  - Pump 2: $W_{P_2} = m_T (h_{6B} - h_{6A})$

    $W_{P_2} = 8.09$ KJ/Kg

$$W_{Total} = \sum W_i = -1308.52 \text{ KJ/Kg}$$

- Efficiency: $\eta = \dfrac{|W_{Total}|}{Q} = \dfrac{1308.52}{2956.93} = 0.4425 \therefore$ 44.25%

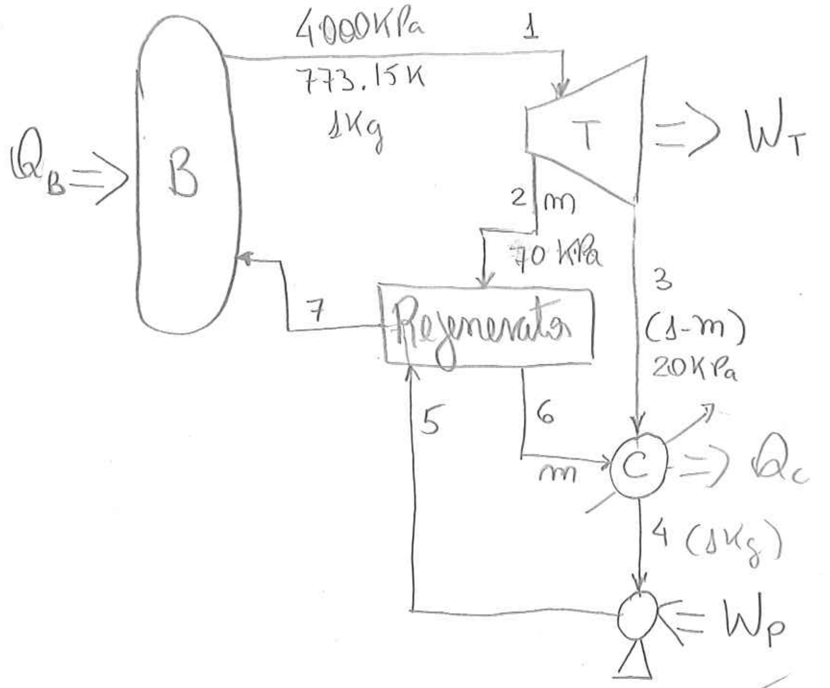
(e) Power developed by the system

$$\dot{W} = \dot{m}_\omega W_{TOTAL} = 50 \frac{Kg}{s} * (-1308.52) \text{ KJ/Kg}$$

$$\dot{W} = -65426 \text{ KJ/s}$$

↳ The system delivered 65.4 MW of power.

P7:



$\eta_T = \eta_P = 0.85$

$\left.\begin{matrix}\eta_{cycle} \\ m\end{matrix}\right\}?$

Calculating the specific enthalpies of all fluid streams:

(1) $\begin{cases} T_1 = 773.15\,K = 500°C \; (< T_{sat} \; (@ 40\,bar)) \\ P_1 = 4000\,KPa = 40\,bar \end{cases}$ superheated vapour

$\begin{cases} h_1 = 3445.3\,KJ/Kg \\ S_1 = 7.0901\,KJ/Kg.K \end{cases}$

(2) Isentropic expansion to 70 KPa (= 0.7 bar)

$S_{2s} = S_1$

$S_{2s} = S_{f2} + x_{2s}(S_{g2} - S_{f2})$

$7.0901 = 1.1919 + x_{2s}(7.4797 - 1.1919)$

$x_{2s} = 0.9380$

$h_{2s} = h_{f2} + x_{2s}(h_{g2} - h_{f2}) \therefore h_{2s} = 2518.44\,KJ/Kg$

$\eta_T = \dfrac{h_2 - h_1}{h_{2s} - h_1} = 0.85 \therefore h_2 = 2657.47\,KJ/Kg$

$$h_2 = h_{f2} + x_2 (h_{g2} - h_{f2}) \therefore x_2 = 0.9989$$

$$S_2 = S_{f2} + x_2 (S_{g2} - S_{f2}) \therefore S_2 = 6.2808 \text{ KJ/Kg.K}$$

(3) Isentropic expansion to 20 KPa (= 0.2 bar)

$$S_{3S} = S_1$$

$$S_{3S} = S_{f3} + x_{3S} (S_{g3} - S_{f3})$$

$$7.0901 = 0.8320 + x_{3S} (7.9085 - 0.8320)$$

$$x_{3S} = 0.8843$$

$$h_{3S} = h_{f3} + x_{3S} (h_{g3} - h_{f3}) \therefore h_{3S} = 2336.84 \text{ KJ/Kg}$$

$$\eta_T = \frac{h_3 - h_1}{h_{3S} - h_1} = 0.85 \therefore h_3 = 2503.11 \text{ KJ/Kg}$$

$$h_3 = h_{f3} + x_3 (h_{g3} - h_{f3}) \therefore x_3 = 0.9548$$

$$S_3 = S_{f3} + x_3 (S_{g3} - S_{f3}) \therefore S_3 = 7.5886 \text{ KJ/Kg.K}$$

(4) Fluid leaving the condenser is saturated liquid at 20 KPa

$$h_4 = h_f (@\, 20 \text{ KPa}) = 251.40 \text{ KJ/Kg}$$

(5) Fluid leaving the pump at $P_5 = P_2$ is incompressible.

$$h_5 = h_4 + \frac{v_4 (P_5 - P_4)}{\eta_P}$$

$$h_5 = 251.40 \frac{\text{KJ}}{\text{Kg}} + 1.0172 \times 10^{-3} \frac{\text{m}^3}{\text{Kg}} (0.7 - 0.2) \text{ bar} \times \frac{1}{0.85}$$

$$h_5 = 251.46 \text{ KJ/Kg}$$

(6) Fluid leaving the regenerator to feed the condenser is saturated liquid at 0.7 bar:

$$h_6 = h_f(@0.7\,\text{bar}) = 376.70\ \text{KJ/Kg}$$

$$T_6 = 89.95\,°\text{C}\ (=363.1\,\text{K})$$

(7) Fluid leaving the regenerator towards the boiler is a mixture of saturated liquid and vapour in which $\begin{cases} T_6 - T_7 = 7\,\text{K} \\ T_7 = 356.1\,\text{K} = 82.95\,°\text{C} \end{cases}$ and $P_7 = P_5$

In order to calculate h_7 of this mixture, we can use the given relation:

$$h_7 = h_{f7} + v_{f7}\,(1-\beta T_7)(P_7 - P_7^{sat})$$

$$\begin{cases} h_{f7}(@82.95\,°\text{C}) = 347.29\ \text{KJ/Kg} \\ v_{f7}(@82.95\,°\text{C}) = 1.0311\times10^{-3}\ \text{m}^3/\text{Kg} \\ P_7^{sat}(@82.95\,°\text{C}) = 0.5355\ \text{bar} \end{cases}$$

The volume expansivity, β, can be approximated by

$$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P = \frac{1}{v_f}\left[\frac{v_f(@82.95\,°\text{C}) - v_f(@80\,°\text{C})}{(82.95-80)}\right]$$

$$\beta = \frac{1}{1.0311\times10^{-3}}\left[\frac{1.0311\times10^{-3} - 1.0291\times10^{-3}}{2.95}\right] = 6.5752\times10^{-4}\,K^{-1}$$

Thus

$$h_7 = 347.29\,\frac{KJ}{Kg} + 1.0311\times10^{-3}\,\frac{m^3}{Kg}\,(1 - 6.5752\times10^{-4}\,K^{-1}\times 356.1\,K)\times(0.7 - 0.5355)\,bar$$

$$h_7 = 347.30\,KJ/Kg$$

(a) m ?

Through energy balance in the regenerator:

$$m_T h_7 + m h_6 = m_T h_5 + m h_2 \quad (\text{with } m_T = 1\,Kg)$$

$$m = \frac{h_7 - h_5}{h_2 - h_6} = \underline{0.04202\,Kg}$$

(b) Efficiency of the cycle:

$$\eta = \frac{|W_{cycle}|}{Q_B} = \frac{|\sum W_i|}{Q_B}$$

$$W_T = \left[(1-m)h_3 + m h_2\right] - m_T h_1 = -935.70\,KJ/Kg$$

$$W_P = h_5 - h_4 = 0.06\,KJ/Kg$$

$$Q_B = h_1 - h_7 = 3098\,KJ/Kg$$

$\eta = 0.3020$

$\underline{(30.20\%)}$