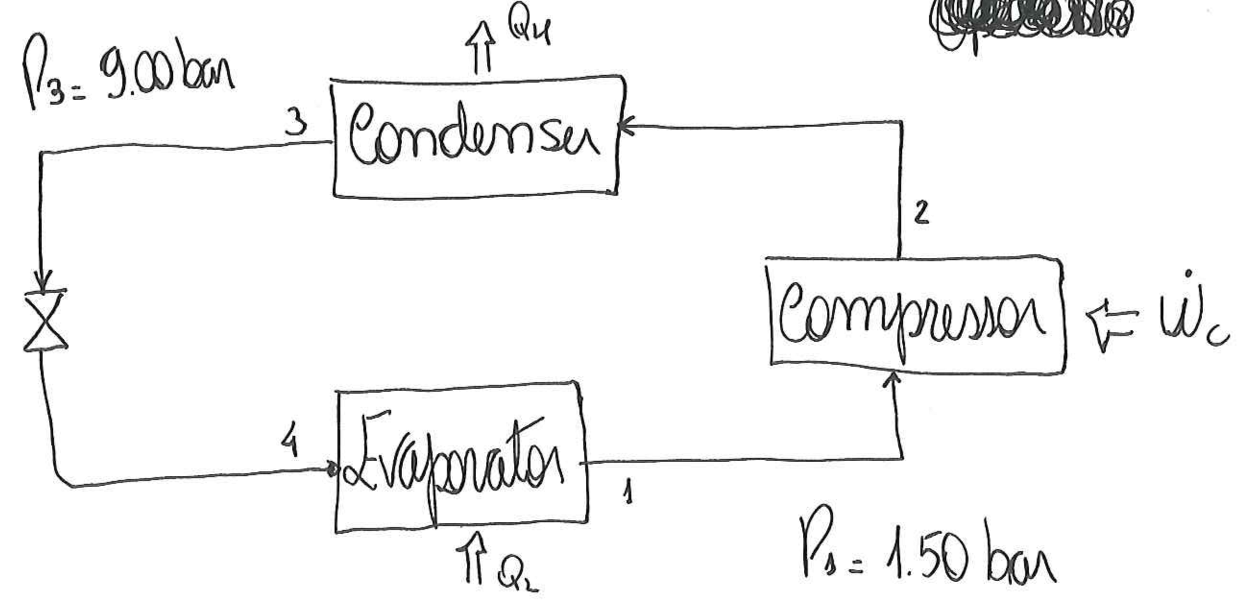
Problem 11: ($C_p = 4.818$ KJ/Kg K)



P (bar)	T_{sat} (°C)	V_g (m^3/Kg)	H (KJ/Kg) H_f	H_g	S (KJ/Kg.K) S_f	S_g
1.50	-25.22	0.[illegible]87	65.32	1410.61	02712	5.6973
9.00	21.52		281.53	1460.97	1.0649	5.0675

• 1: $H_1 = H_g = 1410.61$ KJ/Kg
$S_1 = S_g = 5.6973$ KJ/Kg.K
} saturated vapour

• 2: Superheated vapour ($S_2 = S_1$)
So we don't have the temperature after the compression, we need to use the given entropy in S_2' obtained for $T_{2'} = T_3 = 21.52$°C

$$S_2 = S_2' + C_p \ln\left(\frac{T_2}{T_2'}\right)$$

$$5.6973 = 5.0675 + 4.818 \ln\left(\frac{T_2}{\underbrace{21.52+273.15}_{294.67}}\right)$$

$$T_2 = 335.82\ K$$

And the enthalpy at the entrance of the condenser is:

$$H_2 = H_2' + C_p\,(T_2 - T_2')$$

$$H_2 = 1460.97 + 4.818\,(335.82 - 294.67)$$

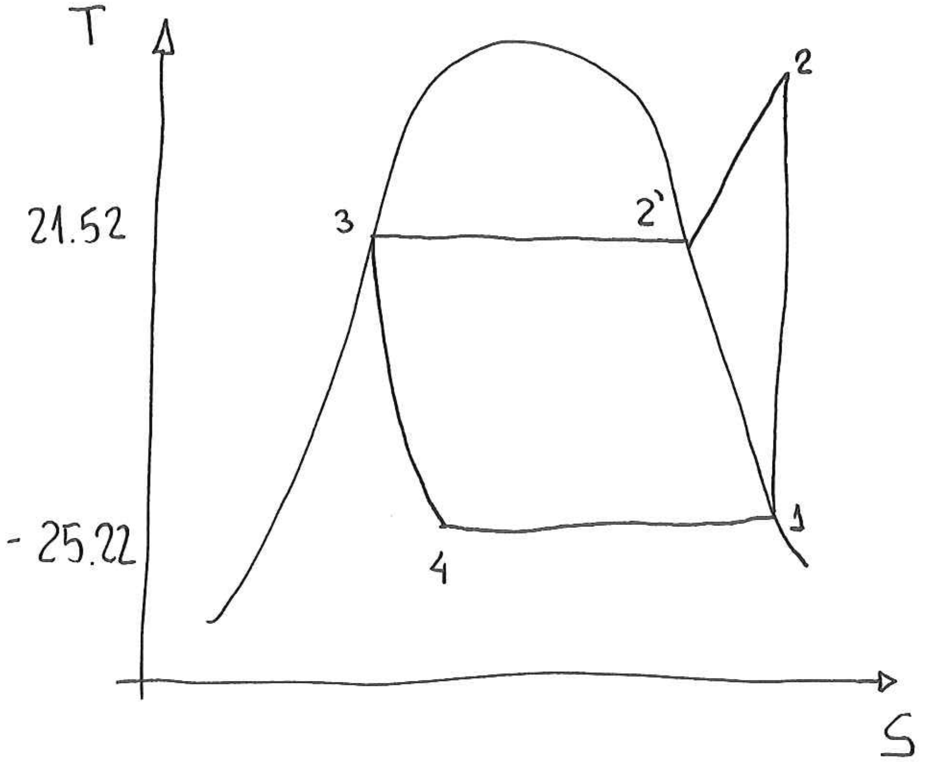
$$H_2 = 1659.23\ KJ/Kg$$

$\underline{3}$: Saturated liquid at $P_3 = 9$ bar

$$H_3 = H_8 = 281.53\ KJ/Kg$$

$\underline{4}$: Isenthalpic expansion $\underline{3-4}$:

$$H_4 = H_3 = 281.53\ KJ/Kg$$



To calculate the mass flow rate of the NH_3 fluid:

$$R_n = Q_L = 35 \ \frac{kJ}{s} = \dot{m}_R \left(H_1 - H_4\right)$$

$$35 = \dot{m}_R \left(1410.61 - 281.53\right)$$

$$\dot{m}_R = 3.10 \times 10^{-2} \ kg/s$$

The power in the compressor can be obtained from

$$\dot{W}_c = \dot{m}_R \left(H_2 - H_1\right) = 3.10 \times 10^{-2} \left(1659.23 - 1410.61\right)$$

$$\dot{W}_c = 7.71 \ kW$$

The piston displacement can be computed from the volumetric efficiency

clearance ratio

$$\eta_{vol} = 1 + C + C\left(\frac{P_d}{P_s}\right)^{1/n}$$

discharge pressure

suction pressure

$$\eta_{vol} = 1 + 0.015 - 0.015\left(\frac{9}{1.5}\right)^{1.21}$$

$$\eta_{vol} = 0.8839 \therefore 88.39\%$$

From the mass flow rate and the specific volume we can calculate the volume of NH_3 at the entrance of the compressor:

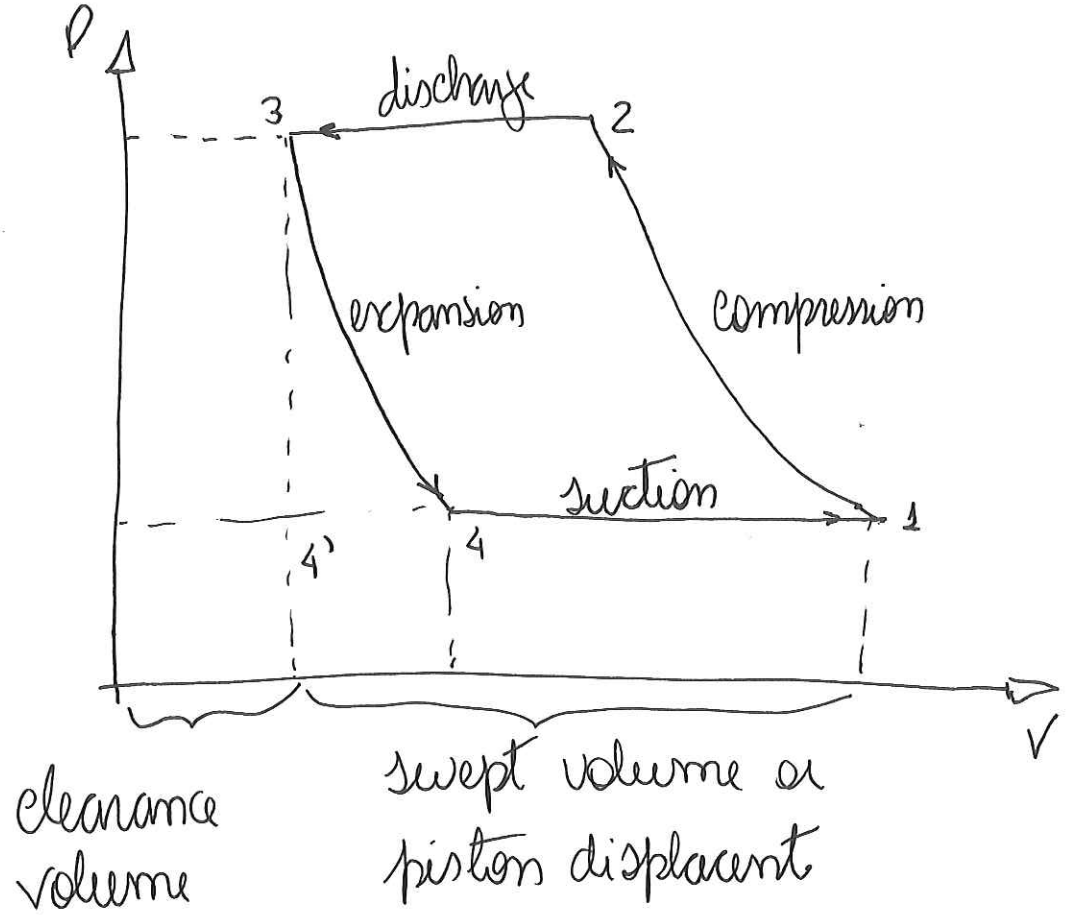
$$\dot{V}_R = \dot{m}_R \, V_g = 3.10\times10^{-2}\,\frac{Kg}{s} \times 07787\,\frac{m^3}{Kg}$$

$$\dot{V}_R = 0.02414\ m^3/s$$

Finally the swept volume rate

$$\dot{V}_{swept} = \frac{\dot{V}_R}{\eta_{vol}} = \frac{0.02414}{08839}$$

$$\dot{V}_{swept} = 2.73\times10^{-2}\ m^3/s$$



Stages in the piston

To calculate the swept volume we need to ~~ob~~ first ~~obtain~~ know how long it takes to fill the piston:

150 rotations — 1 min = 60 s

1 rotation — y ↳ $y = 60/150 = 0.4\,s$

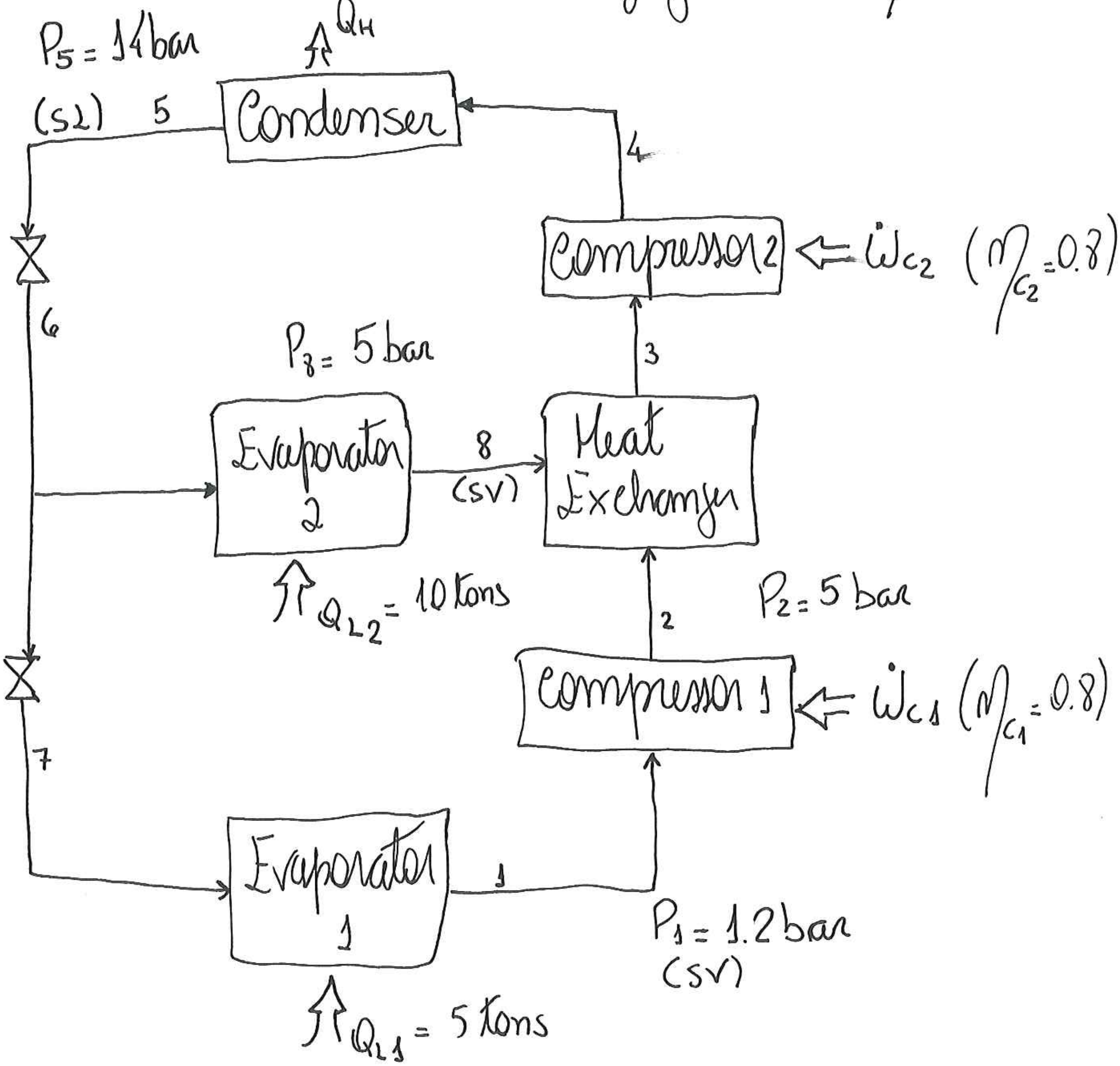
This represents the time it takes to fill the piston, now to know the volume (piston displacement)

$2.73 \times 10^{-2}\,m^3$ — 1 s

x — 0.4 s

$\underline{x = 0.01092\,m^3} = V_{swept}$

Problem 12: NH_3 (2-stage vapour-compression refrigeration system)



We can look at this problem as a coupled single-stage vapour-compression refrigeration cycles, and as usual we should identify the state of the fluids at the exit of each component.

• 1: $P_1 = 1.2$ bar (saturated vapour)

P(bar)	T_{sat}(°C)	H_l	H_{lg}	H_g	S_l	S_g
1.00	-33.60	28.18	1370.23	1398.41	0.1191	5.8391
1.25	-29.07	48.22	1356.89	1405.11	0.2018	5.7610

↳ through linear interpolation at $P_1 = 1.2$ bar

$$T_1^{sat} = -29.98°C$$
$$H_1 = 1403.77 \text{ KJ/Kg} = H_g$$
$$S_1 = 5.7766 \text{ KJ/Kg} = S_g$$

• 2: $P_2 = 5$ bar (superheated vapour). The fluid undertakes a isentropic compression – $S_{2S} = S_1$

T_{sat}(°C)	H (KJ/Kg)	S(KJ/Kg.K)
60	1585.81	5.7362
80	1632.84	5.8733

through linear interpolation

$$H_{2S} = 1599.67 \frac{KJ}{Kg}$$

With the efficiency of compressor 1 – $\eta_{C_1} = 0.8$:

$$\eta_{C1} = \frac{H_{2S} - H_1}{H_2 - H_1} = 0.8$$

$$H_2 = 1648.65 \text{ KJ/Kg}$$

• 3: In order to calculate the enthalpy in 3 we need info from 8. First, let's calculate $\dot{m}_{R1}$ and $\dot{m}_{R8}$; we know that the fluid leaving the condenser is a saturated liquid at $P_5 = 14$ bar, therefore:

$$H_5 = \underbrace{H_6 = H_7}_{\text{isenthalpic expansions}} = 352.97\ KJ/Kg = H_f$$

Thus the energy balance in evaporator 1:

$$\dot{Q}_{L1} = \dot{m}_{R1}\,(H_1 - H_7)$$

$$5 \text{ tons} \times \frac{1.4\times10^4\ KJ/h}{1\text{ ton}} \times \frac{1h}{3600s} = \dot{m}_{R1}\,(1403.77 - 352.97)\ \frac{KJ}{Kg}$$

$19.44\ \frac{KJ}{s}$

$$\dot{m}_{R1} = 1.85\times10^{-2}\ \frac{Kg}{s}$$

And in evaporator 2:

$$Q_{L2} = \dot{m}_{R2}\,(H_8 - H_6)$$

8 is a saturated vapour at $P_8 = 5$ bar:

$$H_8 = 1446.19\ KJ/Kg = H_g$$

Then

38.89 kJ/s

$$10 \text{ tons} \times \frac{1.4\times10^{4}\ \text{kJ/h}}{1\ \text{ton}} \times \frac{1\,\text{h}}{3600\,\text{s}} = \dot{m}_{R2}\,(1446.19 - 352.97)\ \frac{\text{kJ}}{\text{kg}}$$

$$\dot{m}_{R2} = 3.56\times10^{-2}\ \text{kg/s}$$

Now we can calculate the enthalpy in $\underline{3}$ from a simple energy balance around the heat exchanger:

$$\dot{m}_{R1}\,H_2 + \dot{m}_{R2}\,H_8 = (\dot{m}_{R1} + \dot{m}_{R2})\,H_3$$

$$1.85\times10^{-2}\times1648.65 + 3.56\times10^{-2}\times1446.19 =$$

$$(1.85+3.56)\times10^{-2}\times H_3$$

$$H_3 = 1515.42\ \text{kJ/kg}$$

At $\underline{3}$, the pressure P_3 is the same as in $\underline{8}$: $P_3 = P_8 = 5$ bar. At such pressure the saturated NH_3 table gives:

P (bar)	T_{sat} (°C)	H_f	H_{fg}	H_g
5.00	4.13	199.18	1247.02	1446.19

We can notice that $H_3 \gg H_g$; we can then conclude that NH_3 at 3 is a superheated vapour, thus at $P_3 = 5$ bar:

$T(°C)$	H (KJ/Kg)	S (KJ/Kg.K)
30	1513.28	5.5080
40	1537.87	5.5878

through linear interpolation

$$H \qquad\qquad S$$

$$(1537.87 - 1513.28) \;—\; (5.5878 - 5.5080)$$

$$(1515.42 - 1513.28) \;—\; y \;\rightarrow\; y = 6.9448 \times 10^{-3}$$

$$\Downarrow$$

$$S_3 = 5.5149 \ \frac{KJ}{Kg.K}$$

• 4: Isentropic compression – $S_{4S} = S_3$ at $P_4 = 14$ bar (superheated vapour)

$T(°C)$	H (KJ/Kg)	S (KJ/Kg.K)
100	1651.80	5.4433
120	1702.21	5.5765

through linear interpolation

$$H_{4S} = 1678.62 \ \frac{KJ}{Kg\,K}$$

Using the efficiency of compressor 2 ($\eta_{C2} = 0.80$)

$$\eta_{C2} = \frac{H_{4s} - H_3}{H_4 - H_3} = 0.8 \quad \therefore \quad H_4 = 1719.42 \ KJ/Kg$$

The temperature in each evaporator – T_1 and T_8 can be obtained from the saturated table as both are saturated vapour:

$$T_1 = -29.98\,°C$$

$$T_8 = 4.13\,°C$$

The power supplied to both compressors:

$$\dot{W}_{C1} = \dot{m}_{R1}(H_2 - H_1) = 1.85\times10^{-2}(1648.65 - 1403.77)$$

$$\dot{W}_{C1} = 4.53 \ KW$$

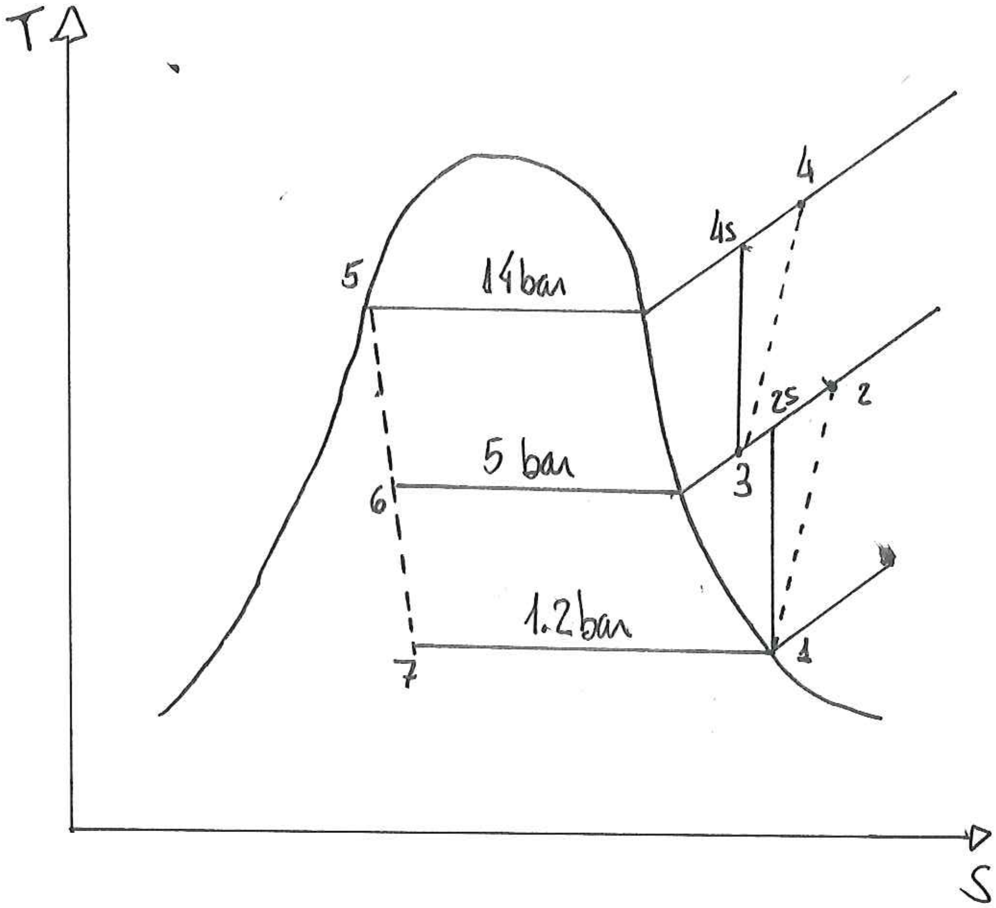
$$\dot{W}_{C2} = (\dot{m}_{R1} + \dot{m}_{R2})(H_4 - H_3)$$

$$= (1.85 + 3.56)\times10^{-2}(1719.42 - 1515.42)$$

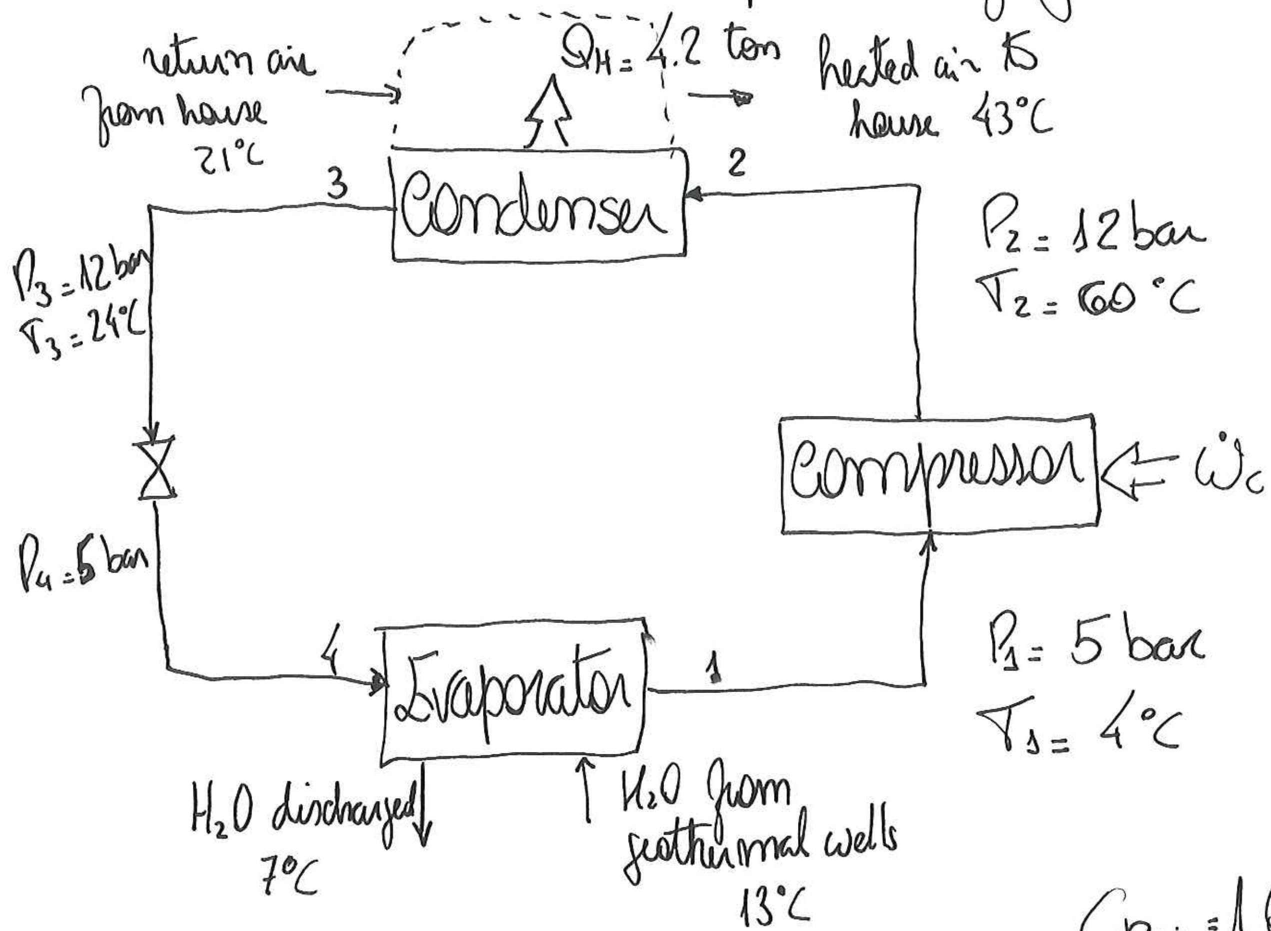
$$= 11.04 \ KW$$

And COP:

$$COP = \frac{Q_{L1} + Q_{L2}}{\dot{W}_{C1} + \dot{W}_{C2}} = \frac{19.44 + 38.89}{4.53 + 11.04} = 3.75$$


T
S
14 bar
5 bar
1.2 bar
1
2
2s
3
4
4s
5
6
7

Problem 13: Heat Pump – Refrigerant R-22



$C_{p_{air}} = 1.004 \frac{KJ}{Kg.K}$

Now calculating enthalpies in all stages:

• 1: At $P_1 = 5$ bar, the saturation temperature is $T_{sat} = 0.12$ °C $<< T_1 = 4$°C. Thus the fluid in 1 is a superheated vapour

T(°C)	H(KJ/Kg)	S(KJ/Kg.K)
0.12	249.97	0.9269
5.00	253.57	0.9399

through linear interpolation:

$H_1 = 252.83$ KJ/Kg

$S_1 = 0.9372$ KJ/Kg.K

• 2: Different from previous problems, the efficiency of the compressor is not explicitly given, but the conditions of the fluid are : $P_2 = 12$ bar
$T_2 = 60°C$

At 12 bar and 60°C the entropy is 0.9666 $\frac{KJ}{Kg.K}$

This means that we do not need to calculate S_2 as a function of $S_{2s} = S_1$, thus

$$S_2 = 0.9666 \ KJ/(Kg.K)$$
$$H_2 = 284.43 \ KJ/Kg$$

• 3 : $P_3 = 12$ bar, $T_3 = 24°C$ — The $T_{sat}(P=12 \text{ bar}) = 30.25°C > T_3$
Thus 3 is a subcooled liquid (or compressed liquid), therefore

$$H_3 = H_f(24°C) = 74.04 \ KJ/Kg$$
$$S_3 = S_f(24°C) = 0.2772 \ KJ/Kg.K$$

• 4 : Isenthalpic process : $H_4 = H_3$
To calculate S_4, we need to compute the quality

of the fluid flow as H_f (5 bar) << H_4

↳ 45.25 KJ/Kg

$$x_4 = \frac{H_4 - H_f}{H_g - H_f} = \frac{74.04 - 45.25}{249.97 - 45.25}$$

$$x_4 = 0.14063$$

For the entropy:

$$x_4 = \frac{S_4 - S_f}{S_g - S_f} = \frac{S_4 - 0.1777}{0.9269 - 0.1777}$$

$$S_4 = 0.2831 \ \mathrm{KJ/Kg.K}$$

In order to calculate the volumetric flow rate of heated air, we first need to calculate the air flow rate:

$$Q_H = \dot{m}_{air}(H^{air}_{out} - H^{air}_{in}) = \dot{m}_{air} C_{p_{air}} (T^{air}_{out} - T^{air}_{in})$$

$$4.2 \text{ ton} \times \frac{1.4 \times 10^4 \ \mathrm{KJ/h}}{1 \text{ ton}} \times \frac{1h}{3600s} = \dot{m}_{air} \times 1.004 \frac{\mathrm{KJ}}{\mathrm{Kg\,K}} (43-21)$$

↳ 16.33 KJ/s

$$\dot{m}_{air} = 0.7395 \ \mathrm{Kg/s}$$

The volumetric flow rate of air is:

$$\dot{V}_{air}^{out} = \dot{m}_{air} \hat{V}_{air}^{out} = \dot{m}_{air} \frac{R T_{air}^{out}}{P_{air}}$$

$$P_{air} = P_{atm} = 1.01325 \text{ bar}$$

$$T_{air}^{out} = 43°C = 316.15 \text{ K} \qquad R = 8.314 \times 10^{-5} \frac{m^3 . bar}{K . Kgmol}$$

$$\dot{V}_{air}^{out} = 0.7395 \frac{Kg}{s} \times 8.314 \times 10^{-5} \frac{m^3 . bar}{K . Kgmol} \times \frac{1 \, Kgmol}{28.97 \, Kg} \times \frac{316.15 \, K}{1.01325 \, bar}$$

$$\dot{V}_{air}^{out} = 6.6218 \times 10^{-4} \, m^3/s$$

The efficiency of the compressor (isentropic)

$$\eta_c = \frac{H_{2s} - H_1}{H_2 - H_1}$$

$$P_2 = 12 \text{ bar} \; ; \quad S_{2s} = S_1 = 0.9372 \frac{KJ}{Kg.K}$$

$T (°C)$	H	S
40	267.62	0.9146
50	276.14	0.9413

linear interpolation at $S_{2s} = 0.9372$

$\hookrightarrow H_{2s} = 274.83 \, KJ/Kg$

$T_{2s} = 48.46°C$

$$\eta_c = \frac{274.83 - 252.83}{284.43 - 252.83} = 0.696 \Rightarrow 69.6\%$$

In order to calculate the power input in the compressor, we need to first calculate the mass flow rate of R-22:

$$Q_H = \dot{m}_R \left(-H_3 + H_2\right)$$

$$16.33 = \dot{m}_R \left(-74.04 + 284.43\right)$$

$$\dot{m}_R = 0.07762 \text{ Kg/s}$$

and the compressor power

$$\dot{W}_c = \dot{m}_R \left(H_2 - H_1\right)$$

$$\dot{W}_c = 0.07762 \left(284.43 - 252.83\right)$$

$$\dot{W}_c = 2.45 \text{ KW}$$

And the COP

$$COP = \frac{Q_H}{\dot{W}_c} = \frac{16.33}{2.45} = 6.67$$

Now, to calculate the volumetric flow rate of water, we first need to calculate the mass flow rate of water - $\dot{m}_\omega$, through an energy balance across the evaporator

$$-\dot{m}_R (H_1 - H_4) = \dot{m}_\omega (H_\omega^{out} - H_\omega^{in})$$

$$-\dot{m}_R (H_1 - H_4) = \dot{m}_\omega C_{p\omega} (T_\omega^{out} - T_\omega^{in})$$

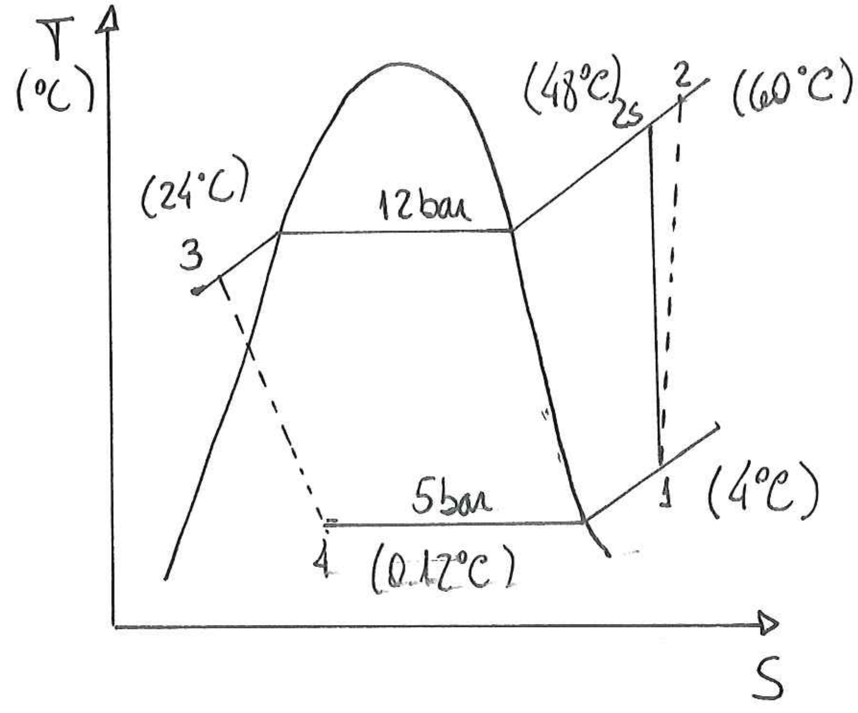
$$-0.07762 (252.83 - 74.04) = \dot{m}_\omega \times 4.1813 (7 - 13)$$

$$\dot{m}_\omega = 05532 \text{ Kg/s}$$

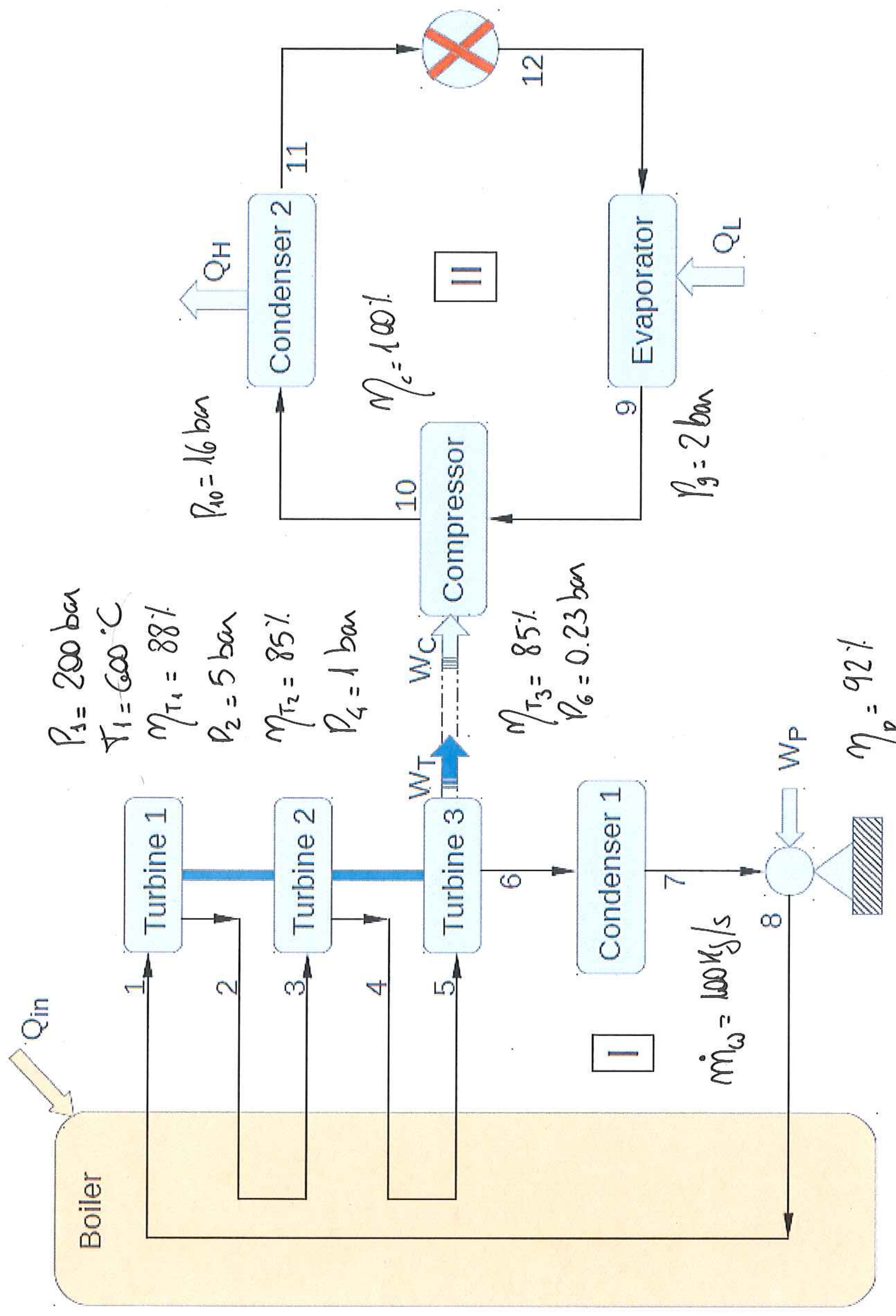
At 13°C the specific volume of the water (saturated water-steam table) is 1.0007×10^{-3} m³/Kg $= v_f$ and the volumetric flow rate of the water is

$$\dot{V}_\omega = \dot{m}_\omega v_f = 05532 \times 1.0007 \times 10^{-3} = 0.00055 \frac{m^3}{s}$$

$$= 1992.91 \text{ l/h}$$


T
(°C)
(24°C)
3
12 bar
(48°C)
2s
2
(60°C)
5 bar
1
(4°C)
4
(0.12°C)
S

Problem 14:



Boiler
Qin
Turbine 1
Turbine 2
Turbine 3
Condenser 1
WT
WC
WP
Compressor
Condenser 2
Evaporator
QH
QL
I
II
1
2
3
4
5
6
7
8
9
10
11
12
P1 = 200 bar
T1 = 600 °C
ηT1 = 88%
P2 = 5 bar
ηT2 = 85%
P4 = 1 bar
ηT3 = 85%
P6 = 0.23 bar
ηp = 92%
ṁw = 100 kg/s
P10 = 16 bar
ηc = 100%
P9 = 2 bar

Let's start from the vapour power plant (I).

1: $P_1 = 200$ bar, $T_1 = 600°C$ { At 200 bar, the saturated temperature is $\boxed{365.8°C << T_1}$ - we can thus conclude that the water is <u>superheated steam</u> and therefore:

$$\boxed{\begin{aligned} H_1 &= 3537.6 \ \text{KJ/Kg} \\ S_1 &= 6.5048 \ \text{KJ/(Kg.K)} \end{aligned}}$$

2: $P_2 = 5$ bar $\therefore$ <u>1-2</u> is an <u>isentropic expansion</u> with <u>$S_{2s} = S_1$</u>. In order to calculate <u>H_2</u>, we first need to obtain the ideal quality - <u>x_{2s}</u> (i.e., before considering the turbine efficiency):

$$x_{2s} = \frac{S_{2s} - S_l}{S_g - S_l} = \frac{6.5048 - 1.8607}{6.8212 - 1.8607}$$

$$x_{2s} = 0.9362$$

$$x_{2s} = \frac{H_{2s} - H_l}{H_g - H_l} = \frac{H_{2s} - 640.23}{2748.7 - 640.23} = 0.9362$$

$$H_{2s} = 2614.18 \ \text{KJ/Kg}$$

For the turbine 1, the efficiency is 88%

$$\eta_{T1} = \frac{H_2 - H_1}{H_{2s} - H_1} = \frac{H_2 - 3537.6}{2614.18 - 3537.6}$$

$$\boxed{H_2 = 2724.99 \ KJ/Kg}$$

And the actual quality is

$$x_2 = \frac{H_2 - H_f}{H_g - H_f} = \frac{2724.99 - 640.23}{2748.7 - 640.23}$$

$$\boxed{x_2 = 0.9888}$$

<u>3</u>: $P_3 = P_2 = 5$ bar
$T_3 = 240°C$

At 5 bar, saturated temperature is 151.86 °C << T_3. Thus the water is a <u>superheated steam</u>, thus:

$$\boxed{\begin{array}{l} H_3 = 2939.9 \ KJ/Kg \\ S_3 = 7.2307 \ KJ/(Kg.K) \end{array}}$$

<u>4</u>: $P_4 = 1$ bar ∴ <u>3-4</u> is an <u>isentropic expansion</u> with <u>$S_{4S} = S_3$</u>. Now to calculate H_4 and assuming a turbine efficiency of 85% :

$$x_{4s} = \frac{S_{4s} - S_f}{S_g - S_f} = \frac{7.2307 - 1.3026}{7.3594 - 1.3026} = 0.9788$$

$$x_{4s} = \frac{H_{4s} - H_f}{H_g - H_f} = \frac{H_{4s} - 417.46}{2675.5 - 417.46} = 0.9788$$

$$H_{4s} = 2627.63 \text{ KJ/Kg}$$

$$\eta_{T2} = 0.85 = \frac{H_4 - H_3}{H_{4s} - H_3} = \frac{H_4 - 2939.9}{2627.63 - 2939.9}$$

$$\boxed{H_4 = 2674.47}$$

And the quality:

$$x_4 = \frac{H_4 - H_f}{H_g - H_f} = \frac{2674.47 - 417.46}{2675.5 - 417.46}$$

$$\boxed{x_4 = 0.9995}$$

5: $P_5 = P_4 = 1$ bar $\therefore$ saturated vapour

$$\boxed{\begin{array}{l} H_5 = 2675.5 \text{ KJ/Kg} \\ S_5 = 7.3594 \text{ KJ/(Kg.K)} \end{array}}$$

6: $P_6 = 0.23$ bar ∴ 5-6 is an isentropic expansion with $S_{6s} = S_5$. From the saturated water-steam ~~pa~~ table:

P(bar)	T(°C)	$V_f \times 10^{-3}$ (m^3/kg)	V_g	H_f (KJ/kg)	H_{fg} (KJ/kg)	H_g (KJ/kg)	S_f (KJ/kg.K)	S_g (KJ/kg.K)
0.20	60.06	1.0172	7.649	251.40	2358.3	2609.7	0.8320	7.9085
0.30	69.10	1.0223	5.229	289.23	2336.1	2625.3	0.9439	7.7686

At 0.23 bar, through linear interpolation:

P — H_f

(0.30 - 0.20) — (289.23 - 251.40)

(0.23 - 0.20) — y ↳ y = 11.35 ∴ H_f(0.23 bar) = 251.40 + 11.35 = 262.75 KJ/kg

Following the same for all properties:

P(bar)	T(°C)	$V_f(\times10^{-3})$	V_g	H_f	H_{fg}	H_g	S_f	S_g
0.23	63.15	1.0187	6.923	262.75	2351.64	2614.38	0.8656	7.8665

$$x_{6s} = \frac{S_{6s} - S_f}{S_g - S_f} = \frac{7.3594 - 0.8656}{7.8665 - 0.8656} = 0.9276$$

$$x_{6s} = \frac{H_{6s} - H_f}{H_g - H_f} = \frac{H_{6s} - 262.75}{2614.38 - 262.75} = 0.9276$$

$$H_{6s} = 2444.12 \text{ KJ/Kg}$$

The efficiency of the turbine is 85%, thus

$$\eta_{T3} = 0.85 = \frac{H_6 - H_5}{H_{6s} - H_5} = \frac{H_6 - 2675.5}{2444.12 - 2675.5}$$

$$\boxed{H_6 = 2478.83 \text{ KJ/Kg}}$$

And the quality (actual) is:

$$x_6 = \frac{H_6 - H_f}{H_g - H_f} = \frac{2478.83 - 262.75}{2614.38 - 262.75}$$

$$\boxed{x_6 = 0.9424}$$

• 7: Saturated liquid at 0.23 bar - Exit of condenser 1:

$$\boxed{\begin{aligned} H_7 &= H_f (P = 0.23 \text{ bar}) = 262.75 \text{ KJ/Kg} \\ S_7 &= S_f (P = 0.23 \text{ bar}) = 0.8656 \text{ KJ/(Kg.K)} \\ V_7 &= V_f (P = 0.23 \text{ bar}) = 1.0187 \times 10^{-3} \text{ m}^3\text{/Kg} \end{aligned}}$$

8: Saturated liquid water after the pump – assuming that the water is incompressible:

$$H_8 \equiv H_7 + \frac{V_7 (P_8 - P_7)}{m_P} \qquad (P_8 = P_1)$$

$$H_8 = 262.75 \frac{kJ}{kg} + \underbrace{1.0187\times10^{-3}\frac{m^3}{kg}\times(200-0.23)\,bar\times10^{+5}\frac{kg/(ms^2)}{1\,bar}\times\frac{10^{-3}\,kJ/kg}{1\,m^2/s^2}\times\frac{1}{0.92}}_{22.12\ kJ/kg}$$

$$\boxed{H_8 = 284.87\ kJ/kg}$$

$H_8 \lll H_8(200\,bar) \rightarrow 1826.3\ kJ/kg$

thus the fluid is subcooled liquid

The net work is:

$$\frac{\dot{W}_{cycle}}{\dot{m}_w} = \frac{\dot{W}_T}{\dot{m}_w} + \frac{\dot{W}_P}{\dot{m}_w}$$

For the set of turbines:

$$\frac{\dot{W}_T}{\dot{m}_w} = (H_1 - H_2) + (H_3 - H_4) + (H_5 - H_6)$$

$$\frac{\dot{W}_T}{\dot{m}_w} = (3537.6 - 2724.99) + (2939.9 - 2674.47) + (2675.50 - 2478.83)$$

$$\boxed{\dot{W}_T/\dot{m}_w = 1274.71\ kJ/kg}$$

And for the pump:

$$\frac{\dot{W}_P}{\dot{m}_w} = H_8 - H_7 = 284.87 - 262.75$$

$$\boxed{\dot{W}_P / \dot{m}_w = 22.12 \text{ KJ/Kg}}$$

The net work for the steam thermal cycle is:

work produced

$$\frac{\dot{W}_{cycle}}{\dot{m}_w} = 1274.71 - 22.12$$

work spent

$$\boxed{\dot{W}_{cycle} / \dot{m}_w = 1252.59 \text{ KJ/Kg}}$$

The power produced by the set of turbines is:

$$\dot{W}_T / \dot{m}_w = 1274.71 \quad \therefore \quad \dot{W}_T = 127471 \text{ KJ/s}$$

100 Kg/s

$$\boxed{\begin{array}{c} \dot{W}_T = 127471 \text{ KW} \\ \text{or} \\ \dot{W}_T = 127.5 \text{ MW} \end{array}}$$

Part of the power from the set of turbines is used to compress the refrigerant fluid X that has the following properties for the 2-level pressure:

P (bar)	T (°C)	V_f ($\times10^{-3}$)	V_g (m^3/kg)	H_f (kJ/kg)	H_g (kJ/kg)	S_f (kJ/kg.K)	S_g (kJ/kg.K)
2.00	-18.86	1.5071	0.5946	93.80	1419.31	0.3843	5.5969
16.00	41.03	1.7306	0.0808	376.46	1470.23	1.3729	4.8542

• 9 : $P_9 = 2.00$ bar (saturated vapour) $\Big\}$ $\boxed{H_9 = H_g = 1419.31 \text{ kJ/kg} \quad S_9 = S_g = 5.5969 \text{ kJ/kg.K}}$

• 10 : Superheated vapour ($S_{10} = S_9$) - isentropic compression

We don't have any information regarding H_{10} and because the superheated vapour table is not available, we can assume that $T_{10}^{sat} = T^{sat}(P = 16 \text{ bar})$:

$$S_{10} = S_{10'} + Cp_R \ln\left(\frac{T_{10}}{T_{10'}}\right)$$

$$5.5969 = 4.8542 + 4.818 \ln\left(\frac{T_{10}}{41.03 + 273.15}\right) \rightarrow 314.18 \text{ K}$$

$$T_{10} = 366.54\ K = 93.39\,°C$$

And the enthalpy:

$$H_{10} = H_{10}' + Cp_R\,(T_{10} - T_{10}')$$

$$H_{10} = 1470.23 + 4.818 \times (366.54 - 314.18)$$

$$\boxed{H_{10} = 1722.50\ KJ/Kg}$$

• 11: Saturated liquid at $P_{11} = 16$ bar

$$\boxed{H_{11} = H_7 = 376.46\ KJ/Kg}$$

• 12: Isenthalpic expansion

$$\boxed{H_{12} = H_{11} = 376.46\ KJ/Kg}$$

The refrigerant capacity is given by:

$$R_n = \dot{Q}_L = \dot{m}_R\,(H_9 - H_{12})$$

We need to calculate $\dot{m}_R$ first.

0.1 % of the power produced by the thermal cycle is used by the compressor

$$\boxed{\dot{W}_C = 0.1 \times 10^{-2}\, \dot{W}_T = 127.471 \text{ KW}}$$

$$\dot{W}_C = \dot{m}_R (H_{10} - H_9)$$

$$127.471 \frac{KJ}{s} = \dot{m}_R (1722.50 - 1419.31) \frac{KJ}{Kg}$$

$$\boxed{\dot{m}_R = 0.4204 \text{ Kg/s}}$$

Now back to the refrigerating capacity:

$$R_n = 0.4204 (1419.31 - 376.46)$$

$$\boxed{R_n = 438.41 \text{ KJ/s}}$$

And converting from KJ/s $\longrightarrow$ ton

$$R_n = 438.41 \frac{KJ}{s} \times \frac{1 \text{ ton}}{1.4 \times 10^4 \text{ KJ/h}} \times \frac{3600 s}{1 h}$$

$$\boxed{R_n = 112.73 \text{ ton}}$$

In order to obtain the piston displacement we first need to calculate the swept volume rate ($\dot{V}_{swept}$)

$$\dot{V}_{swept} = \frac{\dot{V}_R}{\eta_{vol}}$$

where $\dot{V}_R$ is the volume rate of refrigerant fluid X in the entrance of the compressor. η_{vol} is the volumetric efficiency:

clearance ratio

discharge pressure

$$\eta_{vol} = 1 + c - c\left(\frac{P_d}{P_s}\right)^{1/n}$$

suction pressure

$$\eta_{vol} = 1 + 4\times10^{-2} - 4\times10^{-2}\left(\frac{16}{2}\right)^{1.3} = 0.4429 \therefore 44.29\%$$

From $\dot{m}_R$ and the specific volume (V_g), the volume rate is (entrance of the compressor):

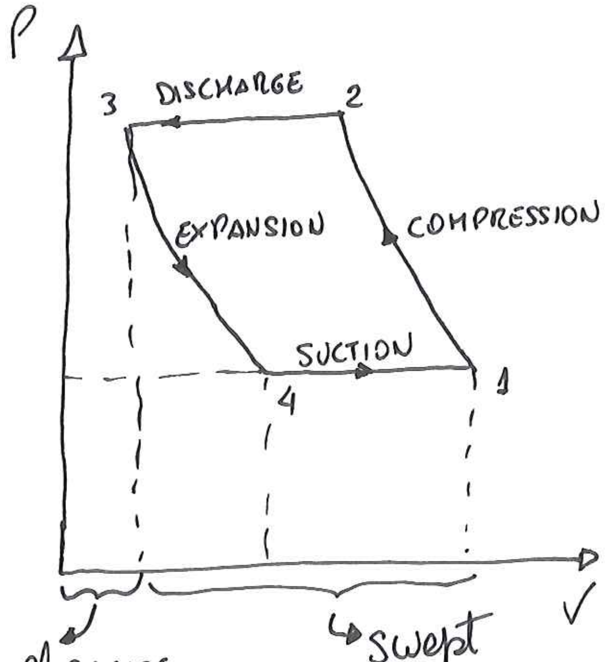
$$\dot{V}_R = \dot{m}_R\, V_g = 0.4204\ \frac{kg}{s} \times 0.5946\ \frac{m^3}{kg}$$

$$\boxed{\dot{V}_R = 0.24997\ m^3/s}$$

Therefore, the swept volume rate

$$\dot{V}_{swept} = \frac{\dot{V}_R}{\eta_{vol}} = \frac{0.24997}{0.4429} = 0.5644\ m^3/s$$

Before we can determine the piston displacement, we need to calculate the time necessary to fill up the piston. Assuming that the motion from BDC to TDC of the piston within the cylinder is of frequency of 360 rpm:



rotation = volume of piston

360 rotations — 1 min = 60 sec

1 rotation — t_R

$$t_R = 0.1667 \text{ sec}$$

Thus, it takes 0.1667 sec to fill up the piston with the refrigerating fluid X in the compressor. Now calculating the piston displacement (V_{swept}):

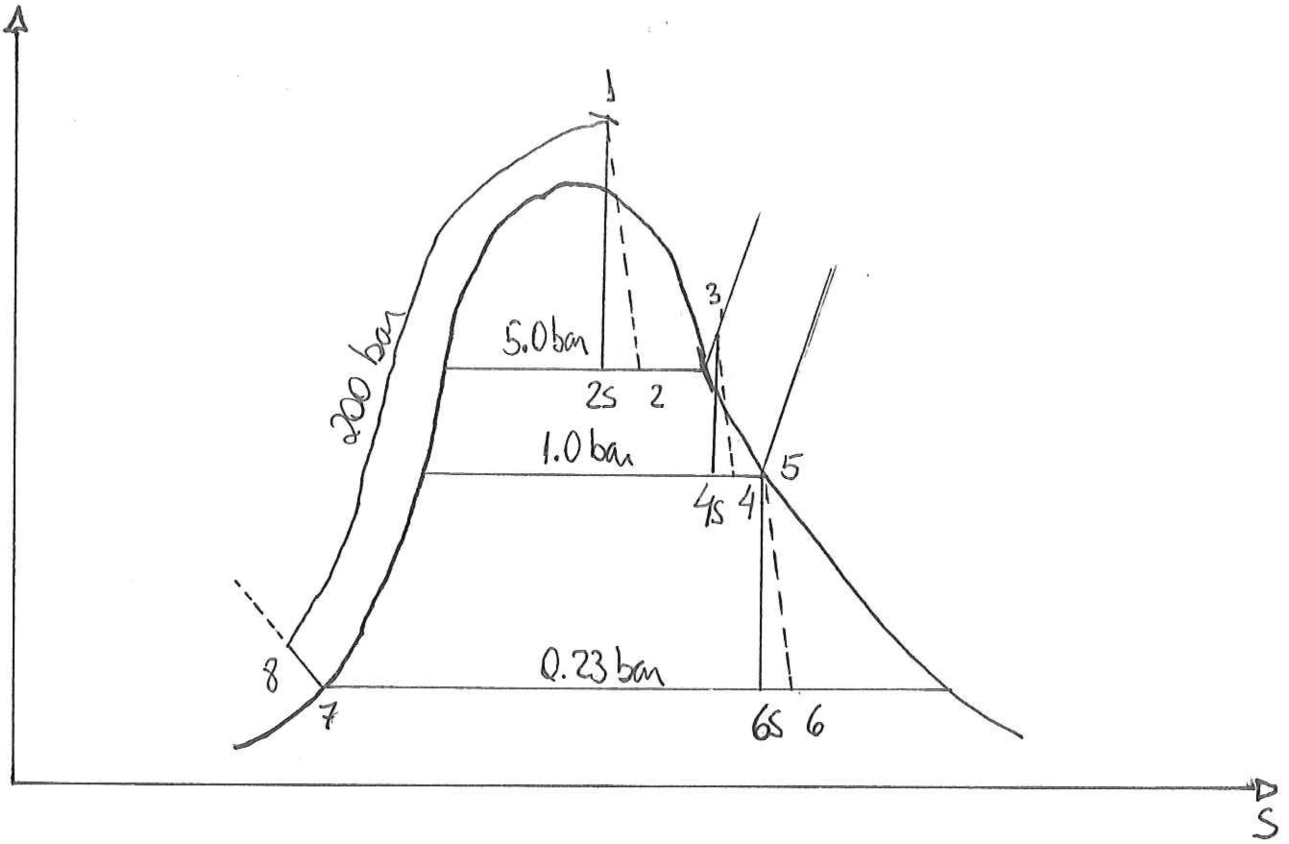
0.5644 m^3 — 1 sec

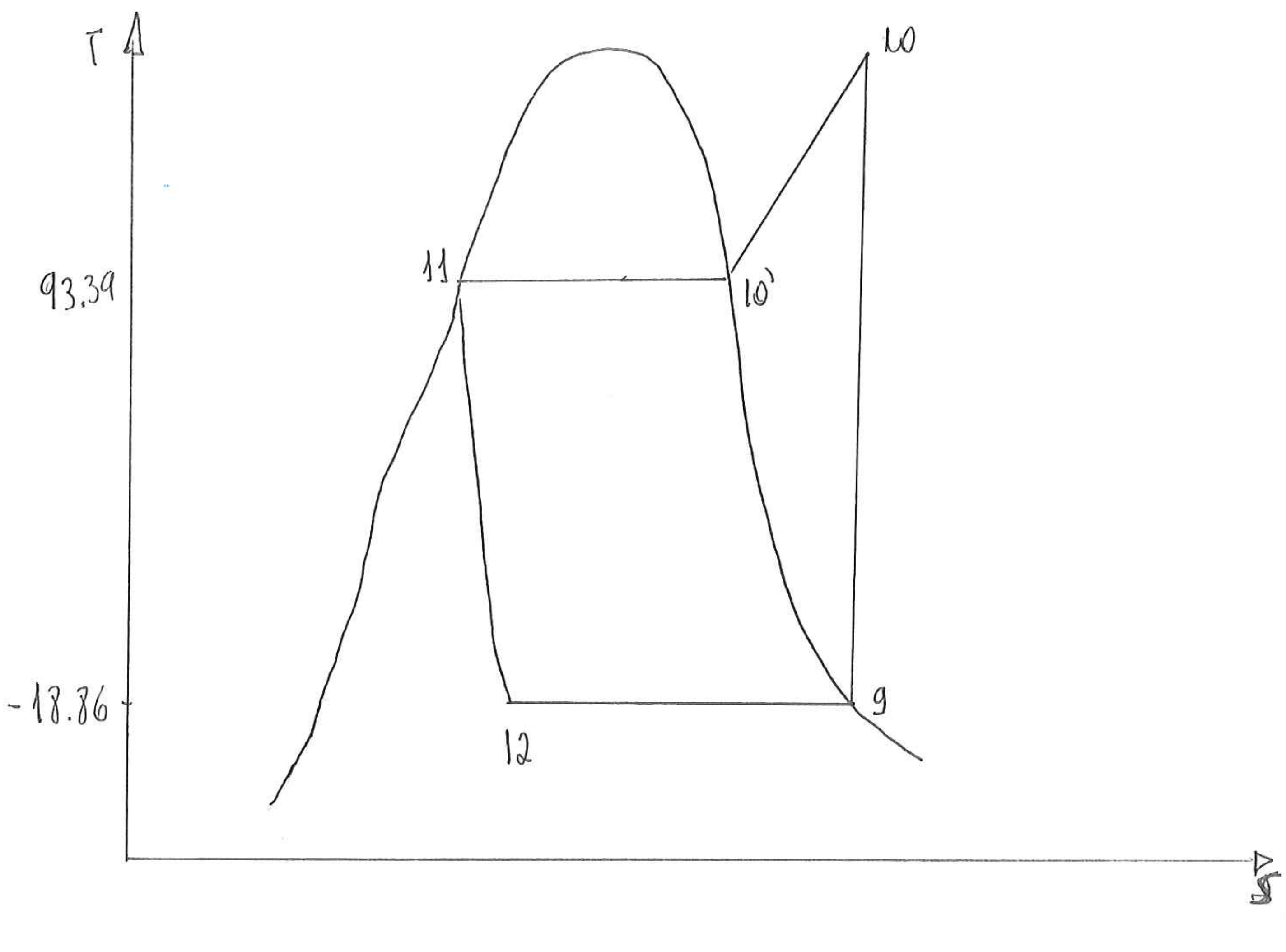
V_{swept} — 0.1667 sec

$$\boxed{V_{swept} = 9.41 \times 10^{-2} \text{ m}^3}$$

Flow	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/(kg.K))	State	Quality of steam
1	**200.0**	**600**	3537.6	6.5048	Superheated Steam	
2	**5.0**		2724.99		**Wet vapour**	0.9880
3	**5.0**	**240**	2939.90	7.2307	Superheated steam	
4	**1.0**		2674.47		**Wet vapour**	0.9995
5	**1.0**	**99.63**	2675.50	7.3594	Saturated Vapour	
6	**0.23**		2478.83		**Wet vapour**	0.9424
7	0.23		262.75	0.8656	Saturated Liquid	
8	200.0		284.87		Subcooled Liquid	
9	**2.0**	-18.86	1419.31	5.5969	Saturated Vapour	
10	**16.0**	93.39	1722.50	5.5969	Superheated Vapour	
11	16.0		376.46		Saturated Liquid	
12	2.0		376.46			

6ϕ


T
1
200 bar
3
5.0 bar
2s
2
1.0 bar
5
4s
4
8
0.23 bar
7
6s
6
S


T
10
11
10'
93.39
-18.86
9
12
S

Flow	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/(kg.K))	State	Quality of steam
1	**200.0**	**600**	3537.6	6.5048	Superheated Steam	
2	**5.0**		2724.99		**Wet vapour**	0.9880
3	**5.0**	**240**	2939.90	7.2307	Superheated steam	
4	**1.0**		2674.47		**Wet vapour**	0.9995
5	**1.0**	**99.63**	2675.50	7.3594	Saturated Vapour	
6	**0.23**		2478.83		**Wet vapour**	0.9424
7	0.23		262.75	0.8656	Saturated Liquid	
8	200.0		284.87		Subcooled Liquid	
9	**2.0**	-18.86	1419.31	5.5969	Saturated Vapour	
10	**16.0**	93.39	1722.50	5.5969	Superheated Vapour	
11	16.0		376.46		Saturated Liquid	
12	2.0		376.46			