Engineering Thermodynamics 1
Module 2, Energy and Materials (201700122)

Mechanical Engineering, B1
Faculty of Engineering Technology
University of Twente

Date: Sample exam, solutions (ET 1)
Time: 13.45 - 16.45 (+25% for students with the right on extra time)
Location: Therm
Teacher: G.G.M. Stoffels

Name Student:

Student number:

This test consists of four questions. Instructions for the test and the answering of the assignments:

- With the test it is allowed to use a thermodynamics textbook of choice. Also, a calculator may be used.
- Make diagrams, sketches and schemes when asked for in the blank space between the assignments, and fill out the tables given with the assignments. Use for the remaining questions the loose exam paper.
- The relative weight of each assignment is indicated. In total, 300 points can be scored.
- Use the correct symbols and do not forget the units (no units = wrong)!
- Give in your answers the expressions and formulas first in symbols, and fill out the numbers later.
- When you lack time or cannot find a value, then give the answers of successive questions in symbols.
- Make clear and neat tables, schemes and sketches which are not too small (unclear = wrong)!
- Mollier diagrams (water and/or air) on A3-format belong to some of the exercises. These are delivered as attachment to the test. Hand in these diagrams with your name and student number on it.
- At the end of the test, hand in all paper with solutions, the assignments and the Mollier diagram, folded in a standard exam sheet of double A4-format. Make sure that your name is on all papers.

Good luck!

1 The Piston Compressor (80)

An amount of gas is is a cylinder of steel, closed by a piston that is locked and cannot move. The gas is heated from state 1 with a temperature $T_1 = 27°\text{C}$ and a pressure $P_1 = 100$ kPa to state 2 with a temperature $T_2 = 327°\text{C}$.
The gas behaves as an ideal gas and has $Pv = RT$ as equation of state. The gas constant is $R = 0.5$ kJ/(kg·K) and $k = \frac{c_p}{c_v} = 1.3$. It may be assumed that the specific heat is constant.

a (5): Is this an open, closed or isolated system, and why?

b (5): Which thermodynamic property is constant in this process? How do you call such a process?

c (10): Calculate c_p and c_v.

d (10): Give the formula with which the pressure in the cylinder after heating of the gas can be determined, and calculate the pressure.

e (10): Give the differential expression with which the specific work can be calculated, and calculate the specific work being done in this process. Does the gas perform work on the surroundings, or do the surroundings perform work on the gas?

f (10): Give the formula with which the change in specific internal energy of the gas in the change of state 1 to state 2 can be determined, and calculate the change in specific internal energy.

g (10): Give the formula with which the added specific heat can be determined, and calculate the added specific heat.

h (20): Give the formula with which the change in specific entropy of the gas in the transition of state 1 to state 2 can be determined, and calculate the specific entropy change of the gas. Does the entropy of the gas increase or decrease, and why?

The Piston Compressor (80): Answers

a (5): Closed system. There is no mass transfer over the system boundaries, but there is energy transfer.

b (5): The volume is constant. This is called an isochoric process.

c (10):

$$R = 0.5\ \frac{\mathrm{kJ}}{\mathrm{kgK}}, \qquad k = \frac{c_p}{c_v} = 1.3$$

$$\left.\begin{array}{ll} R = c_p - c_v & \Rightarrow c_p = R + c_v \\ \dfrac{c_p}{c_v} = k & \Rightarrow c_p = c_v k \end{array}\right\} \qquad R + c_v = c_v k \Rightarrow R = c_v(k-1)$$

$$c_v = \frac{R}{k-1} = \frac{0.5}{1.3-1} = \frac{0.5}{0.3} = 1.67\ \frac{\mathrm{kJ}}{\mathrm{kgK}}$$

$$c_p = R + c_v = 0.5 + 1.67 = 2.167\ \frac{\mathrm{kJ}}{\mathrm{kgK}}$$

$$c_v = 1.67\ \frac{\mathrm{kJ}}{\mathrm{kgK}}, \qquad c_p = 2.167\ \frac{\mathrm{kJ}}{\mathrm{kgK}}$$

d (10):

$$\left.\begin{array}{r} Pv = RT \\ v = \text{constant} \end{array}\right\} \Rightarrow \frac{P}{T} = \text{constant} \Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2} \Rightarrow P_2 = P_1\frac{T_2}{T_1}$$

$$P_2 = 100 \cdot \frac{327+273}{27+273} = 200\ \mathrm{kPa}$$

e (10): Work: $\delta w = P\mathrm{d}v = 0$ kJ/kg, because $\mathrm{d}v = 0$. From this it follows that $w = 0$ kJ/kg, so no work is being done.

f (10): $\mathrm{d}u = c_v \mathrm{d}T \Rightarrow \Delta u = c_v(T_2 - T_1) = 1.67 \cdot 300 = 501$ kJ/kg

g (10): $\mathrm{d}u = \delta q + \cancelto{0}{\delta w} = \delta q \Rightarrow q = \Delta u = 501$ kJ/kg

h (20):

$$u = T\mathrm{d}s - P\mathrm{d}v \Rightarrow \mathrm{d}s = \frac{\mathrm{d}u}{T} + \frac{P}{T}\mathrm{d}v = \frac{c_v \mathrm{d}T}{T} + \frac{R}{v}\cancelto{0}{\mathrm{d}v} = \frac{c_v}{T}\mathrm{d}T$$

$$\Delta s = \int_{T_1}^{T_2} \frac{c_v}{T}\mathrm{d}T = c_v \ln\frac{T_2}{T_1} = 1.67 \ln\frac{273+327}{273+27} = 1.67\ln 2 = 1.16\ \frac{\mathrm{kJ}}{\mathrm{kgK}}$$

2 Brayton cycle with heat user (110)

An open gas turbine installation consists of a compressor, a combustion chamber and a turbine. The turbine drives a compressor and an electrical generator. The heat in the hot exhaust gases is used by a heat user. This user cools the exhaust gases to 120°C. (A heat user is for example a company that uses the heat of the exhaust gases for a process.)

The air enters the compressor of the installation with a pressure of 1 bar and a temperatrue of 20°C. The compressor has a pressure ratio of 8.0 and the compressed air that comes out of the compressor has a temperature of 320°C. In the combustion chamber, the air is heated to 1000°C. The turbine has an isentropic efficiency of 0.8.

Kinetic and potential energies may be neglected in the calculations. Also pressure losses in the pipe lines may be neglected.

Remark: when you lack time or cannot find all enthalpy values, give the formulas for the calculation of the desired properties in symbols (h_1, h_2, etc.).

a (10): Give a scheme of the above described installation, and number the characteristic points. Draw the scheme in the blank space on the next page.

b (10): Give in the table on the next page per point of the installation the two known thermodynamic properties with which the cycle can be analysed, and **circle** them. Determine yourself what you put in the table, and add other values that you find later.

c (25): Determine on every point in the cycle the specific enthalpy, and collect the values found in the table. Use the delivered Mollier diagram on A3-format to find the enthalpy values. **Draw the cycle in the A3-format Mollier diagram.**

d (10): Give the formula that determines the isentropic efficiency of the compressor, and calculate the isentropic efficiency of the compressor.

e (10): Give the formula for the thermal efficiency of this gas turbine installation, and calculate the thermal efficiency.

f (15): How much specific heat does the heat user extract from the exhaust gases. Give the formula for the utilisation factor of this installation, and calculate the utilisation factor.

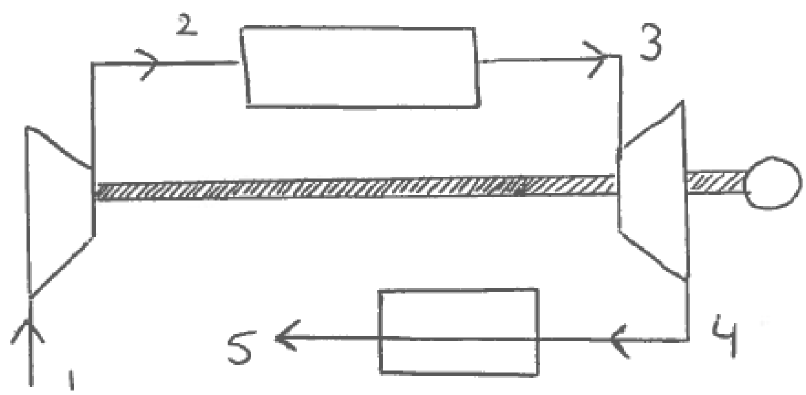
g (10): Another way of usefully using the exhaust gases is the use of a regenerator in the installation. What does a regenerator do, and where do you place it?

h (10): Determine how much heat can be regenerated when the effectiveness of the regenerator is 100%. Also indicate this in the Mollier diagram.

i (10): What is the efficiency of the installation with the regenerator?

Brayton cycle with heat user (11x): Answers

a) Schematic overview of the installation



b) Table with thermodynamic values

	P [bar]	T [°C]	h [kJ/kg]	other		
1	$\boxed{1}$	$\boxed{20}$	295			
2s	$\boxed{8}$		540	$\boxed{s_{2s} = s_1}$		
2	$\boxed{8}$	$\boxed{320}$	600			
3	$\boxed{8}$	$\boxed{1000}$	1370			
4s	$\boxed{1}$		770	$\boxed{s_{4s} = s_3}$		
4	$\boxed{1}$		890	$\boxed{\eta_{s,turb} = 0.8}$		
5	$\boxed{1}$	$\boxed{120}$	395			

Remark: it is not required to fill in all values at all points. Some cells can remain empty. If you do not need a value on a certain point, you do not need to fill in something in the table.

c) 1, 2s, 2, 3, 4s and 5 $\rightarrow$ read from Mollier diagram. Point 4: $\eta_{s,turb} = \frac{h_3 - h_4}{h_3 - h_{4s}} \Rightarrow h_4 = h_3 - \eta_{s,turb}(h_3 - h_{4s}) = 1370 - 0.8(1370 - 770) = 890$ kJ/(kgK)

d) $\eta_{s,c} = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{540 - 295}{600 - 295} = 0.8$, so $\eta_{s,c} = 80\%$

e) $\eta_{th} = \frac{w_{turb} - w_{comp}}{q_{comb}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} = \frac{(1370 - 890) - (600 - 295)}{1370 - 600} = \frac{480 - 305}{770} = \frac{175}{770} = 0.227$
$\eta_{th} = 23\%$

f) q_{hu} is the heat used by the heat user

$q_{hu} = h_4 - h_5 = 890 - 395 = 495$ kJ/kg

utilisationfactor $= \varepsilon_u = \dfrac{w_{net} + q_{hu}}{q_{comb}} = \dfrac{(h_3 - h_4) - (h_2 - h_1) + (h_4 - h_5)}{h_3 - h_2} = \dfrac{175 + 495}{770} = 0.87$

$\varepsilon_u = 87\%$

g) A regenerator uses the heat of the exhaust gases to preheat the air coming out of the compressor prior to going into the combustion chamber. It is placed between the compressor and the combustion chamber.

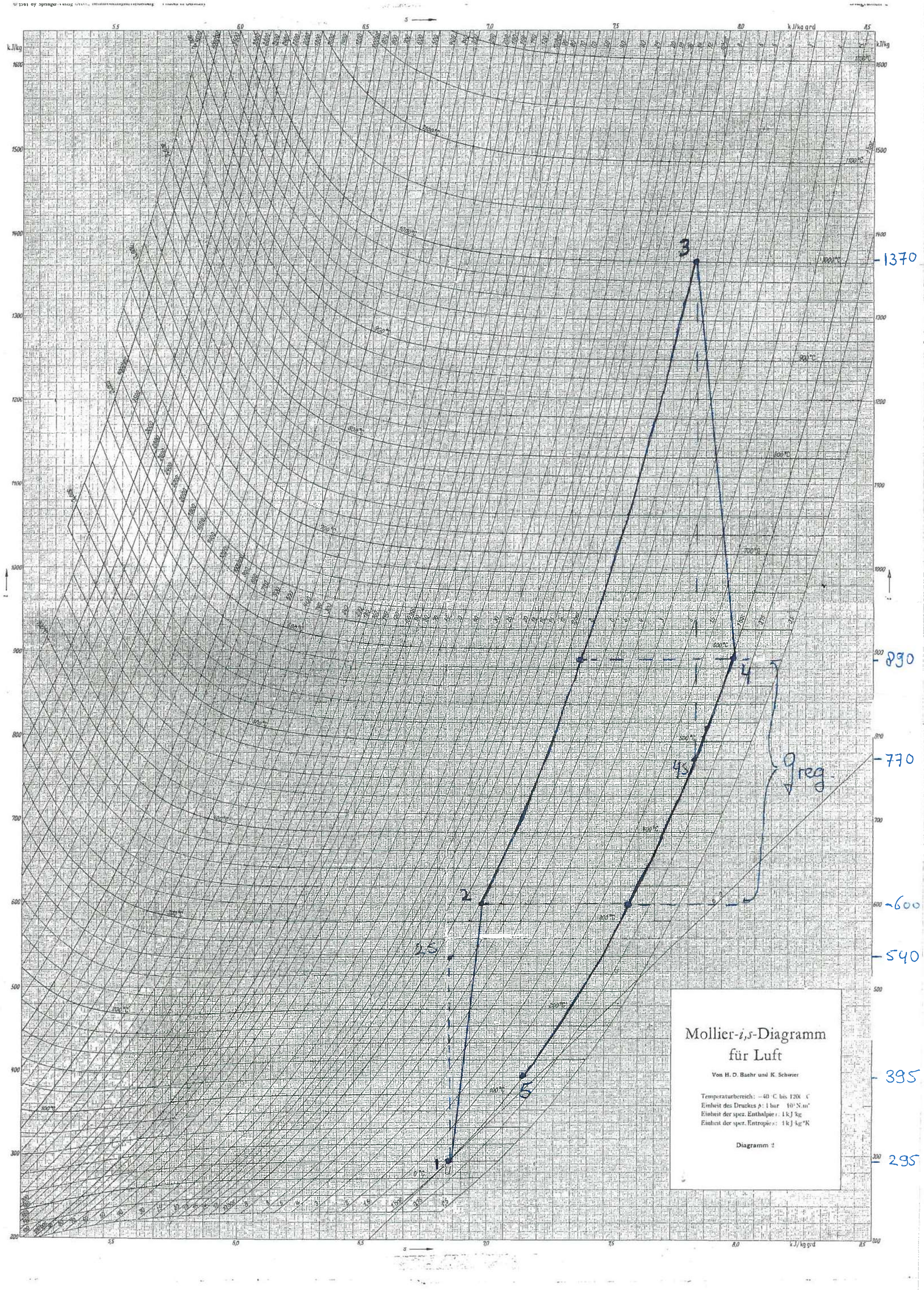
h) At 100% effectiveness of the regenerator: $q_{reg} = h_4 - h_2 = 890 - 600 = 290$ kJ/kg.

i) The thermal efficiency with the regenerator is:

$$\eta_{th,reg} = \frac{w_{net}}{q_{in}} = \frac{w_{turb} - w_{comp}}{q_{comb,noreg} - q_{reg}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2) - (h_4 - h_2)} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_4)}$$

$$= \frac{480 - 305}{1370 - 890} = \frac{175}{480} = 0.36 \rightarrow \eta_{th,reg} = 36\%$$

So 13% higher than without a regenerator.



Mollier-i,s-Diagramm
für Luft
Von H. D. Baehr und K. Schwier
Temperaturbereich: −40 °C bis 1200 °C
Einheit des Druckes p: 1 bar = 10⁵ N/m²
Einheit der spez. Enthalpie i: 1 kJ/kg
Einheit der spez. Entropie s: 1 kJ/kg °K
Diagramm 2
kJ/kg
kJ/kg grd
s
3
4
4s
2
2s
1
5
q reg.
1370
890
770
600
540
395
295

3 Rankine Cycle with Open Feed Water Heater (110)

A steam installation (Rankine cycle) with regenerative open feed water heating delivers a nett power of 150 MW. The installation consists of a boiler, an ideal steam turbine, a condenser, an open feed water heater and two ideal pumps.

In the boiler, steam is produced with a pressure of 100 bar and a temperature of 600°C. The steam is led to the turbine. In the steam turbine, part of the steam is tapped to heat the feed water. This steam is tapped on a pressure of 5 bar and led to the open feed water heater.

The remaining steam goes fully through the turbine. The steam that comes out of the turbine is then fully condensed in the condenser. The pressure in the condenser is 10 kPa (0.1 bar). The condensate from the condenser is pressurized in the first pump and led to the open feed water heater. This first pump requires so little work that it may be neglected, so $h_{in} = h_{out}$. The saturated liquid coming out of the open feed water heater is then being pressurized in the second pump to the boiler pressure.

Kinetic and potential energies may be neglected in the calculations. Also pressure losses in the pipe lines may be neglected.

Remark: when you lack time or cannot find all enthalpy values, give the formulas for the calculation of the desired properties in symbols (h_1, h_2, etc.).

a (10): Give, in the blank space on the next page, the scheme of the steam installation and number the characteristic points, **call the point after the condenser point 1**.

b (15): Give, in the table on the next page, per point of the installation the two known thermodynamic properties that can be used to analyse the cycle, and **circle** them. Determine yourself what you put in the table, and add other values that you find later.

c (10): Make a clear sketch of the Ts-diagram of this installation on the next page. Clearly indicate the numbered points and give, where possible, the values of isobars and temperatures (possibly add them later).

d (20): How many different mass flows are there? Which mass flows are equal to each other? Give the formulas with which the mass flows in the cycle can be determined, in terms of h_1, h_2, etc. and $\dot{m}_1$, $\dot{m}_2$, etc. (use the minimum number of different mass flows).

e (10): Give the formula with which the thermal efficiency of the cycle can be calculated in terms of h_1, h_2, etc. and $\dot{m}_1$, $\dot{m}_2$, etc. (use the minimum number of different mass flows).

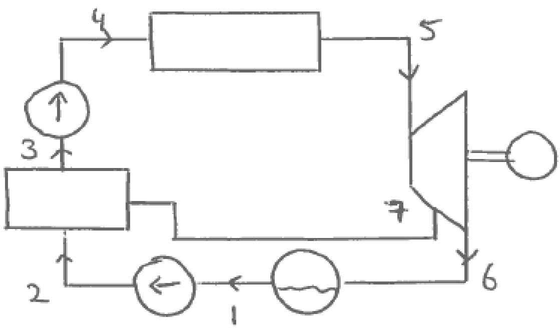
f (25): Determine on every point in the cycle the specific enthalpy and collect the values found in the table. Use the delivered Mollier diagram on A3-format to find the enthalpy values in the region on the diagram. Use the book for points that are not in the diagram (probably in combination with a calculation). **(Neatly!) Draw the cycle in the A3-format diagram as far as possible.**

g (10): Read in the diagram the temperature of the in the turbine tapped steam, and what the vapour fraction is of the mixture coming out of the steam turbine.

h (10): Calculate the mass flows and the thermal efficiency.

Rankine Cycle with Open Feed Water Heater (11x): Answers

a) Schematic overview of the installation

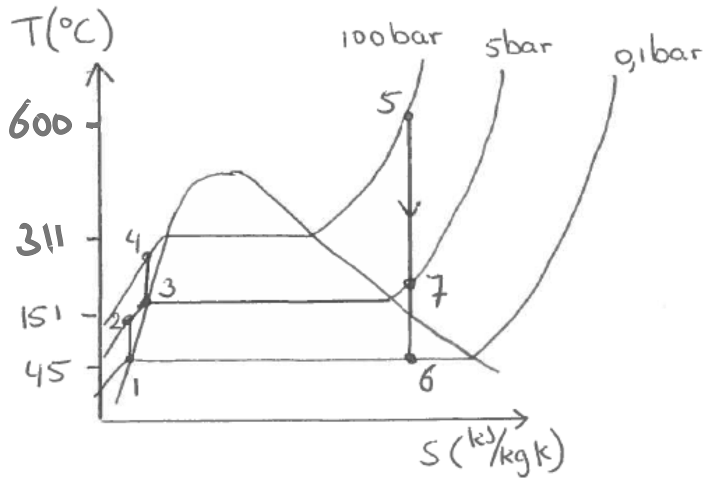


b) Table with thermodynamic values

	P [bar]	T [°C]	h [kJ/kg]	other	$\dot{m}$ [kg/s]	
1	$\boxed{0.1}$	45	191.8	$\boxed{x=0}$	$\dot{m}_2$	
2	$\boxed{5}$		192.3*	$\boxed{\eta_{s,p}=1}$	$\dot{m}_2$	
3	$\boxed{5}$	151	640	$\boxed{x=0}$	$\dot{m}_3$	
4	$\boxed{100}$		650		$\dot{m}_3$	
5	$\boxed{100}$	$\boxed{600}$	3625		$\dot{m}_3$	
6	$\boxed{0.1}$		2190	$\boxed{\eta_{s,t}=1}$	$\dot{m}_2$	
7	$\boxed{5}$		2800	$\boxed{\eta_{s,t}=1}$	$\dot{m}_7$	

*In this solution, the work of the pump has not been neglected. When you do this, h_2 becomes equal to h_1, so 191.8 kJ/kg. Hence $h_1 = h_2 = 192$ kJ/kg. Rounding off is allowed in this case because you cannot read the values more accurate in the diagram either.

c) Ts-diagram



Remark: the turbine and the pumps are ideal (isentropic efficiency of 1), so $s_{in} = s_{out}$. Therefore, there should be vertical lines from 1 to 2, from 3 to 4 and from 5 to 6 and 7.

d) There are 3 different mass flows:

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_6, \qquad \dot{m}_3 = \dot{m}_4 = \dot{m}_5 \text{ (mainflow)}, \qquad \dot{m}_7 \text{ (tapped)}$$

Note that there are 3 equations required for 3 different mass flows.

1) Conservation of mass: $\dot{m}_3 = \dot{m}_2 + \dot{m}_7 \Rightarrow \dot{m}_7 = \dot{m}_3 - \dot{m}_2$
2) Conservation of energy in mixing chamber: $\dot{m}_2 h_2 + \dot{m}_7 h_7 = \dot{m}_3 h_3$
3) Nett power: $\dot{W}_{nett} = \dot{m}_3(h_5 - h_7) + \dot{m}_2(h_7 - h_6) - \dot{m}_2(h_2 - h_1) - \dot{m}_3(h_4 - h_3)$ where the first term represents the work done by the first part of the turbine (with full mass flow), the second term represents the work done by the second part of the turbine (after a part has been tapped, smaller mass flow) and the last two terms represent the work required by the two pumps.

e) $\eta_{th} = \frac{\dot{W}_{nett}}{\dot{Q}_{in}} = \frac{\dot{m}_3(h_5-h_7)+\dot{m}_2(h_7-h_6)-\dot{m}_2(h_2-h_1)-\dot{m}_3(h_4-h_3)}{\dot{m}_3(h_5-h_4)}$

f) h_1: Search in book. $h_1 = 191.8$ kJ/kg $= h_{sat@0.1bar}$ (for neglected pump work: $h_2 = h_1 =$ 192 kJ/kg)

h_2: $h_2 = h_1 + v(P_2 - P_1) = 191.8 + 0.001(500 - 10) = 192.3$ kJ/kg

h_3: Search in book. $h_3 = h_{sat@5bar} = 640$ kJ/kg

h_4: $h_4 = h_3 + v(P_4 - P_3) = 640 + 0.001(10000 - 500) = 649.5$ kJ/kg

h_5: Read from diagram. $h_5 = 3625$ kJ/kg

h_6: Vertically below 5: $s_5 = s_6$ on the correct isobar $\rightarrow h_6 = 2190$ kJ/kg

h_7: Vertically below 5: $s_5 = s_7$ on the correct isobar $\rightarrow h_7 = 2800$ kJ/kg

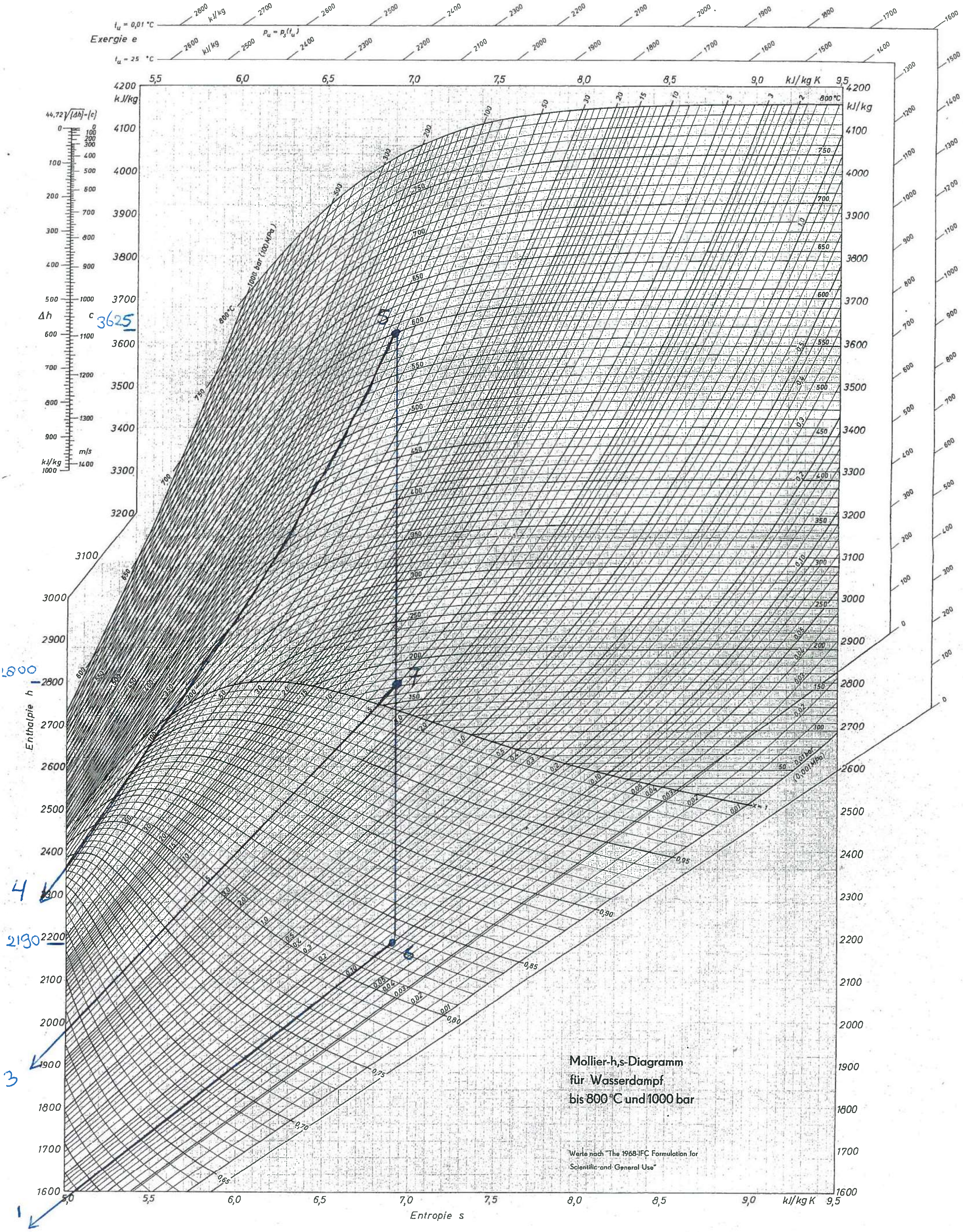
g) $T_{steam,tapped} = T_7 = 170°\text{C}$, vapour fraction: $x_6 = 0.835$.

h) Combine 1 and 2 from d) and eliminate $\dot{m}_7$ from this relation (because we need $\dot{m}_2$ in terms of $\dot{m}_3$ for the nett power (or vice versa):

$$\dot{m}_2 h_2 + (\dot{m}_3 - \dot{m}_2)h_7 = \dot{m}_3 h_3$$
$$\dot{m}_2(h_2 - h_7) = \dot{m}_3(h_3 - h_7)$$
$$\dot{m}_2 = \dot{m}_3\left(\frac{h_7 - h_3}{h_7 - h_2}\right) = 0.86\dot{m}_3 \quad \text{or vice versa} \quad \dot{m}_3 = \dot{m}_2\left(\frac{h_7 - h_2}{h_7 - h_3}\right) = 1.16\dot{m}_2$$

Substitute $\dot{m}_2 = 0.86\dot{m}_3$ in the equation for $\dot{W}_{nett}$:

$$\dot{W}_{nett} = \dot{m}_3(h_5 - h_7) + 0.86\dot{m}_3(h_7 - h_6) - 0.86\dot{m}_3(h_2 - h_1) - \dot{m}_3(h_4 - h_3)$$
$$\dot{m}_3 = \frac{\dot{W}_{nett}}{h_5 + h_7(0.86 - 1) - 0.86h_6 - 0.86h_2 + 0.86h_1 - h_4 + h_3}$$
$$\dot{m}_3 = \frac{150 \cdot 10^3}{1340} = 111 \ \frac{\text{kg}}{\text{s}}$$
$$\dot{m}_2 = 0.86\dot{m}_3 = 95 \ \frac{\text{kg}}{\text{s}}$$
$$\dot{m}_7 = \dot{m}_3 - \dot{m}_2 = 16 \ \frac{\text{kg}}{\text{s}}$$
$$\eta_{th} = \frac{\dot{W}_{nett}}{\dot{Q}_{in}} = \frac{\dot{W}_{nett}}{\dot{m}_3(h_5 - h_4)} = \frac{150 \cdot 10^3}{111(3625 - 650)} = 0.45$$
$$\eta_{th} = 45\%$$



Mollier-h,s-Diagramm
für Wasserdampf
bis 800 °C und 1000 bar
Werte nach "The 1968-IFC Formulation for Scientific and General Use"
Exergie e
Enthalpie h
Entropie s
kJ/kg
kJ/kg K
1000 bar (100 MPa)
0,01 bar (0,001 MPa)
3625
2800
2190