

# Preparation Exam

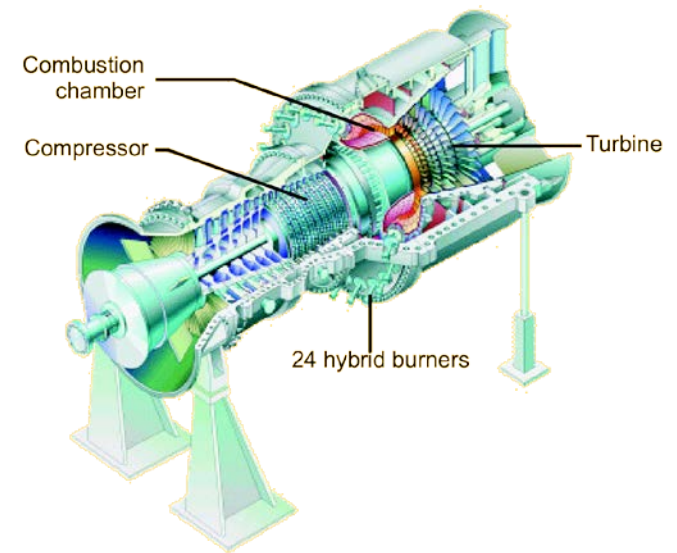
## Engineering Thermodynamics 1



F 16 jet engine, former air base Twente

# Objectives Engineering Thermodynamics

## 1. Conversion of heat into work / electricity → heat engine



## 2. Transportation of heat using work / electricity → refrigerator / heat pump

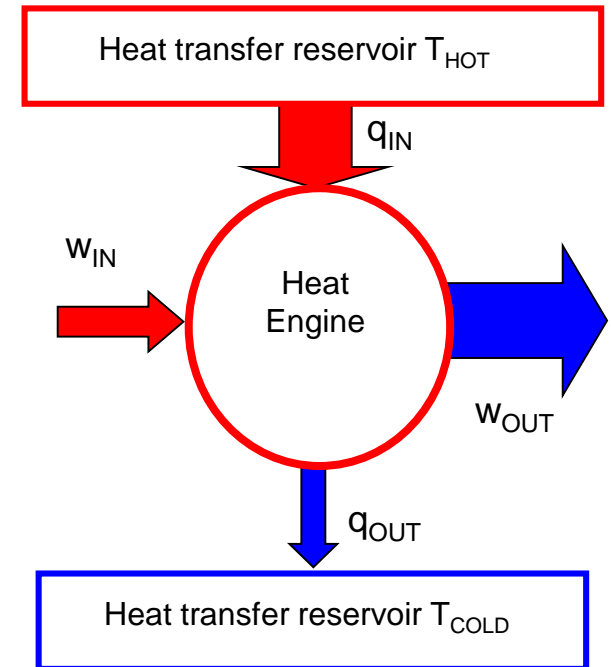


# Objectives Engineering Thermodynamics

1. Heat engine → installation to convert heat from a hot temperature source into work

Examples:

- Vapor power cycle using a steam turbine / Rankine cycle
- Gas power cycle using a gas turbine / Brayton cycle
- Efficiency can never be 100% (due to second law always some of the input heat has to be rejected)
- Maximum efficiency for ideal cycle:  $\eta_{Carnot} = 1 - \frac{T_L}{T_H}$



# Objectives Engineering Thermodynamics

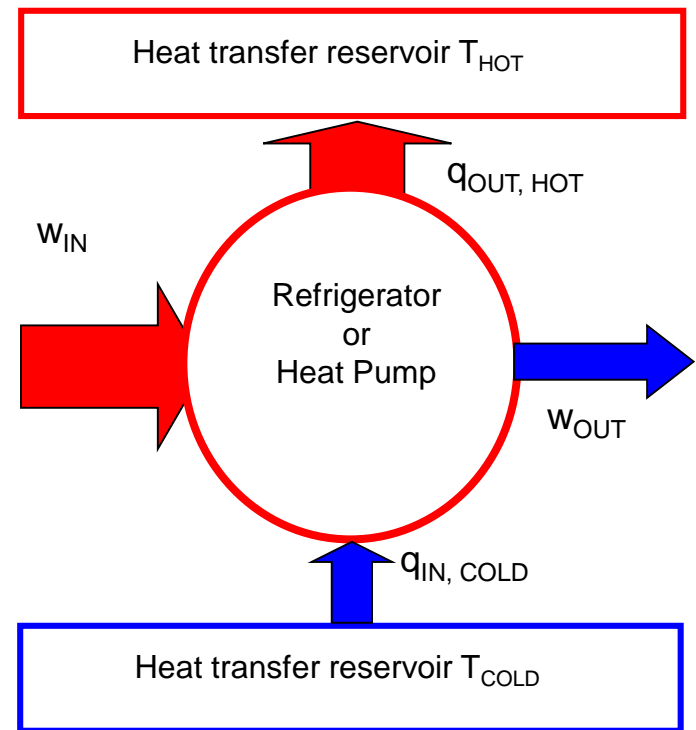
2. Refrigerator / heat pump → installations that use power to transport heat from a cold environment to a hot environment (the non-natural way)

- Goals:

- Refrigerator: cooling,  $q_{in,cold}$
- Heat pump: heating,  $q_{out,hot}$

- COP instead of efficiency, mostly higher than 1

- Maximum COP for ideal cycle:  $COP_{Carnot}$



Notify the reversed direction of the flows

# Outline Engineering Thermodynamics (ET)

- Basic knowledge and tools
  - Thermodynamic concepts and definitions (class 1)
  - Thermodynamic states and processes (class 1)
  - Classification of energy into various forms (class 2)
  - Thermodynamic properties of substances (class 3 & 9)
  - First law energy conservation / transformation (class 4)
  - Entropy and the second law (class 5)
  - Building thermodynamic power cycles (class 6)
- Engineering applications
  - Vapor power cycles (class 7 & 8)
  - Gas power cycles (class 10 & 11)

# Exam Engineering Thermodynamics

- How will the exam look like?
- The exam consists of some MC questions and 3 or 4 open questions
  - One or two exercises are about a single device with gas and/or fluid
  - One exercise about a Brayton cycle (Class 10 -11)
  - One exercise about a Rankine cycle (Class 7 - 8)
  - **100.00% an exercise with a Mollier diagram (water and / or air)**
- Content: Everything that was treated in the lectures, look at the slides (exceptions are clearly mentioned in the slides)
- Subjects can be found in the book, the book provides more information

# Exam Engineering Thermodynamics

- Open book exam
  - You are allowed to bring your Thermodynamic book, text can be highlighted, **small** notes inside the book can be made but complete solutions are not accepted. Also post it's can be used as bookmarks. Prints from the slides or others papers are not allowed. You need the book for the Thermodynamic tables (there is no time during the exam to study the material)
  - You can also bring a printed version of the book or the tables
- A calculator is useful
- A3 Mollier diagram for water and air will be provided out as well (If you need a new one during the exam you can ask us during the exam)

# Exam Engineering Thermodynamics

- **Some remarks for the exam (in random order) :**
- **Read the instructions on the first page (see also sample exam)**
- **Work clean**, make tables and figures easy to read
- Use the space at the question sheets to make the figures and fill out the tables at the questions sheet when asked for
- Don't write down too little, this prevents calculation/rewriting mistakes
- Don't forget **the units**, no units are mistakes and are punished
- Be careful while converting units from kilo/mega, Bar/Pascal, Kelvin/Celsius and others
- Give your **solutions first as a formula** and after the numerical value. The correct value is less important/ gives less points



# Exam Engineering Thermodynamics

- **Remarks continued:**
- Work smart :
  - Calculating intermediate answers is not necessary and costs a lot of time
  - Look for variables that cancel out
  - Sometimes you can combine formulas which can lead to the answer even though you do not have the value of all variables, e.g:
    - $T_1 = T_2$  then  $v_1/v_2 = (T_1 R/P_1) (P_2/T_1 R) = P_2/P_1$  and the value of  $v$  is not necessary if you know the pressure
  - Don't waste your time to calculate things that you don't need!  
You will need the time for the rest of the exam!

# Exam Engineering Thermodynamics

- Important theory / formulas / concepts for the exam that often go wrong, “pitfalls” in a random order :
- First law of thermodynamics → conservation of energy
- For a **closed system**  $\Delta u = q_{\text{net}} - w_{\text{net}}$
- For a **stationary system**  $\Delta h = q_{\text{net}} - w_{\text{net}}$   
(neglecting kinetic and potential energy)
- For a cycle is  $\Delta h = \Delta u = 0$  hence  $q_{\text{net}} = w_{\text{net}}$  and  $w_{\text{out}} - w_{\text{in}} = q_{\text{in}} - q_{\text{uit}}$
- In several sub-parts  $q$  or  $w$  is absent and it reduces to  $q = \Delta h$  of  $w = \Delta h$
- For a pump in a Rankine cycle:  $\Delta h = v\Delta P$  (for sure needed at the exam)

# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- Energy conservation is not sufficient to describe the direction of a process
- **Second law of thermodynamics** → entropy increases in the total world
- Entropy, needed to predict the direction of a process
  - Higher temperature → more entropy
  - Higher pressure → less entropy
  - Mixture → more entropy than a liquid
  - Mixture → less entropy than a vapor
- Remember in a spontaneous process entropy always increases, e.g. a throttle valve, turbines, nozzle, diffuser
- Entropy of a system can decrease but then the entropy of the environment should increase, more than the decrease of the entropy of the system

# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- For ideal gas holds  $dh = c_p dT$  and  $du = c_v dT$  and  $Pv = RT$  and for isentropic ( $ds = 0$ ) processes  $Pv^k = \text{constant}$
- Volume work is  $\delta w = Pdv$  and if you integrate you can not just write  $P$  outside of the integral! That is only allowed if  $P$  is constant during the change in volume and that is often not the case for gas  $\rightarrow w = \int Pdv = \int (TR/v)dv = TR \ln(v_1/v_2) = TR \ln(P_2/P_1)$  if  $T$  is constant. If  $P$  is constant it would be  $\rightarrow w = \int Pdv = P(v_2 - v_1)$
- For compressed liquid at low pressures, there is no table, the  $h$  value is taken from saturated water at the same temperature (the ICL approximation); for example water at 20 degree C and 1 Bar,  $h = 83,915 \text{ kJ/kg}$

# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- While analyzing the cycle you will be asked to mention the 2 unique values which you need to calculate all other data, mark them **clearly**.
- Remember that you need **two values per point**, to calculate all other values
- These values can be, pressure, temperature, isentropic efficiency or  $s_a = s_b$ , but also saturated water/vapor (Pay attention, **superheated vapor is no unique** value, together with the pressure you still can not calculate other values like enthalpy), energy and mass balance can also be one of those.

# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- The pressure at the outlet of a gas turbine is the pressure of the surrounding which is equal to the inlet pressure (around 1 Bar)
- The phase at the end of a condenser and the outlet of a mixing chamber is saturated water (if nothing else is mentioned)
- If there are **different mass flows in one cycle**, then you need extra conditions, that can be **mass balance or energy balance** at the point where the flow splits or meet again or for example the power that is delivered by the turbines or the power that is needed in the heating chamber

# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- Remember the difference between **power** and **work**
- Power is in J/s = W, specific work is in J/kg, work times mass flow (kg/s) results in power  $\rightarrow \dot{W} = \dot{m}w$
- The **net work** of a cycle is the work that is delivered by the turbines minus the work that is needed by the pump/compressor (do **not** neglect those !!!)  
 $\rightarrow W_{\text{net}} = W_{\text{out}} - W_{\text{in}}$
- Heat enters the cycle at the heating chamber/ boiler (with reheating this happens more than ones)
- Keep in mind that if the mass flow is different through sub-parts of the cycle that the power is also different! (important for the Rankine cycle)

# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- The **thermal efficiency** is :  $\eta_{TH\_HE} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{Q}_{in}} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}}$
- Keep in mind that with several turbines, compressor or pumps you also get several terms for  $w_{OUT}$ ,  $w_{IN}$  and for reheating several terms of  $q_{IN}$  ; be aware of different mass flows through these parts
- If there are several mass flows, then while mixing, the energy and mass balances are needed to solve the system !
- Energy balance:  $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$  and mass balance:  $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$
- In a mixing chamber all in and outgoing pressures need to be the same
- An efficiency is **always smaller then 100%**

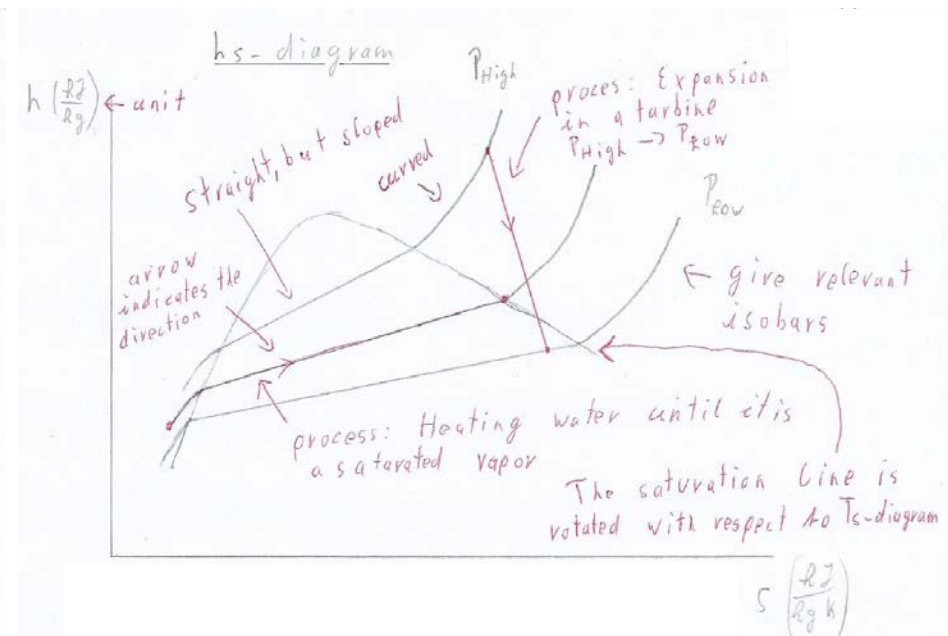
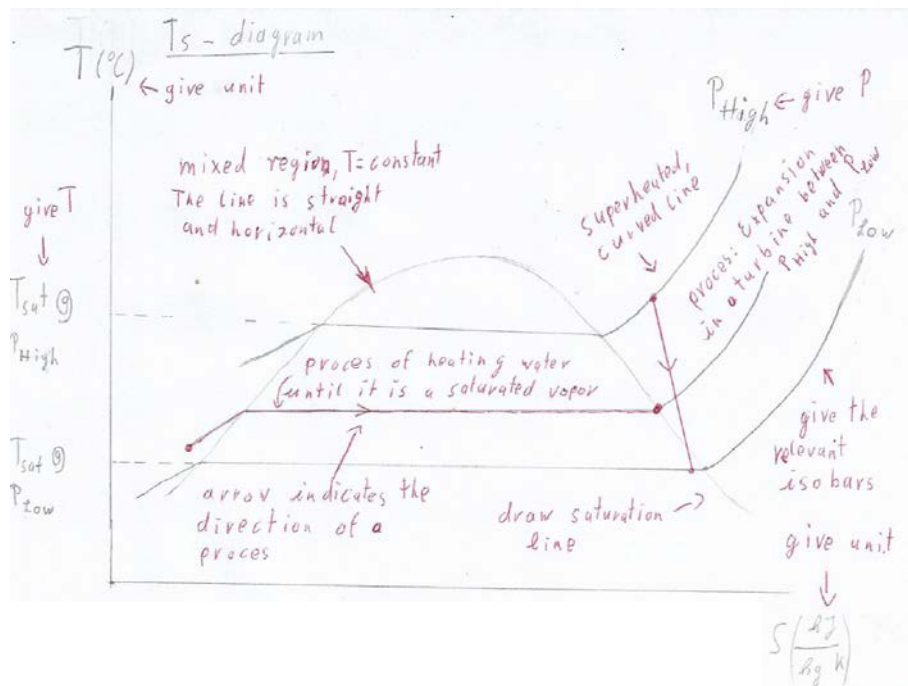


# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- **Co-generation power plant:** Plant that produces (process) heat,  $\dot{Q}_{Process\ heat}$  and power  $\dot{W}_{net}$
- More of the total input energy is used in a useful way
- The **utilization factor** is :  $\varepsilon_{\mu} = \frac{\dot{W}_{net} + \dot{Q}_{Process\ heat}}{\dot{Q}_{in}} = \frac{\dot{W}_{out} - \dot{W}_{in} + \dot{Q}_{Process\ heat}}{\dot{Q}_{in}}$
- Meaning how much of the total energy is use in a useful way
- The **utilization factor may be 100%**, but mostly it is lower but it should be higher than the thermal efficiency

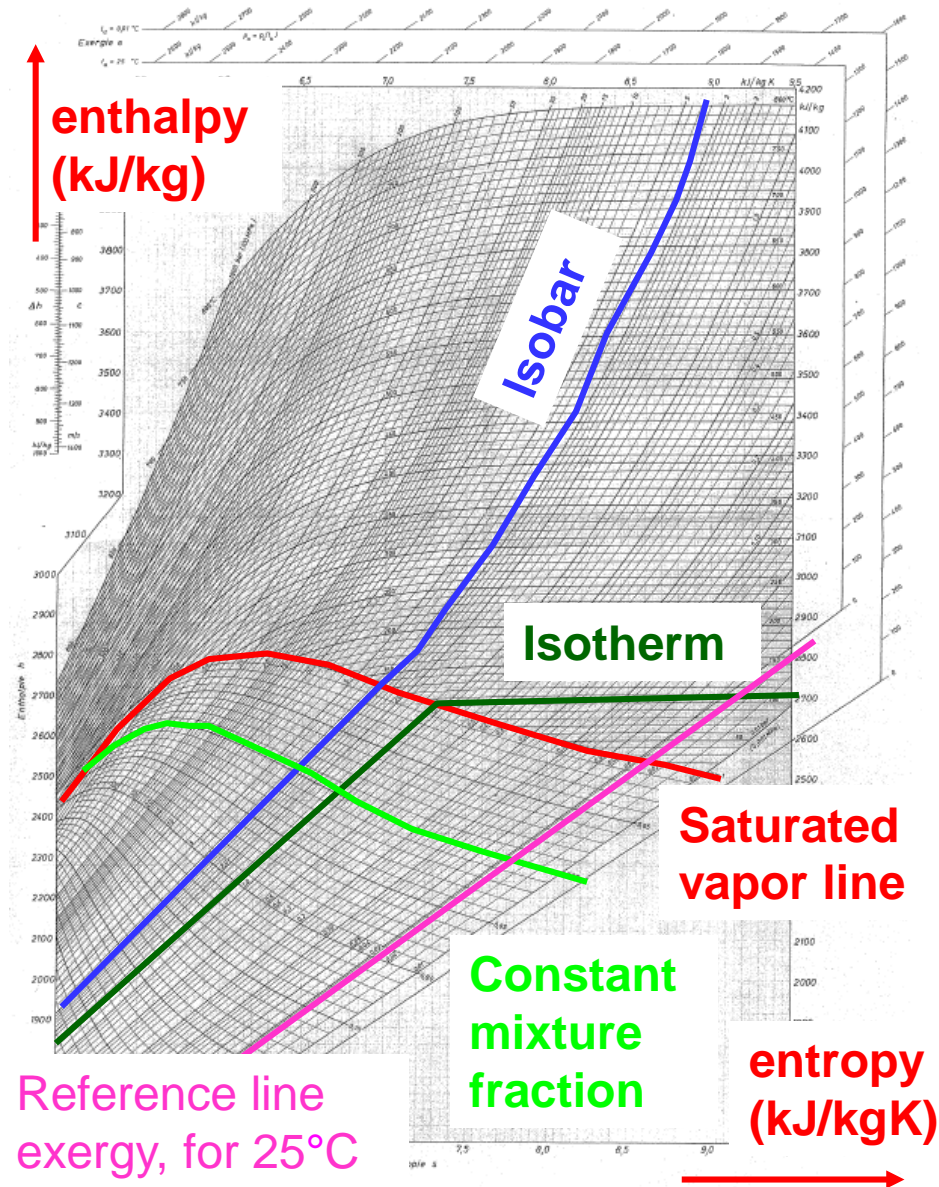
# Exam Engineering Thermodynamics

- ...“pitfalls” continued:
- Be certain that you can draw **Ts - diagrams** and **hs - diagrams**
- Remember the difference between the Ts - diagrams and hs diagram
  - Remember that water has a saturation line, but not air/gas
  - See also the document on BB



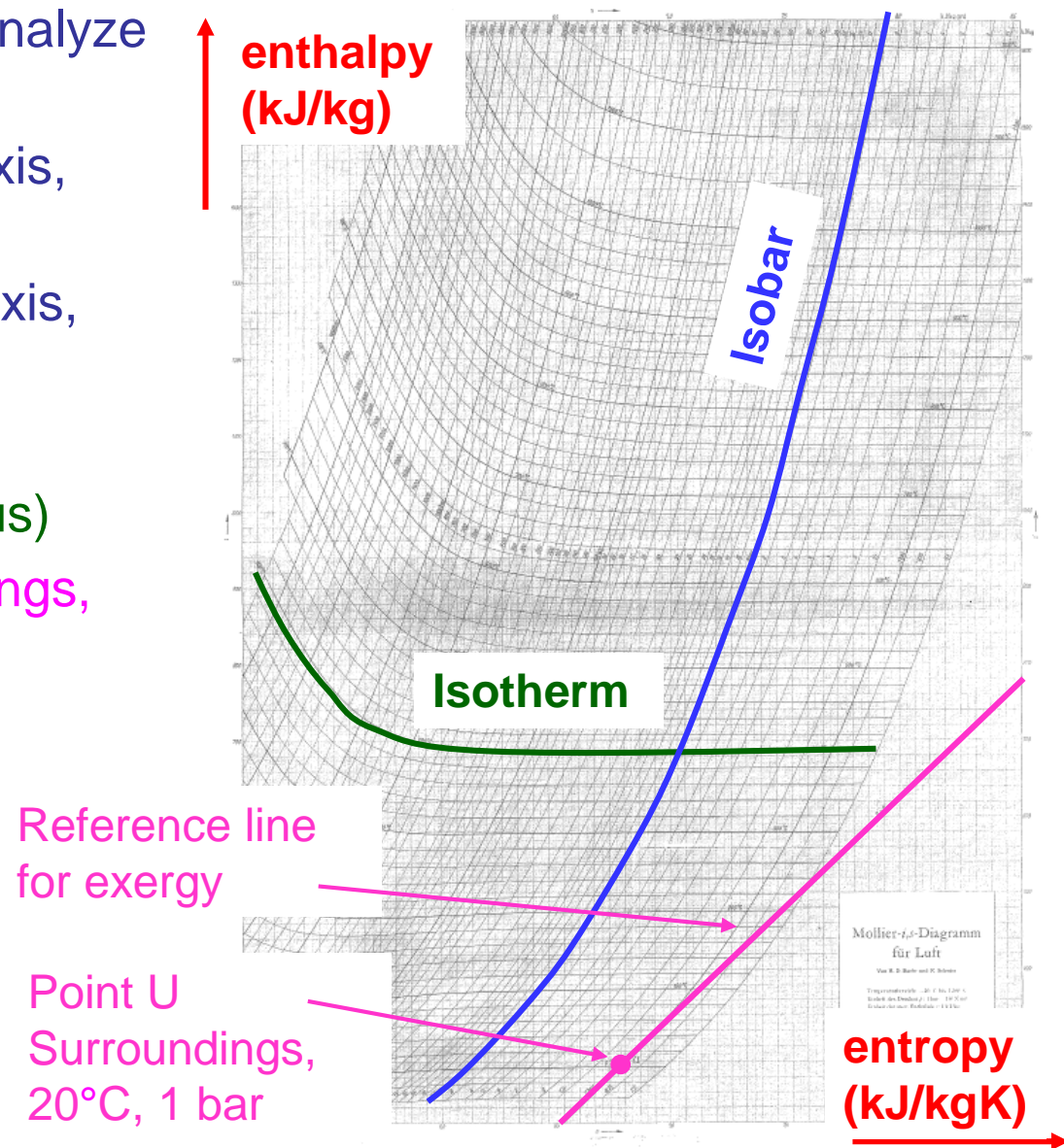
# Mollier Diagram Water for Rankine Cycle

- Use the Mollier diagram for water to analyze the Rankine cycle
  - Enthalpy (kJ/kg) on the y-axis, horizontal line  $\rightarrow dh = 0$
  - Entropy (kJ/kgK) on the x-axis, vertical line  $\rightarrow ds = 0$
  - **Saturated vapor line** divides superheated vapor and mixture region
  - Isobars (in **Bar !!**)
  - Isotherms (in degree Celsius)
  - Constant mixture fraction lines
  - Reference line for exergy, tangent at  $T_0$  (25°C here)
- Compressed liquid area is not shown  $\rightarrow$  diagram not usable, use tables



# Mollier Diagram Air for Brayton Cycle

- The Mollier diagram for air to analyze the Brayton cycle
  - Enthalpy (kJ/kg) on the y-axis, horizontal line  $\rightarrow dh = 0$
  - Entropy (kJ/kgK) on the x-axis, vertical line  $\rightarrow ds = 0$
  - Isobars (in **Bar** !!)
  - Isotherms (in degree Celsius)
  - Conditions of the surroundings,  $T = 20^{\circ}\text{C}$ ,  $P = 1 \text{ bar}$
  - Reference line for exergy, tangent at  $T_0$
- In contrast to the diagram for water also the point at low temperatures and pressures can be found in the diagram





# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- **Mollier diagrams** → pressure in BAR and temperature in °C and remember 1 bar = 100 kPa = 0.1 MPa and 0°C = 273 K
  - Be sure that you understand how the diagrams work and what the difference between the A3 water and air diagram is
  - The **air diagram** consists **all data for the cycle**
  - The **water diagram**, consists **only** the **superheated vapor** and a **part of the saturated mixture region**, hence the compressed liquid part is not present (the saturation line ( $x=1$ ) is present, the saturated liquid line ( $x=0$ ) not)
  - You cannot draw the full cycle on the A3 Mollier diagram
  - Uses tables for values outside the diagram
  - **100.000% certainty** you need to draw cycles on the A3 diagram

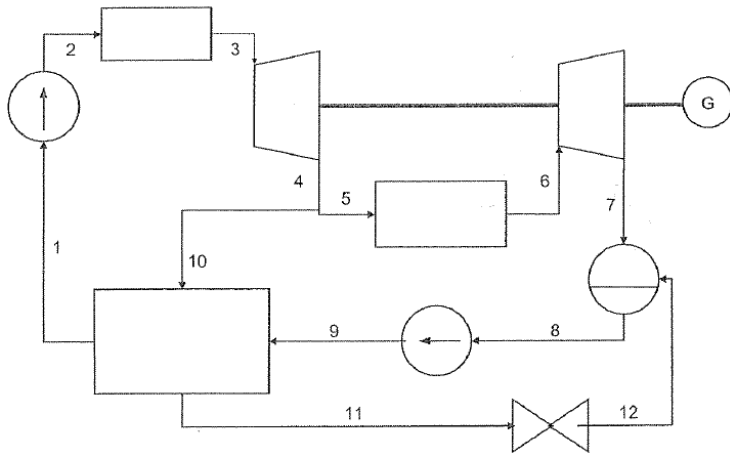
# Exam Engineering Thermodynamics

- .... “pitfalls” continued:
- **Mollier diagrams** → Use it for the analysis of water and gas cycles
  - Using the diagram is quicker than using the tables
  - Reading off the diagram doesn't need to be super precise (per '20' is more than accurate)
  - Draw the cycle in the diagram, trace all important lines. Draw “help” lines thin or dotted. A pencil is useful, because you can erase the lines.
  - Also show the processes which leave the diagram, example: slide 24.
  - Open gas turbine cycle: do not connect the inlet and the outlet
  - Caution! Entropy has to increase for turbines, compressor and pumps ,  $ds > 0$ , if not something is wrong
  - Try not to scribble!

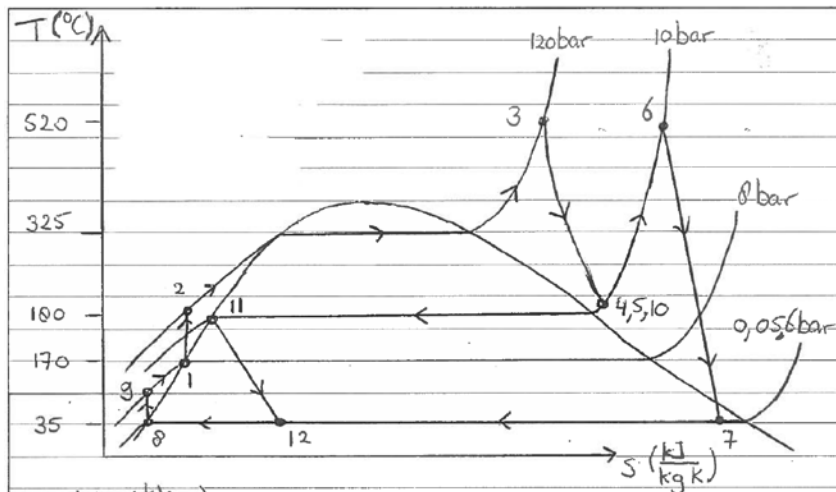
# Exam Engineering Thermodynamics

- .... “pitfalls” continued: (as promised in the lecture. some examples of strange diagrams, that I saw on exams)

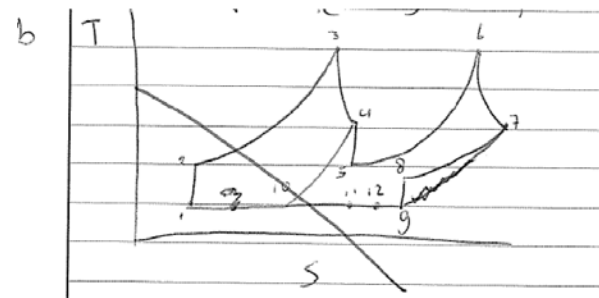
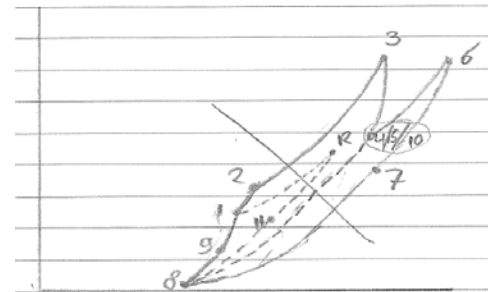
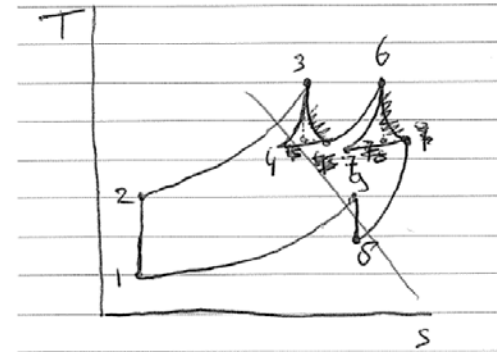
The Rankine cycle with closed feedwater preheating



A correct Ts-diagram for the Cycle



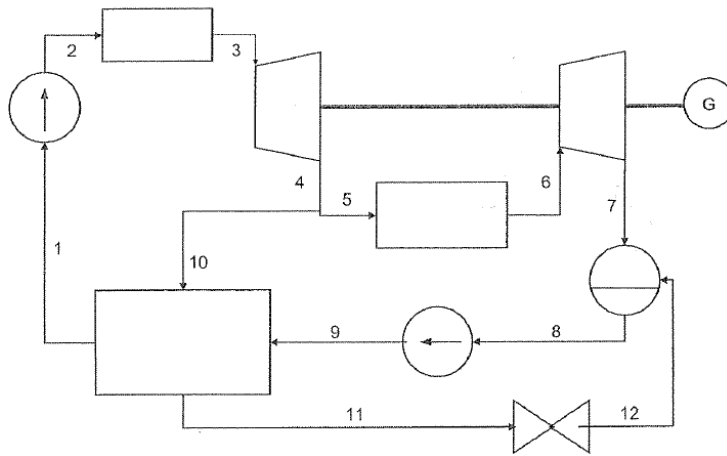
Below some wrong answers from an exam: Vapor dome is missing, in the vapor dome horizontal isobars. Points 1, 8 and 11 should be on the saturated liquid line.



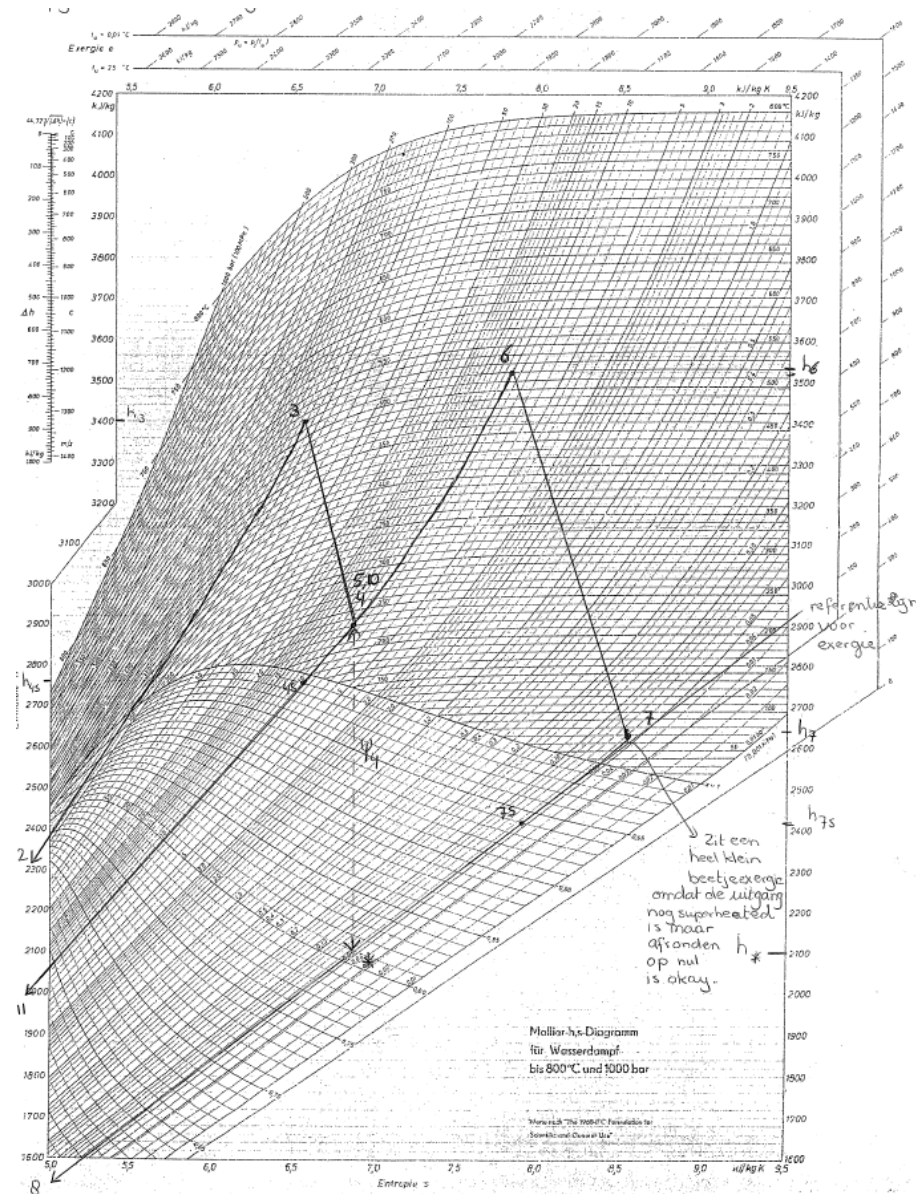
# Exam Engineering Thermodynamics

- .... “pitfalls” continued: (as promised in the lecture, some examples of strange diagrams, that I saw on exams)

The cycle, Rankine with closed feedwater preheating



This is the correct A3 Mollier diagram. Notice that you also need to draw the lines from point 3 and from point (4, 5, 10) and point 7 towards 1 and 11 (leaving the diagram). On the next 2 slides are examples what I saw on the exam. Notice that you can not draw the full cycle on this diagram and how some people still tried it.

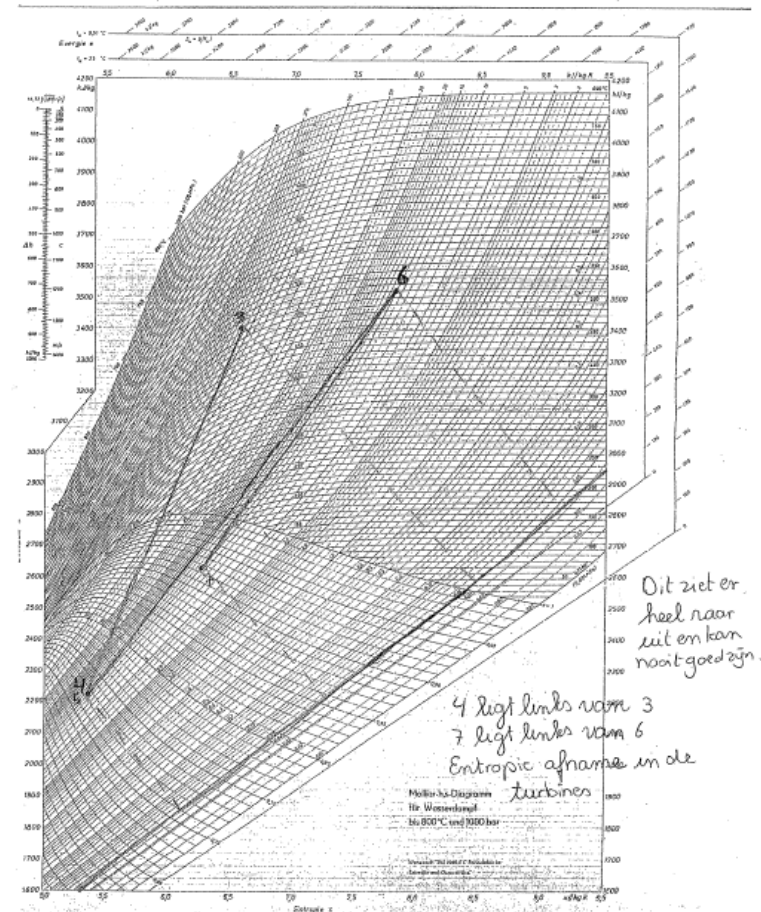
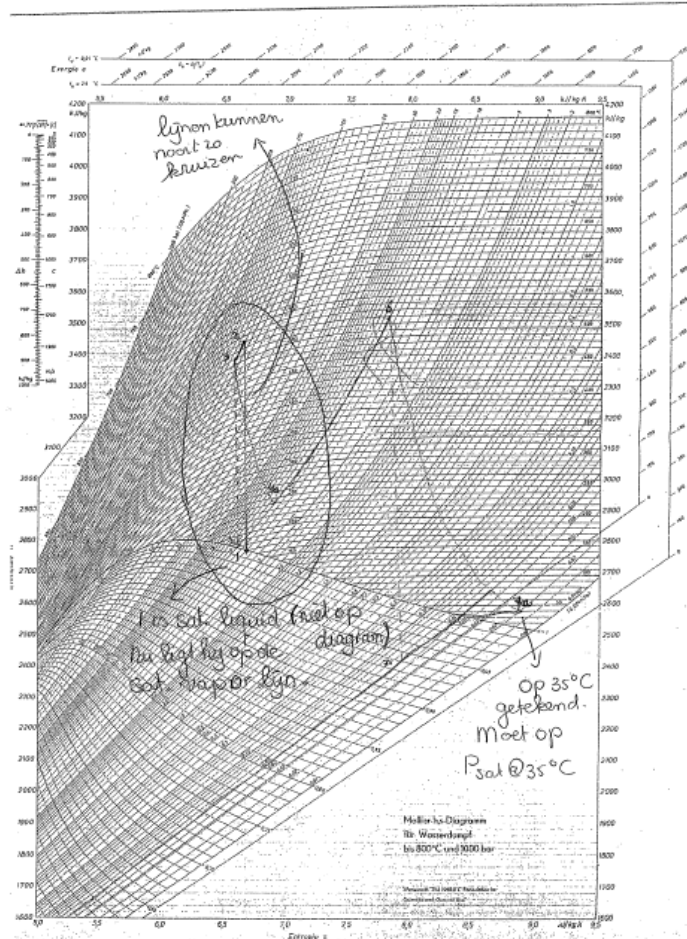




# Exam Engineering Thermodynamics

- .... “pitfalls” continued: (some examples of strange diagrams, that I saw on exams, sorry for the Dutch I don not have English ones yet, try to avoid that yours are here next year.....)

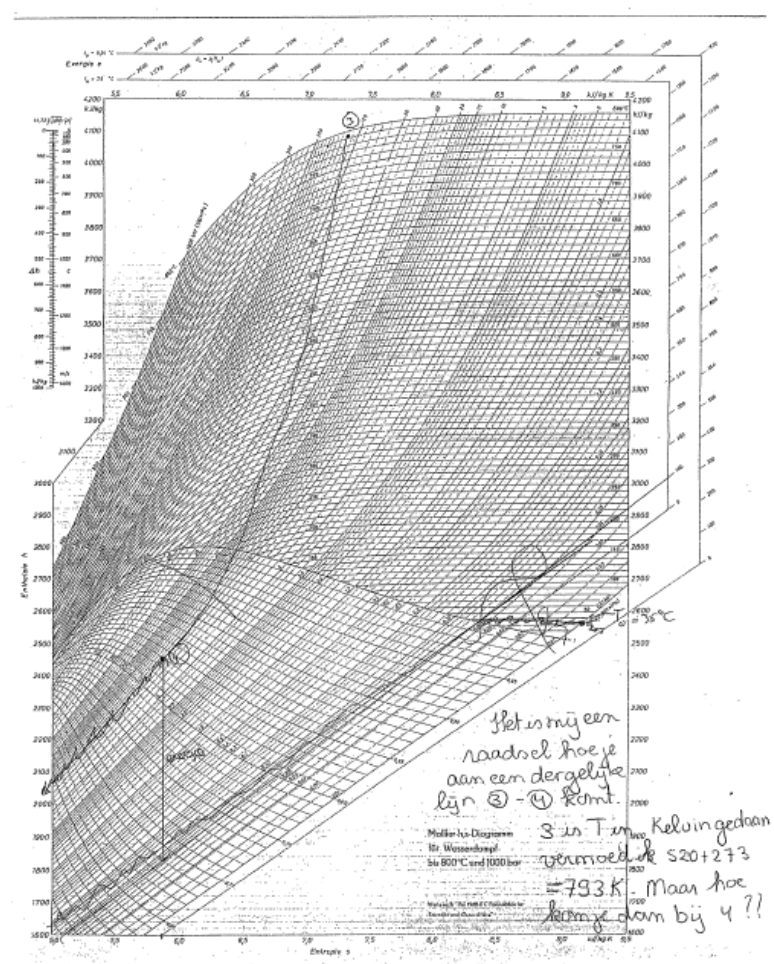
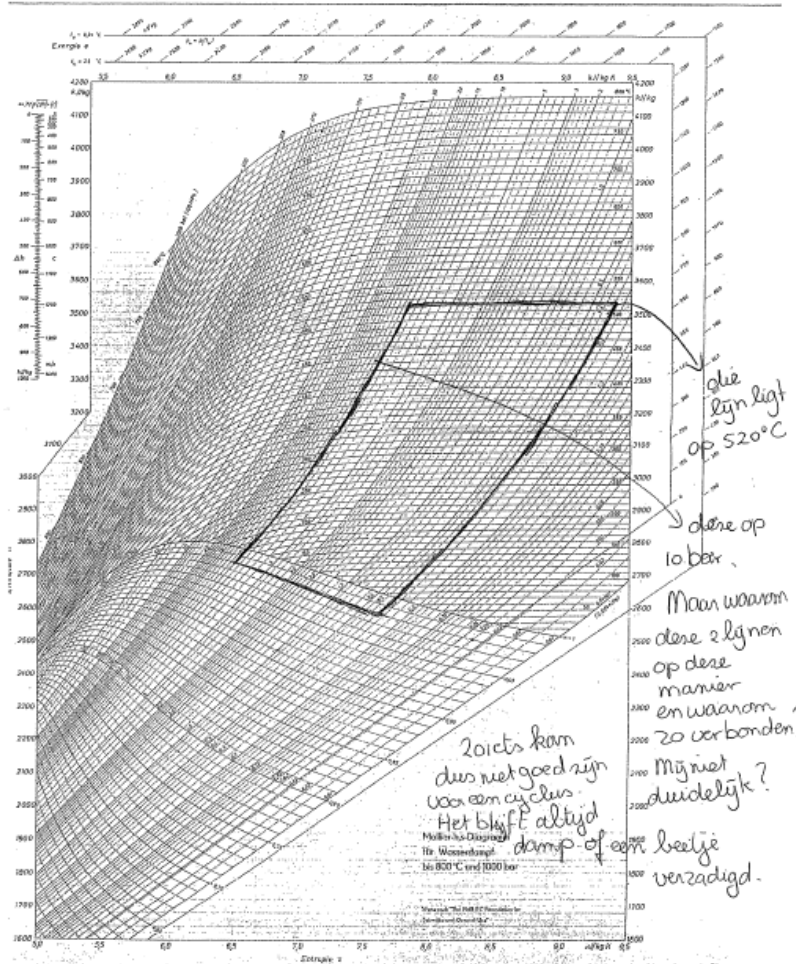
Rankine cycle with closed feedwater preheating, **wrong diagram !!**



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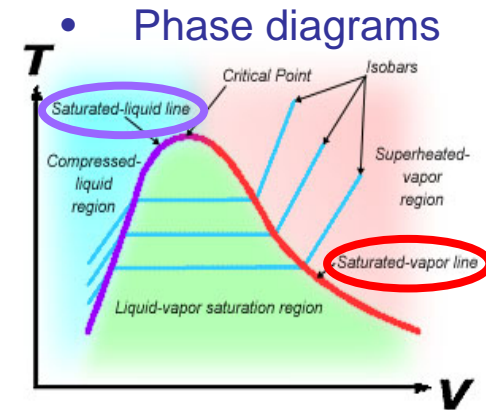
Rankine cycle with closed feedwater preheating, **wrong diagram !!**





# Keep in mind: Important Formulas

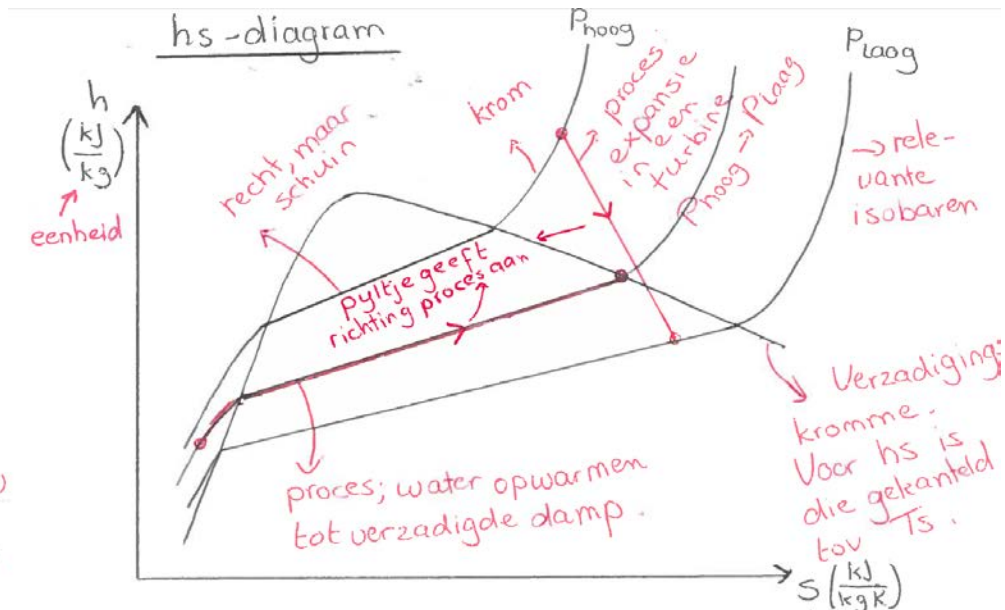
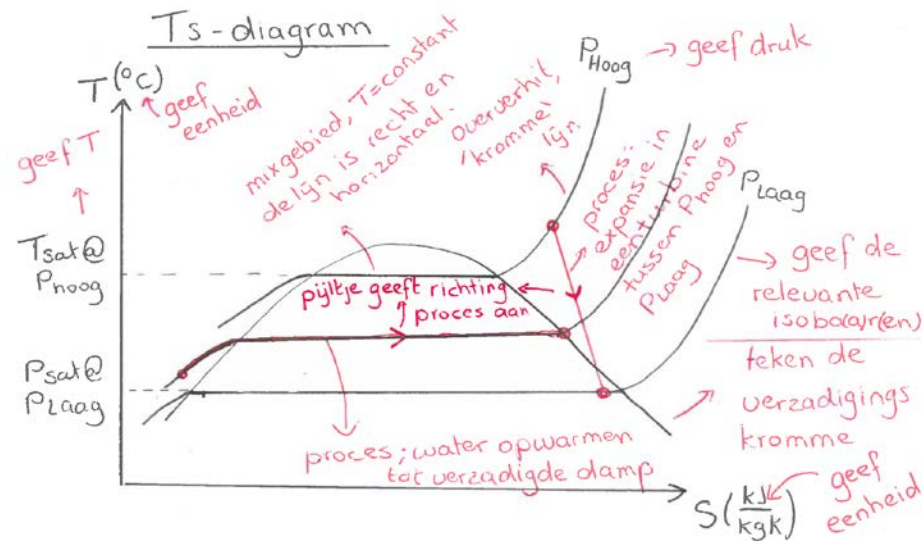
- Specific volume  $v = V/m$  [ $\text{m}^3/\text{kg}$ ] and density  $\rho = 1/v = m/V$  [ $\text{kg}/\text{m}^3$ ]
- Volume work  $\delta w = P dv$
- Enthalpy  $h = u + Pv$ , ( $u$  internal energy,  $P$  pressure,  $v$  volume)
- Thermal efficiency  $\eta_{\text{thermal}} = \frac{\text{Net electrical power output}}{\text{Rate of fuel energy input}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}}$
- Mixture fraction  $x = \frac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
- Ideal gas law  $Pv = RT$ ,  $R = c_p - c_v$
- For an ideal gas  $du = c_v dT$  and  $dh = c_p dT$
- Conservation of mass  $m_{\text{in}} = m_{\text{out}}$ , mass flow rate  $\dot{m} = \rho v A$
- Conservation of energy, first law of thermodynamics
  - Closed system  $du = \delta q - \delta w \rightarrow \Delta u = q - w$
  - Open system  $q_{\text{in}} + w_{\text{in}} + (h + ke + pe)_{\text{in}} = q_{\text{out}} + w_{\text{out}} + (h + ke + pe)_{\text{out}}$
- S increases, second law  $ds_{\text{total}} = ds_{\text{system}} + ds_{\text{surroundings}} = \delta s_{\text{gen}} \geq 0$
- Inequality of Clausius  $ds \geq \frac{\delta q_{\text{net}}}{T_{\text{res}}}$  (= for reversible process)
- Reversible heat transfer  $\delta q_{\text{net,rev}} = T ds$ , irreversible  $\delta q_{\text{net,irrev}} < T ds$
- Gibbs equations  $T ds = du + P dv$  and  $T ds = dh - v dP$
- Isentropic efficiencies  $\eta_{\text{INPUT,S}} = \frac{w_{\text{IN,S}}}{w_{\text{IN,A}}}$ ,  $\eta_{\text{OUTPUT,S}} = \frac{w_{\text{OUT,A}}}{w_{\text{OUT,S}}}$
- Isentropic processes ideal gas  $Pv^k = \text{constant}$ ,  $Tv^{k-1} = \text{constant}$ ,  $P^{(k-1)/k}/T = \text{constant}$
- Thermal efficiency power cycles  $\eta_{\text{he}} = \frac{w_{\text{out}} - w_{\text{in}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}$



Carnot efficiency  $\eta_{\text{carnot}} = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}$

# Exam Engineering Thermodynamics

- ...“pitfalls” continued:
- Be certain that you can draw **Ts - diagrams** and **hs - diagrams**
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  - Remember that water has a saturation line, but not air/gas
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Let op de verschillen. hs-diagram gekanteld tov Ts-diagram. Geef de verzadigingskromme en relevante isobaren. Geef waar bekend temperaturen en drukken.