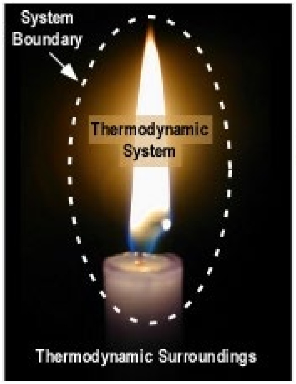
Class 7
Vapor power cycles, simple

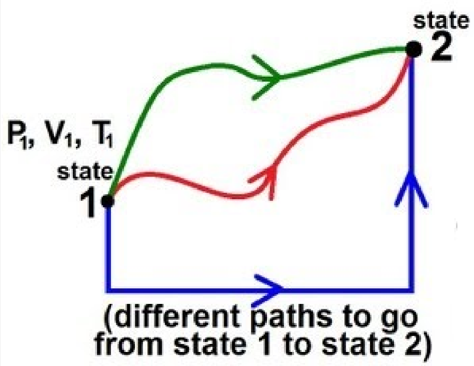
A field of mirrors concentrates solar energy onto a tower. This concentrated solar energy (heat) is used to drive a vapor power cycle. (PS20 and PS10 Solar Power Plant in Andalusia, Spain)

Roadmap Engineering Thermodynamics

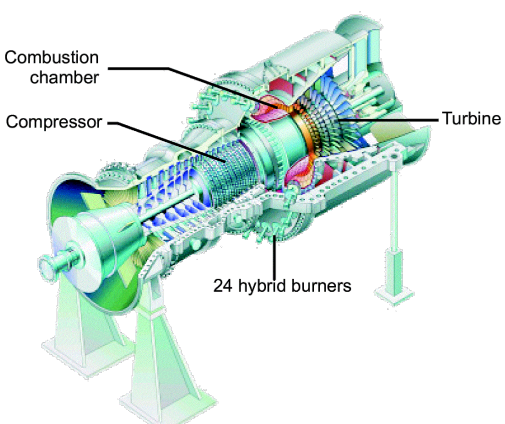
- Using thermodynamics for practical applications requires knowledge of:

Concepts and definitions (Class 1) → Various forms of energy (Class 2)

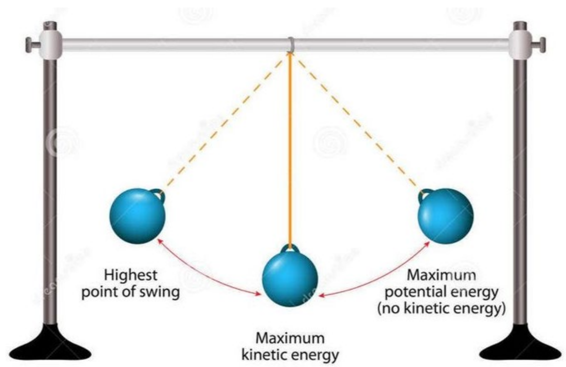




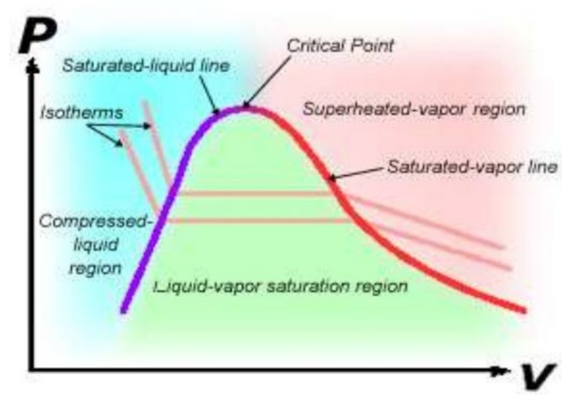
Power cycles (Class 6 – 11)



Laws of Thermo (Class 4 and 5)

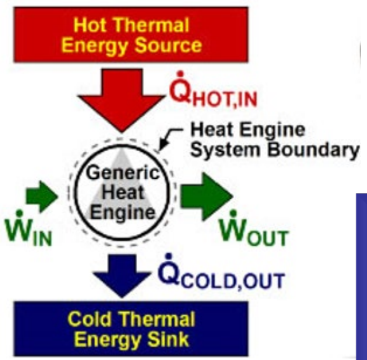


Properties of Substances (Class 3, 9)

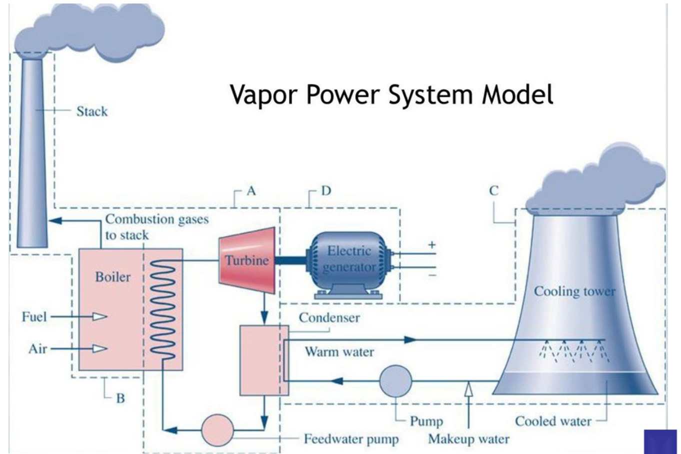


Roadmap Engineering Thermodynamics

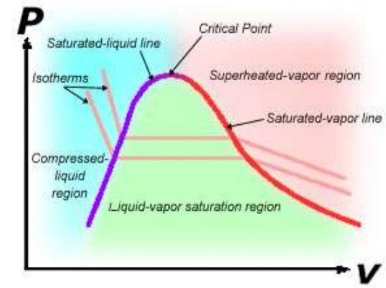
Thermodynamic cycles (Class 6)



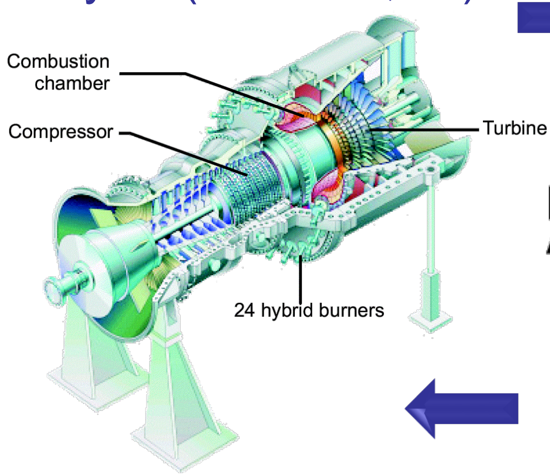
Vapor power cycles – Rankine cycle (Class 7, 8)



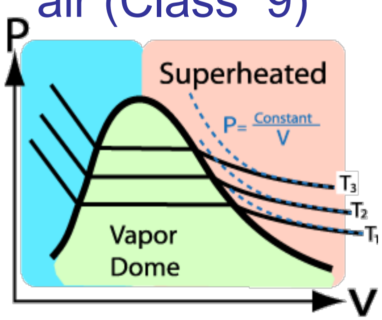
Properties of water (Class 3)



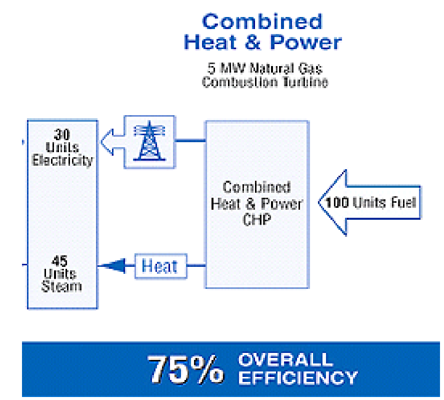
Gas power cycles – Brayton cycle (Class 10, 11)

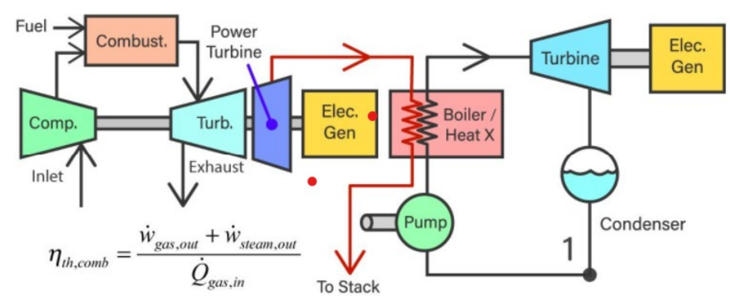


Properties of air (Class 9)



Combined cycles Combined heat & power (Class 8, 11)





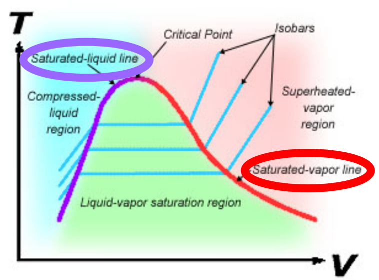
Recapitulate class 1 - 5

- **Class 1: Introduction and basic concepts**
  - What is thermodynamics? → Science on using heat and power
  - Properties, open/closed/isolated system, states, processes, equilibrium

- **Class 2: Energy, work and heat transfer**
  - The energy of a system (e=u+ke+pe) can change due to work (w) and/or heat transfer (q) and/or mass flow (m) with flow work (Pv) over the system boundary
  - Enthalpy: h = u + Pv, entropy: s, efficiency

- **Class 3: Thermodynamic properties of water**
  - Phases, phase change, phase diagrams and tables to look up values
  - Saturated liquid, saturated vapor, saturated mixture, quality of the mixture (x), compressed liquid, superheated vapor

$$x = \frac{v - v_l}{v_v - v_l}$$



- **Class 4: The first law of thermodynamics**
  - Conservation of energy and conservation of mass
  - Closed system: $du = \delta q + \delta w$
  - Open system: $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$

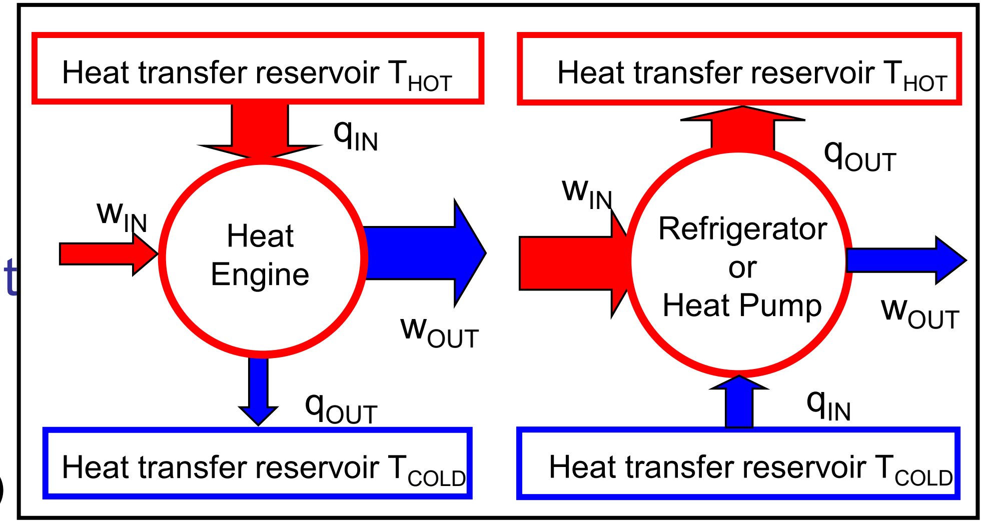
- **Class 5: The second law of thermodynamics**
  - To describe the direction of spontaneous processes **entropy** (s in kJ/kgK) is introduced, it is a measure of disorder and entropy is maximal in equilibrium,
  - Entropy is not conserved, in the universe **entropy always increases (second law)**

Recapitulate class 6

- A **thermodynamic cycle** is composed of a series of processes which return to the initial state and works between a hot and a cold thermal reservoir
  1. **Heat power cycles** produce power from heat
  2. **Refrigeration / heat pump cycles** transport heat using power
- First law for a cycle: $w_{net} = q_{net}$
- Second law for a cycle: $\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} \leq 0$ or $\oint \frac{\delta q net, i}{T_i} \leq 0$
- Thermal efficiency for heat / power cycles: $\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$
- Carnot (ideal) cycle
- Carnot (maximum) efficiency

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

- Kelvin-Planck & Clausius statement (second law applied to cycles)



Energy flows in a heat engine (left) and in a refrigeration or heat pump cycle (right)

Next classes 7 – 11: Thermodynamic Power Cycles

- In class 1 to 6 we introduced the all the (basic) tools we need to study thermodynamic systems that generate power or heat / cold

- Now it time for the real job
- The thermodynamics power cycles !

- Class 7 & 8: **vapor power cycles,** cycles using **a working fluid that undergoes a phase transition** (mostly water) through the cycle (Rankine cycle)

- Class 10 & 11: g**as power cycles**, cycles using **gas as working** fluid through the whole cycle (Brayton cycle)

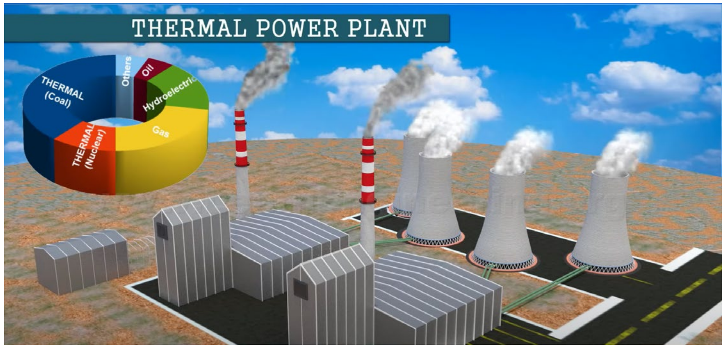
- **Refrigeration and heat pump cycles**, cycles moving heat opposite to the natural direction using power are treated in module 3

Jet engines are an example of gas power cycles

Power plants typically use vapor power cycles to generate electricity, e.g. the power plant in Geertruidenberg (NL)

Content Class 7

- **Vapor power cycles – Rankine cycles, simple**
- **Vapor power cycles** use a working fluid that undergoes a phase transition (mostly water) through the cycle, are studied
  - Piston steam engine & some history
  - Steam turbine
  - Comparison to Carnot
  - Ideal and real Rankine cycles
    - Heat and power in- and output
    - Thermal efficiency
  - Design parameters
  - Mollier diagram for water

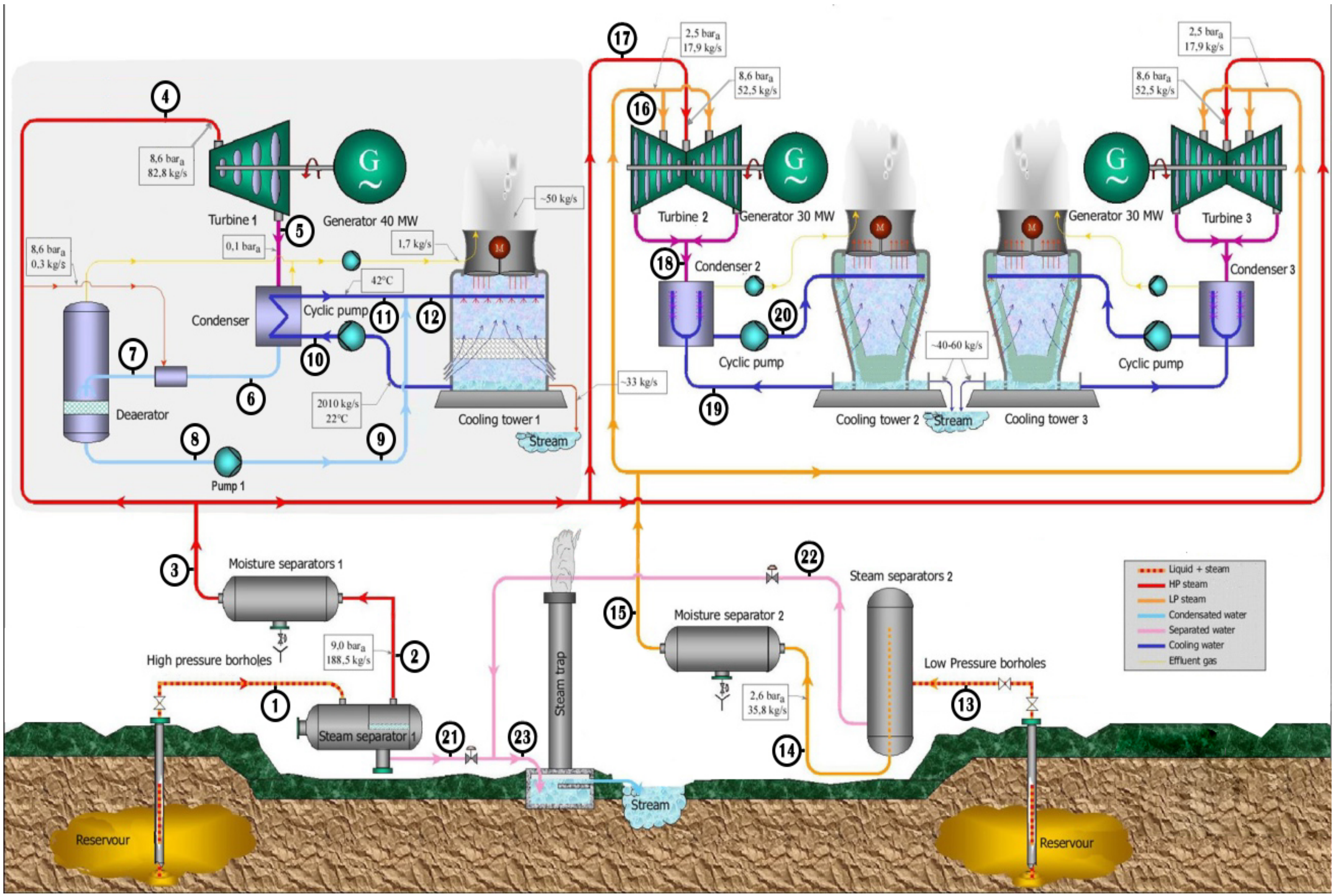


https://www.youtube.com/watch?v=IdPTuwKEfmA

- **Learning goal:** recognize a **simple** thermodynamic system to produce work, explain the configuration, analyse the thermodynamic aspects from the viewpoint of the first law of thermodynamics, interpret and evaluate the results and suggest improvements

Example Vapor Power Cycle: Project 2

- Landsvirkjun geothermal power plant to be analysed in the project



Vapor power cycles

- To produce power a **thermodynamic cycle** is used
- In a thermodynamic gas cycle the working medium is in the gas phase throughout the whole cycle (chapter 9, class 10 & 11)
- In a **vapor power cycle** the working medium **changes phase** (chapter 10, class 7 & 8)
  - Liquid → Vapor → Liquid
- The vapor power cycle is externally heated, the heat is transferred to the fluid using a boiler or a heat exchanger
- Mostly vapor power cycles are closed cycles (an exception is the steam train)

A steam train uses a piston steam engine, some of them are still in use

- Vapor power cycles are first used in piston steam engines begin 1700
- Around 1900, vapor power cycles are also used in **steam turbine cycles**
- Today the biggest application of vapor power cycles is in **steam turbine cycles (Rankine cycles)** in power generation in power plants

The Aeolipile van Heron van Alexandrië

- Although the first steam engine was developed around 1700 already in antiquity the power of steam fascinated people
- An **aeolipile** (or **aeolipyle**, or **eolipile**), also known as a **Hero's engine**, is a simple bladeless radial steam turbine which spins when the central water container is heated. Torque is produced by steam jets exiting the turbine, much like a tip jet or rocket engine. In the 1st century AD, Hero of Alexandria described the device in Roman Egypt, and many sources give him the credit for its invention.
- The aeolipile Hero described is considered to be the first recorded steam engine or reaction steam turbine. The name – derived from the Greek word Αἴολος and Latin word *pila* – translates to "the ball of Aeolus", Aeolus being the Greek god of the air and wind.

https://en.wikipedia.org/wiki/Aeolipile

Some history, background information, not for the exam

The piston steam engine

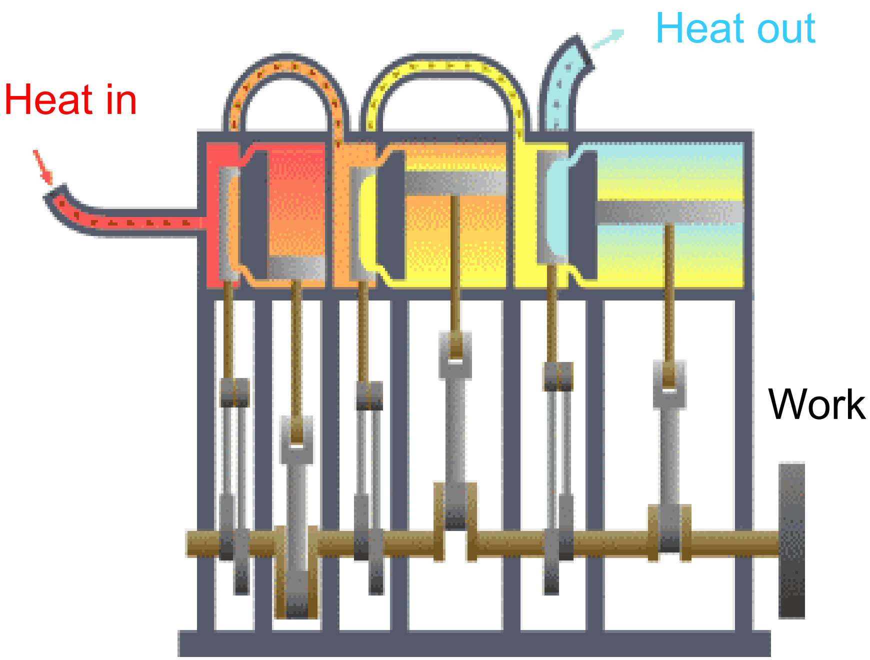
- A **piston steam engine** is a type of engine (or, more broadly a kind of machine) that uses the thermodynamic characteristics of water to produce work (power / electricity)

- The machine converts the energy of hot, pressurized steam into mechanical work, by expanding the steam in one or more cylinder / piston systems

- The piston will be squeezed by the expanding steam and generates volume work $\rightarrow \delta w = Pdv$

- Using a crank-connecting rod mecha-nism, the energy of the expansion is transferred to a flywheel

- Electricity can be produced using a generator



Animation from http://en.wikipedia.org/wiki/Thermodynamics

The Piston Steam Engine

- The invention of the (industrial) piston steam engine marked the beginning of the industrial revolution
- For the first time mechanical power was available to drive machines, where before manual power, draft animals, water and wind mills had to be used
- The first piston steam engine is developed by **Thomas Newcomen in 1712** and used in the coal mines in England

- Historically piston steam engines are used for
  - Trains, boats and cars for propulsion
  - Pumping stations to move water for draining the polders in The Netherlands
  - Factories e.g. textile-industry here in Twente (Museum Twentse Welle)

- Nowadays the piston steam engine is almost completely replaced by the steam turbine (Rankine cycle)

Newcomen Steam Engine

- The **atmospheric engine** invented by Thomas Newcomen in 1712, today referred to as a **Newcomen steam engine** (or simply Newcomen engine), was the first practical device to harness the power of steam to produce mechanical work
- First used to pump water out of coal mines, starting in the early 18th century

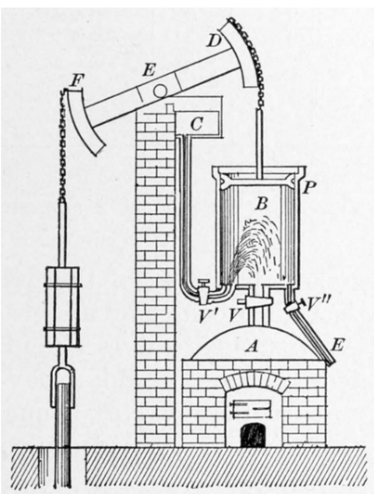
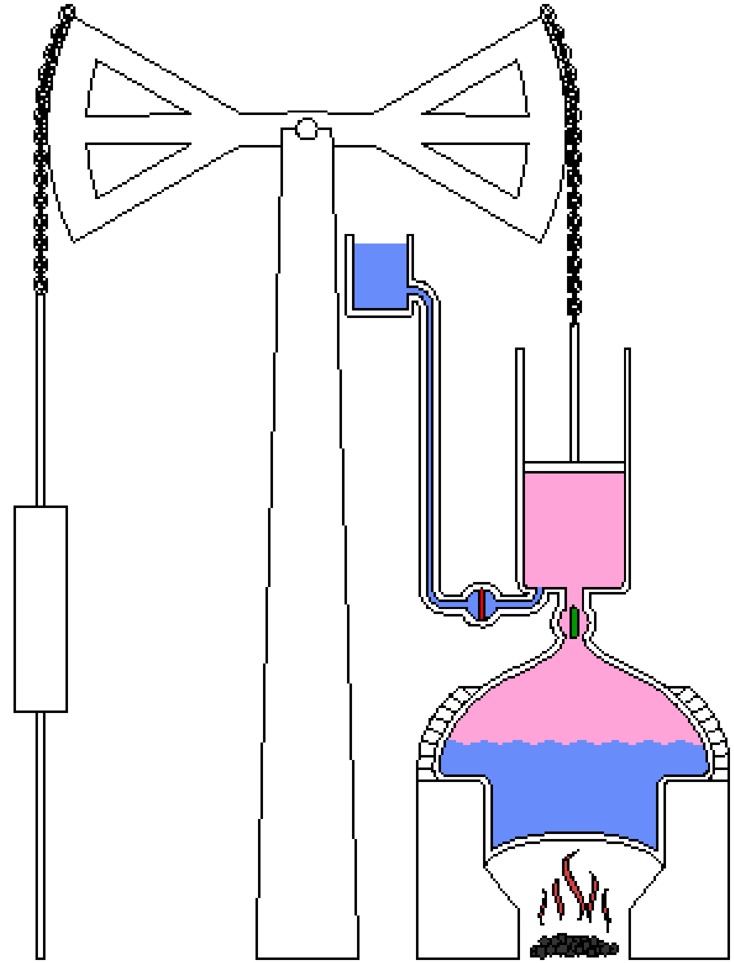


Diagram of the Newcomen steam engine and a Newcomens style engine at Elsecar Centre



Animation of a schematic Newcomen steam engine
– Steam is shown pink and water is blue.
– Valves move from open (green) to closed (red)

Some history, background information, not for the exam

James Watt and the Steam Engine

- James Watt's (1736 – 1819) later engine was an improved version of the Newcomen steam engine
- Although Watt is far more famous, Newcomen rightly deserves the first credit for the widespread introduction of steam power

James Watt's workshop

James Watt

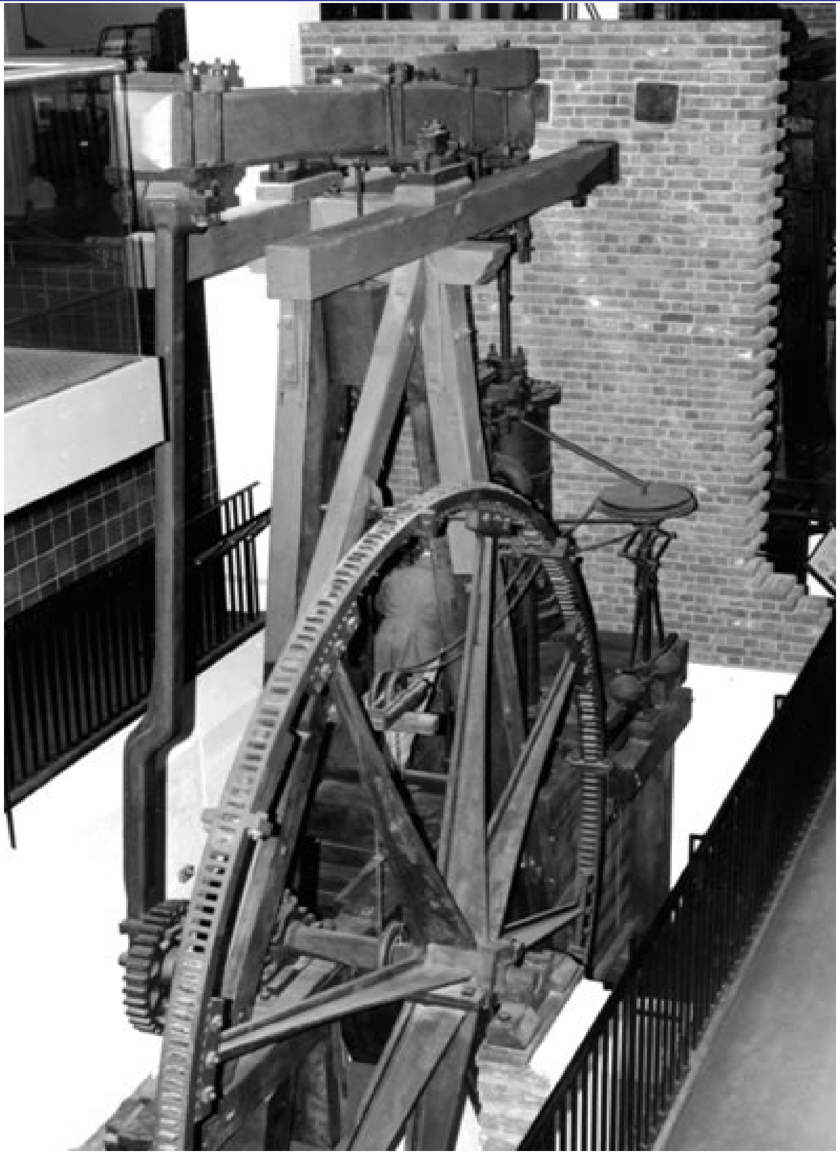
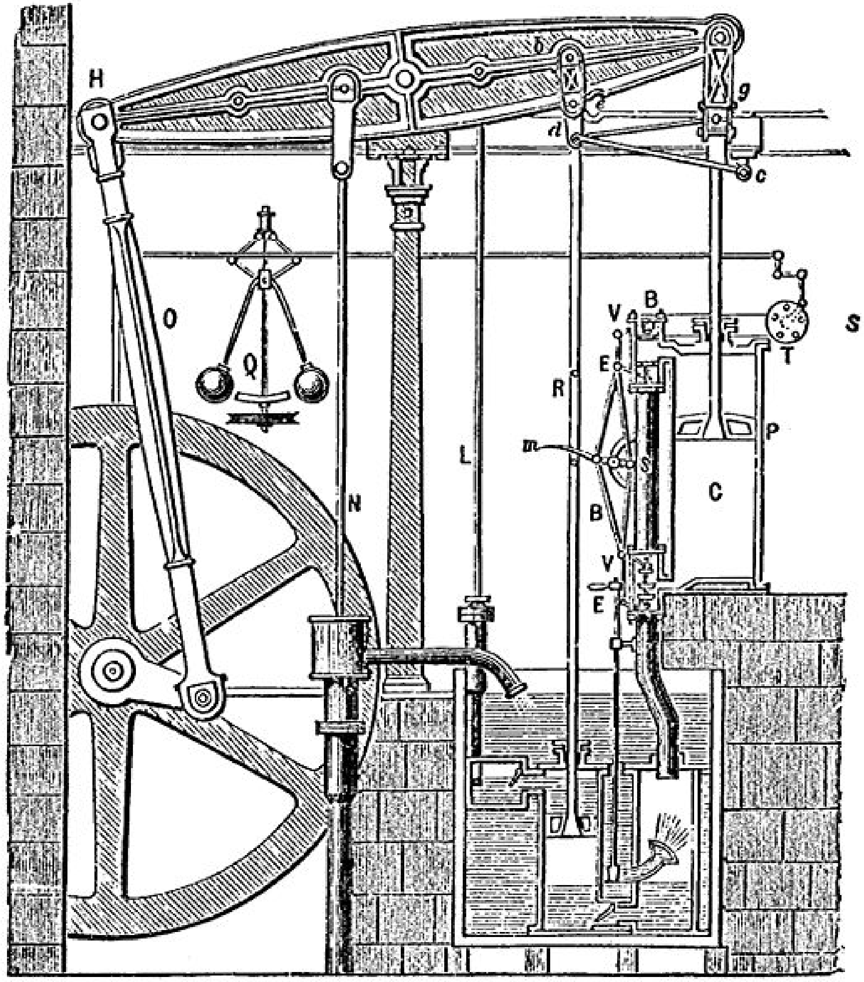


Photo: British Science Museum, London

Some history, background information, not for the exam

Boulton and Watt Steam Engine

- The Newcomen steam engine was very slow and inefficient
- In 1763 James Watt was asked to repair a Newcomen steam engine
- He made a number of improvements and modifications and transformed the engine to a more efficient one
  - He added the condenser
  - He used the up as well as the down stroke of the piston
  - He added a crank to transform the translation motion into rotation
- Used in 1777 in a mine in Cornwal



Steam engine designed by Boulton & Watt.
Engraving of a 1784 engine

Some history, background information, not for the exam

Cruquius Stoomgemaal, The Netherlands

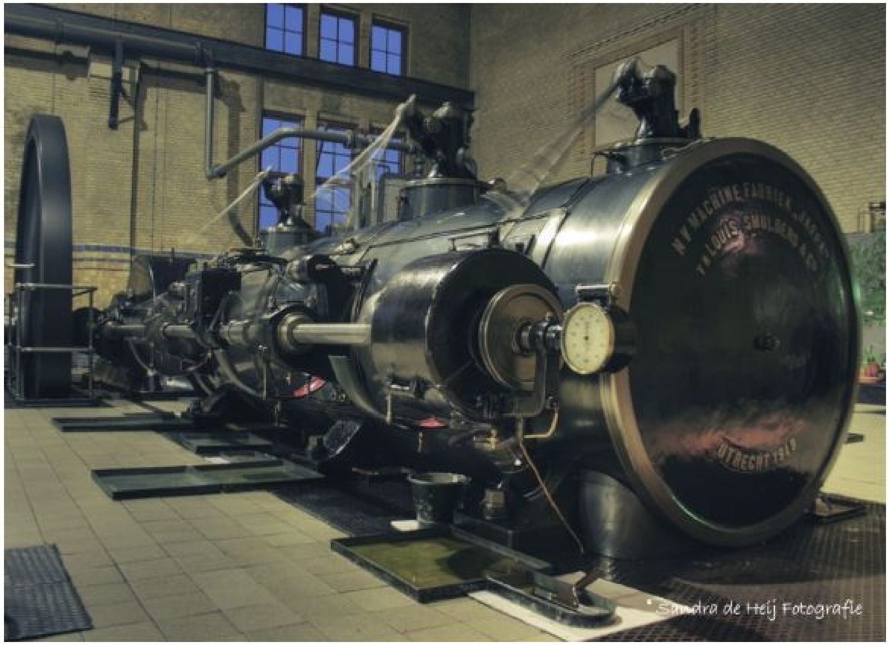
- In the Netherlands steam engines were used to move water for draining
- **‘Stoomgemaal Cruquius’,** build in 1849, had a piston diameter of 3.66m
- This diameter made it the largest steam engine in the world
- Pumping-engine **’De Cruquius’** is one of the three pumping-engines used for draining ‘De Haarlemmermeer’ between 1849 and 1852
- It is used for draining till 1933 when it is replaced by a more modern engine
- It is named after the Dutch engineer *Nicolaus Samuelis Cruquius*, born as Nicolaas Kruik, in 1678 in Vlieland (NL)

Background information, not for the exam

Woudagemaal in The Netherlands

- The steam engine seems to be old fashioned but is still in use
- The **Ir. D.F. Woudagemaal** is the largest steam engine in the world that is still used
- Its function is to lower the water level in Friesland (het FZP)
- In 1966 its function is taken over by the J.L. Hooglandgemaal in Stavoren
- The Ir. D.F. Woudagemaal however, is still used if the capacity of the new pumping-engine is too low (last times at the storm at 2-9 January 2012 and Christmas 2012)
- The pumping-engine is positioned in Tacozijl (close to Lemmer) and is placed on the *UNESCO – world heritage list* in 1998

Background information, not for the exam



Steam Locomotive: De Arend

- ***De Arend***: First Steam Locomotive running in The Netherlands

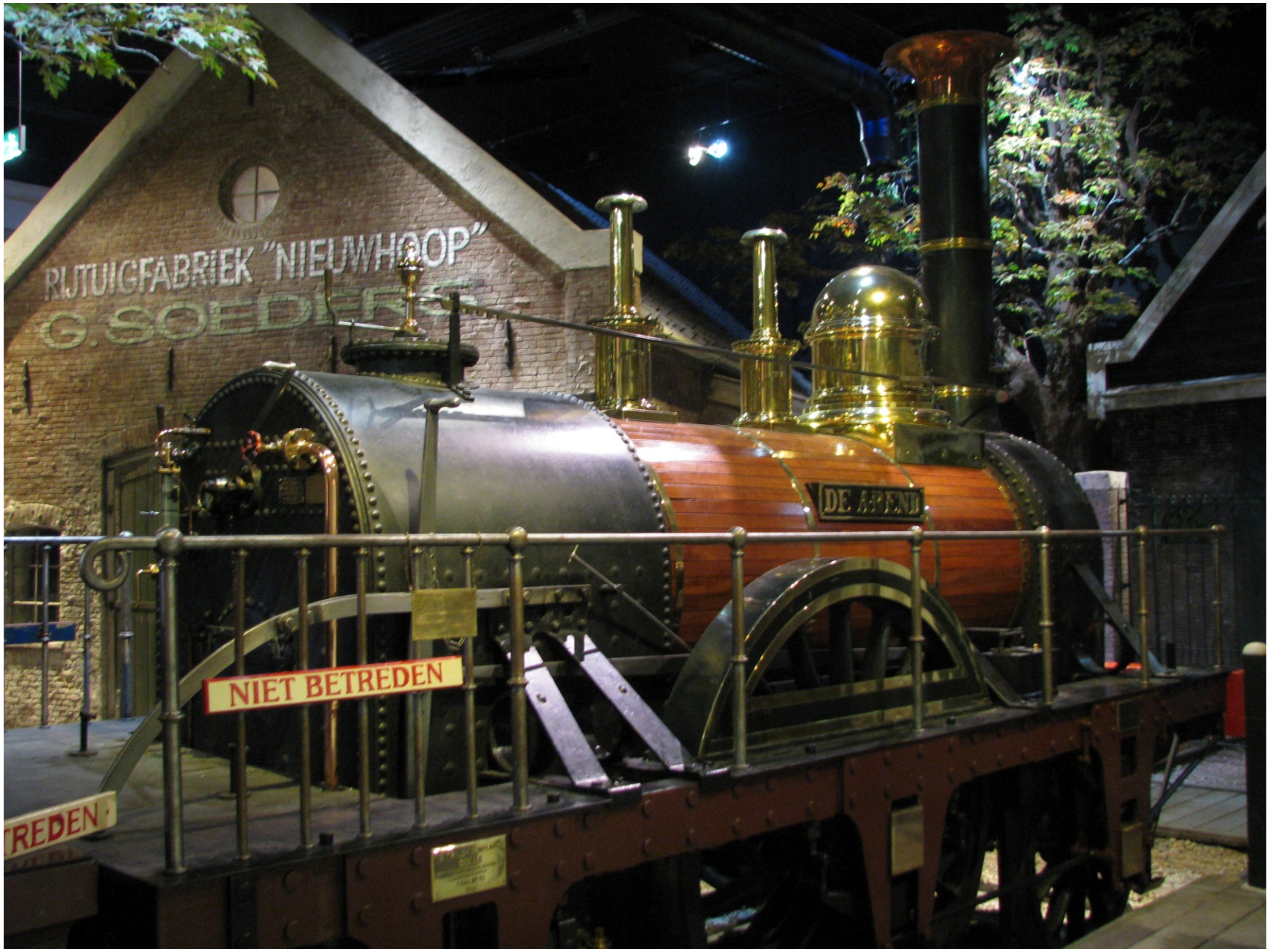


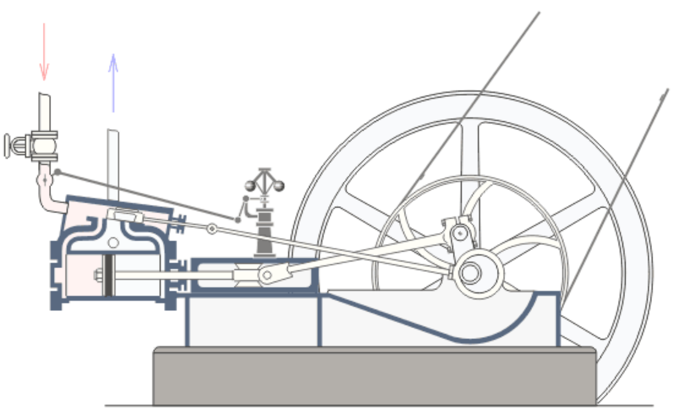
Photo taken in *Het Spoorwegmuseum* in Utrecht, The Netherlands

- **Route:** Amsterdam ↔ Haarlem
- **First ride:** 20 September 1839

Some history, background information, not for the exam

Historical Importance of Steam Power

- It might be clear that the invention of the industrial piston steam engine was very important and had a large impact on society
- The steam engine is marked as the beginning of the industrial revolution
- The theory of heat (thermodynamics) would later be formulated in an attempt to make the first steam engines more efficient
- The concept of entropy was only discovered in 1865 (150 years later) by Clausius to close the theory
- Nowadays steam power is mostly used in steam turbines to produce electricity



http://www.zaans-industrieel-erfgoed.nl/pages_4/rep_no_engeland_tyne.html

Some history, background information, not for the exam

Steam Turbine

- A **steam turbine** is a mechanical device that extracts thermal energy from pressurized steam, and converts it into rotary motion, its modern manifestation was invented by Sir Charles Parsons in 1884

- It has almost completely replaced the reciprocating piston steam engine primarily because of its greater thermal efficiency and higher power-to-weight ratio

- Because the turbine generates rotary motion, it is particularly suited to be used to drive an electrical generator – a large amount of all electricity generation in the world is by use of steam turbines

A rotor of a modern steam turbine, used in a power plant

Steam Power Plant

- Nowadays most of the electricity is generated in power plants that use **steam turbines in vapor power cycles**
- Vapor power cycles using steam turbine are called **Rankine cycles**, named after William John Macquorn Rankine (1820 – 1872)

Steam power plant for power generation

The British Steam Car

- **Application of a steam turbine in a modern vehicle**

De British Steam Car trekt op. De moderne stoomauto moet later dit jaar het 103 jaar oude snelheidsrecord voor stoomauto's (153 kilometer per uur) breken. Gestookt op lpg verhitten boilers water tot 400 graden en 40 bar. Turbines moeten alle stoomkracht omzetten in 274 kilometer per uur.

Intermediair 15, 9 april 2009

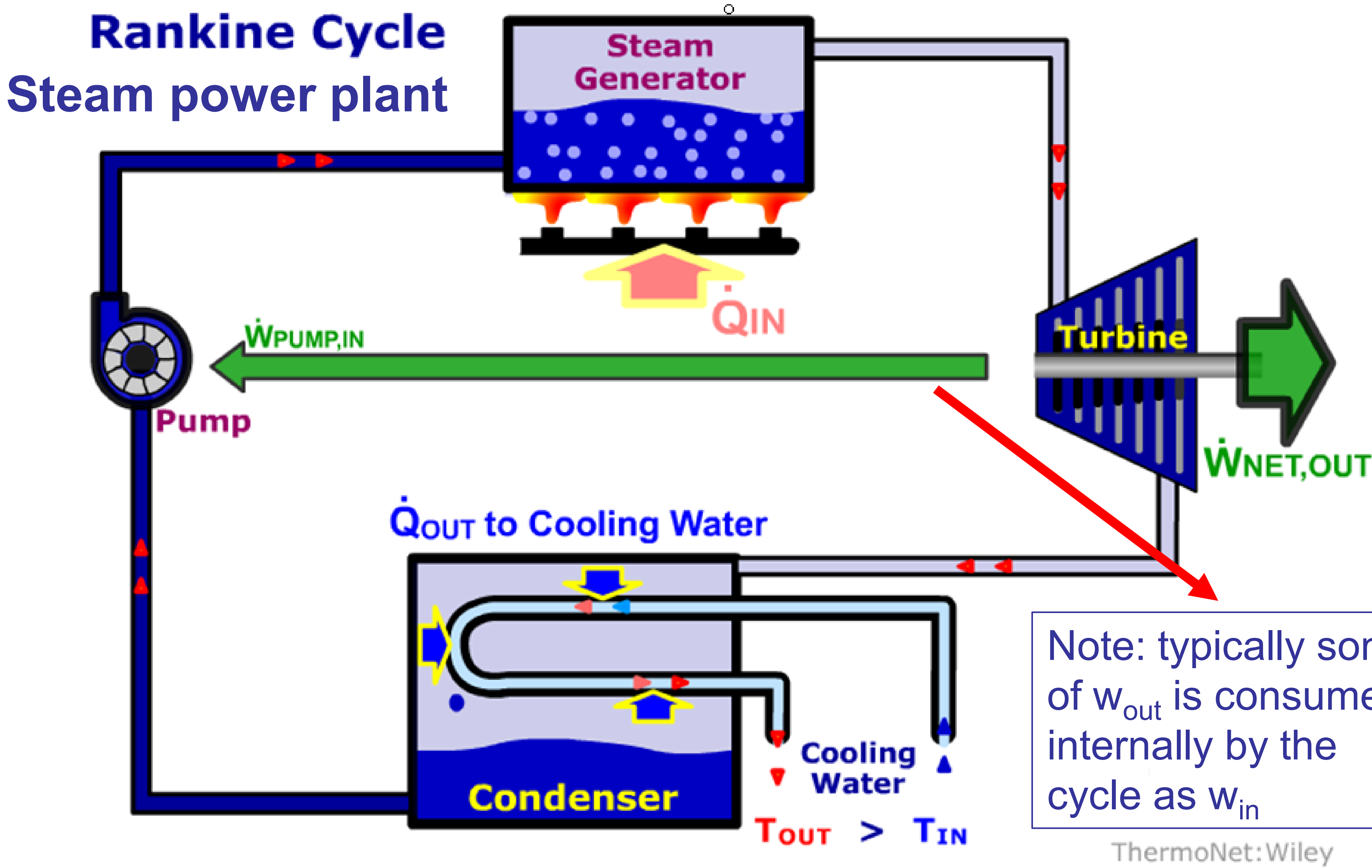
Background information, not for the exam

The British Steam Car

- **The British Steam Car; Official Land Speed Record Holder**
- On 25 August 2009, Team Inspiration of the British Steam Car Challenge broke the long-standing record for a steam vehicle set by a Stanley Steamer in 1906, setting a new speed record of 225.055 km/h at the Edwards Air Force Base, in the Mojave Desert of California. This was the longest standing automotive record in the world. It had been held for over 100 years.
- The car was driven by Charles Burnett III. FIA land speed records are based on an average of two runs (called 'passes') in opposite directions, taken within an hour of each other – in this case the maximum speeds reached were 219.037 km/h on the first run and 243.148 km/h on the second. As of August 25 the record is subject to official confirmation by the FIA.
- On August 26, 2009 the British Steam Car, driven this time by, the grandson of Sir Malcolm Campbell, broke a second record by achieving an average speed of 238.679 km/h over two consecutive runs over a measured kilometer. This was also recorded and again, has since been ratified by the FIA.

Background information, not for the exam

The Rankine Cycle

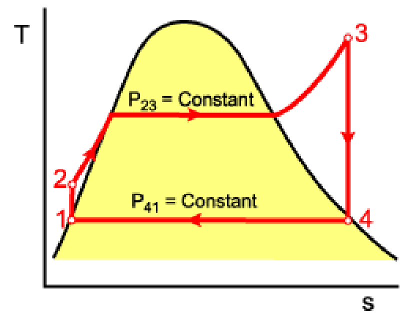


Note: typically some of w_{out} is consumed internally by the cycle as w_{in}

Principle of the Ideal Rankine Cycle

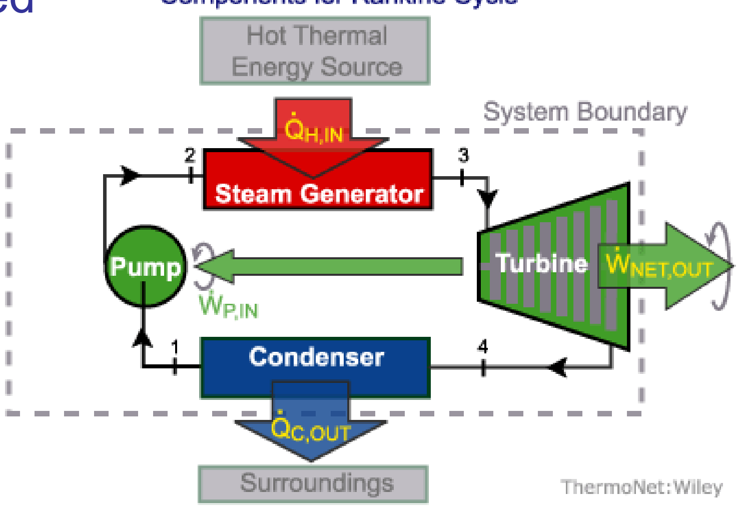
Principle of the ideal Rankine cycle (reversible)

- **1 → 2 isentropic compression (w_{in})**
  Fluid enters the pump and is compressed to a higher pressure, the pump is assumed to be adiabatic and ideal (reversible, isentropic) work is taken from the turbine
- **2 → 3 isobaric heat addition (q_{in})**
  At high constant pressure heat is added to the fluid in the boiler, the fluid starts boiling and vaporizes (phase change), it results in hot high-pressure vapor
- **3 → 4 isentropic expansion (w_{out})**
  The hot vapor is expanded in the turbine producing work, at the turbine outlet the working fluid is still in the gas phase or it is a mixture at low temperature and pressure, the turbine is assumed to be adiabatic and ideal (reversible, isentropic)
- **4 → 1 isobaric heat rejection (q_{out})**
  Heat rejection at constant low pressure, in the condenser the vapor / mixture is cooled and condensed to fluid again (phase change)



Rankine Cycle with Superheat

Components for Rankine Cycle



Rankine Cycle

- The external source of hot thermal energy is not important for the analysis of a Rankine cycle
- The heat source can be coal, nuclear, wood, solar, geothermal, etcetera
- Only the **amount of energy** (Q_{in}) transferred to the working fluid is important
- A boiler or heat exchanger is used to transfer the heat to the working fluid

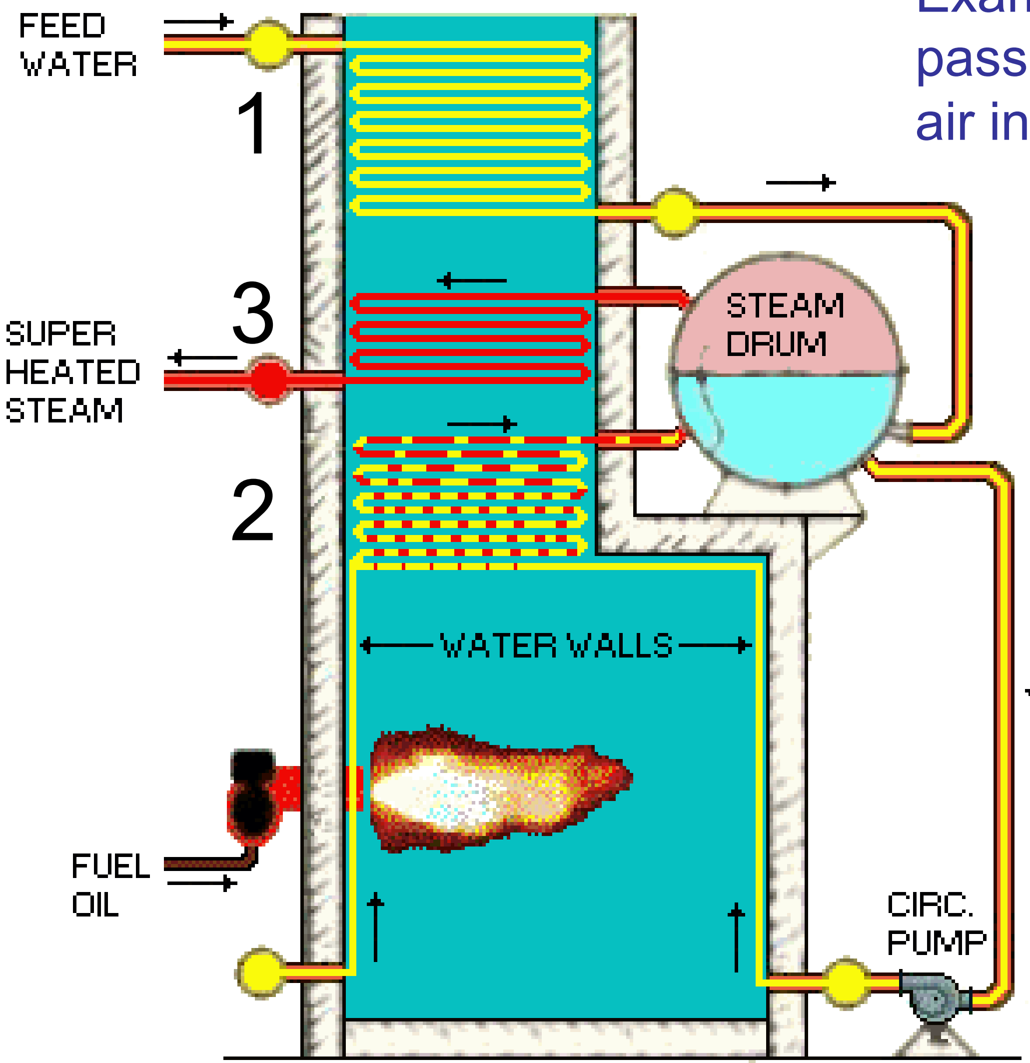
Huge cooling towers are characteristic for nuclear power plants, a nuclear reactor produces the heat

A solar power plant, uses solar radiation to produce the steam

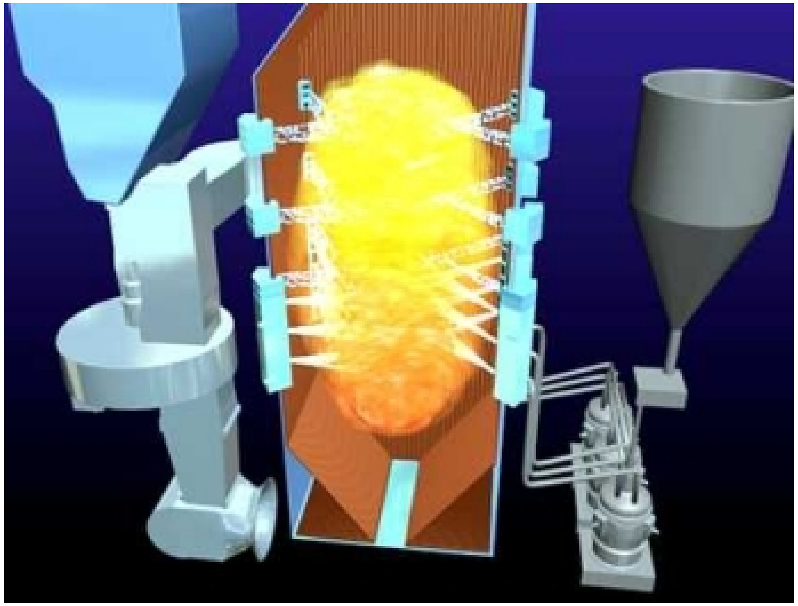
The biomass power plant of Twence in Hengelo uses biomass to produce heat

A geothermal power plant uses heat from a geothermal source

Steam Boiler Construction



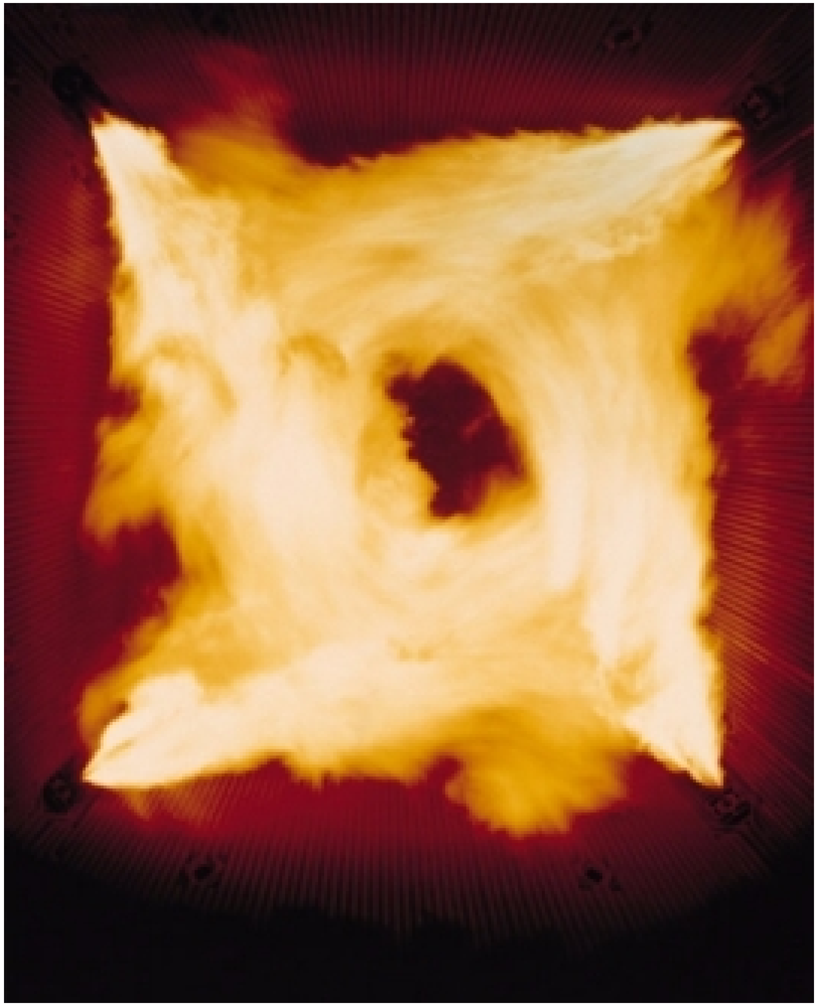
- Example of a steam boiler, the steam passes three times through the heated air in the boiler
  1. Preheating
  2. Evaporating
  3. Superheating



Tangentially coal fired furnace

Steam Boiler

Rentech vertical boiler



Tangentially fired furnace

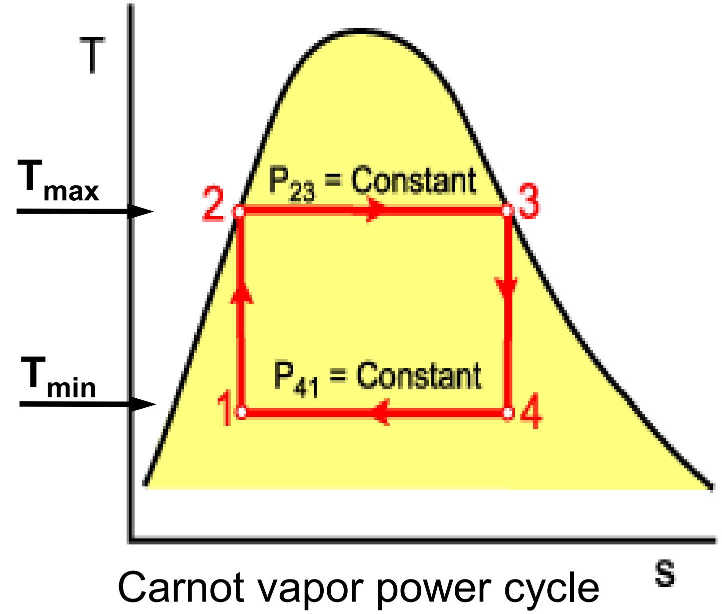
Steam Turbine

Alstom Steam Turbine double action rotor

Alstom Steam turbine

Comparison of Rankine to Carnot Cycle

- The ideal vapor power cycle is a Carnot vapor power cycle
- It is a cycle operating between two heat reservoirs (see class 6)
- The maximum efficiency of a thermodynamic cycle operating between two temperature reservoirs T_{max} and T_{min} is → $\eta_{carnot} = 1 - \frac{T_{\min}}{T_{\max}}$
- Following the theory of Carnot the ideal Rankine cycle would be the one shown in the diagram consisting of isentropic compression (1-2), isobaric heat addition (2-3), isentropic expansion (3-4) and isobaric heat rejection (4-1)
- However in process 1→ 2 the pressure of a 2-phase mixture needs to be increased
- This is mechanically difficult to do in a reliably process
- So the cycle needs to be modified



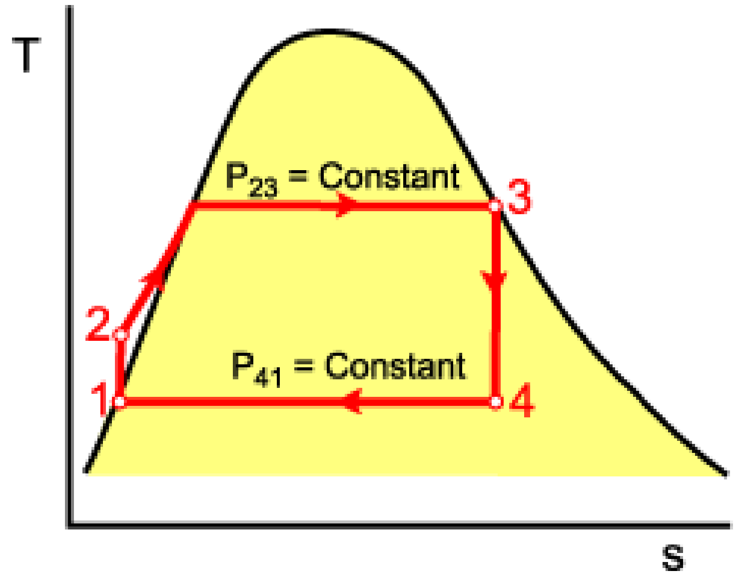
Carnot vapor power cycle

Comparison of Rankine to Carnot Cycle

- **Simple Rankine power cycle without superheating**
- The cycle following the theory of Carnot is modified by changing the position of point 1
- The mixture is completely condensed to the saturated water phase
- The advantage is that this is a pure liquid which is easily and to compress using a pump (the disadvantage is that more heat should be rejected)

- This is mechanically more reliable, thermodynamically easier to implement and uses less work (note: $w_{pump} << w_{turbine}$)
- However the efficiency is lower than the efficiency of the Carnot cycle as the heat rejected increases while the heat input doesn't change

$$\eta_{th} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{Q}_{in}} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}}$$

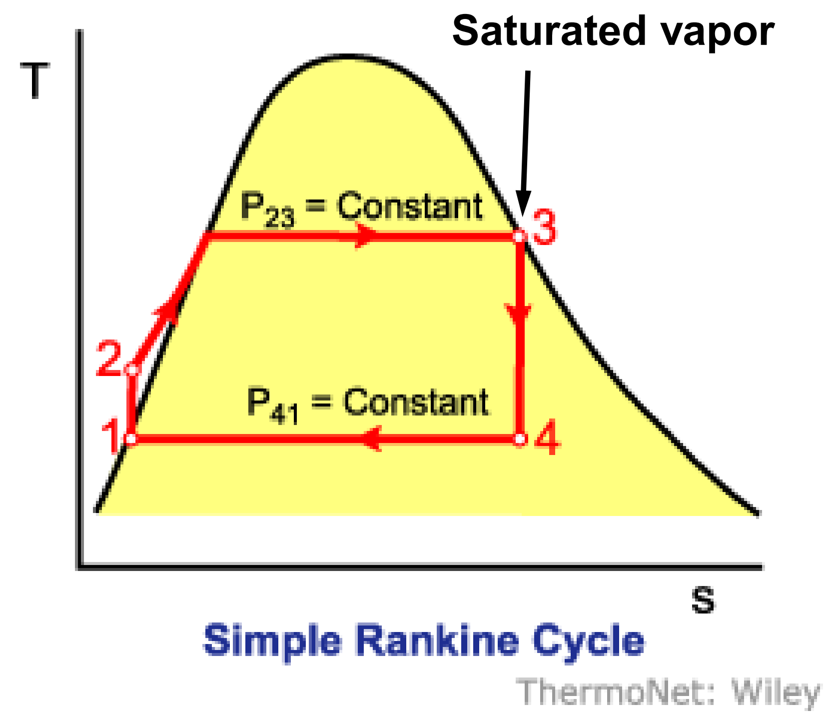


Simple Rankine Cycle

ThermoNet: Wiley

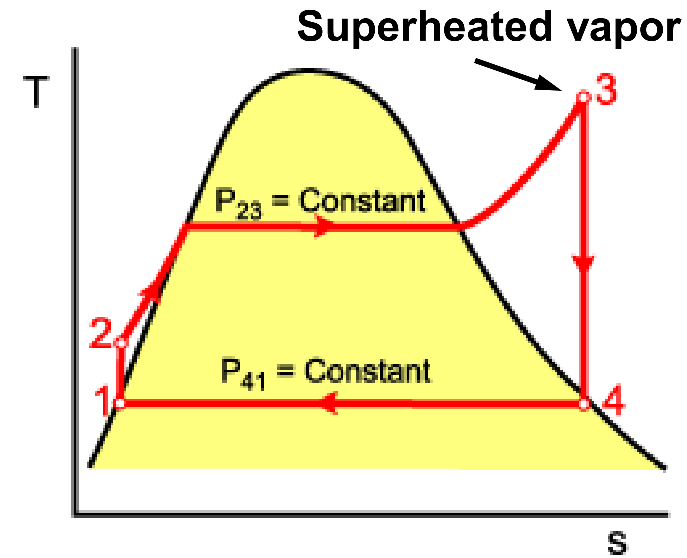
Simple Ideal Rankine Cycle without Superheat

- The simple Rankine cycle without superheating was representative for early fossil fuel steam engines, but it was still not very reliable and efficient
- It should be improved further to make it more reliable and efficient
- The expansion process (3 – 4) ends in the 2-phase region, during the expansion process the fluid becomes a mixture and consists of vapor with an increasing amount of water droplets
- These water droplets causes erosion and reliability problems in the turbine (see Materials Science)
- On the other hand the temperature of point 2 & 3, the highest temperature in the cycle is not very high resulting in a low efficiency
- The solution is superheating, heat the saturated vapor to higher temperatures so that point 3 shifts to the right and up



Ideal Rankine Cycle with Superheat

- **The ideal Rankine cycle with superheating**
- Superheating reduces turbine erosion and reliability problems as the working fluid in the turbine is mostly in the vapor phase
- At the end of the expansion process it may end up in the mixture region some droplets in the turbine are allowed
- The temperature after the boiler or heat exchanger gets higher than the saturation temperature, the vapor gets superheated after the fluid has vaporized completely
- The advantage is that the fluid during the expansion process is mostly in the vapor phase and the highest temperature is higher than without superheat



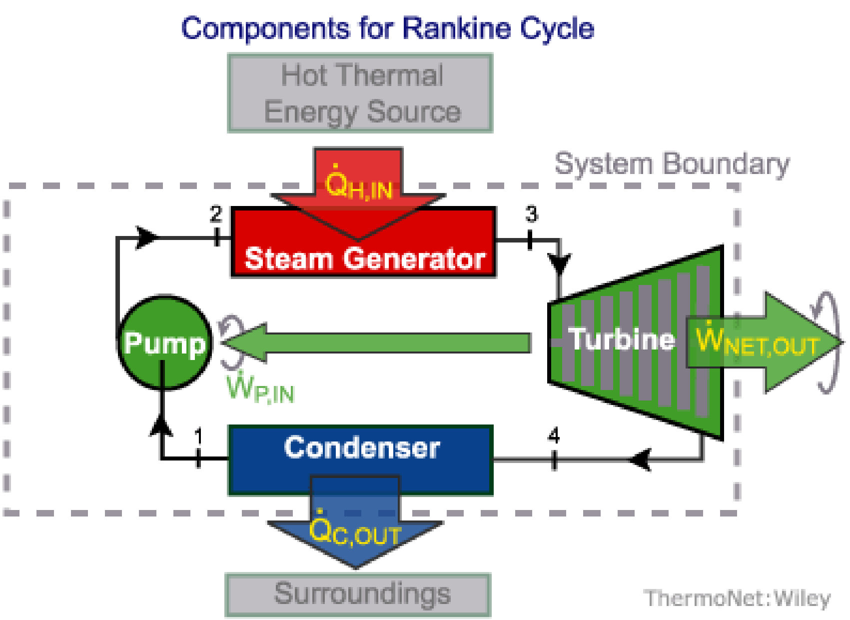
Rankine Cycle with Superheat

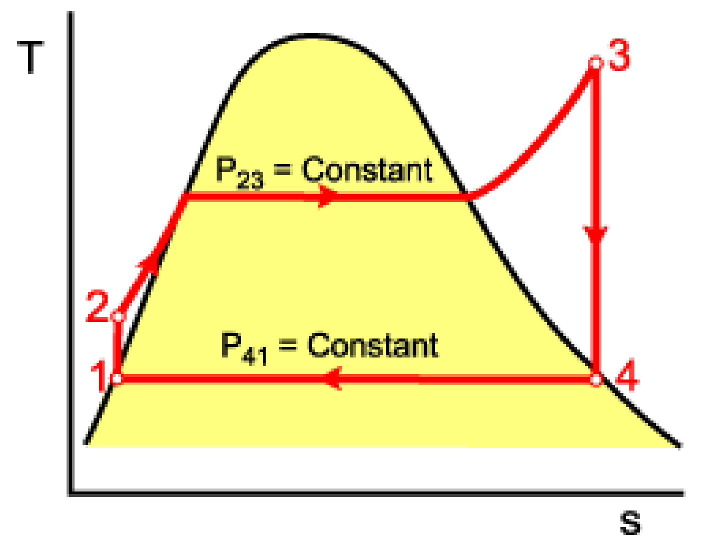
- Fossil plants have more superheat than nuclear or solar power plants or geothermal plants due to the higher tempersture of the heat source (the temperature in a combustion process is higher than the temperature of nuclear, solar or thermal heat)

Ideal Rankine Cycle

- The 4 basic components and processes of the Rankine cycle

Process	Component	q	w	Constant
1 → 2	Pump	0	w_{IN}	s
2 → 3	Steam generator (boiler, superheater)	q_{IN}	0	P
3 → 4	Turbine	0	w_{OUT}	s
4 → 1	Condenser	q_{OUT}	0	P





Rankine Cycle with Superheat

ThermoNet: Wiley

Ideal Rankine Cycle Analysis

- **We have seen that a Rankine cycle consist of 4 basic processes occurring in a series of open devices**
- For each device is assumed
  - There is no change in kinetic and potential energy
  - In an **ideal** cycle devices are adiabatic and reversible → isentropic (s = constant, ds = 0)
  - The liquid phase is incompressible (v = constant, dv = 0)

- Remember for each process the energy balance is given by

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}(h + \cancel{ke + pe})_{in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}(h + \cancel{ke + pe})_{out}$$

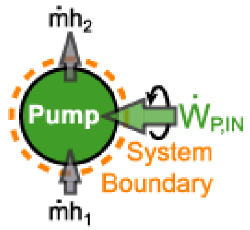
$$\Rightarrow \left(\dot{Q}_{in} + \dot{W}_{in}\right) - \left(\dot{Q}_{out} + \dot{W}_{out}\right) = \dot{m}(h_{out} - h_{in})$$

$$\Rightarrow (q_{in} + w_{in}) - (q_{out} + w_{out}) = h_{out} - h_{in} = \Delta h$$

- Each device is analyzed separately to analyse the total cycle

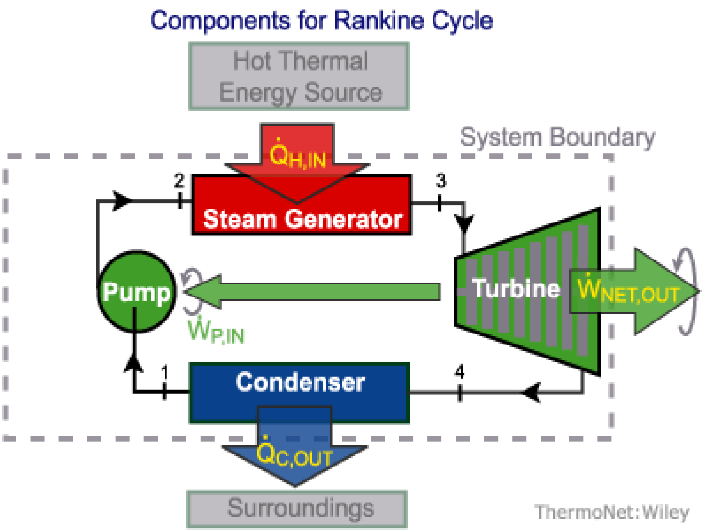
Ideal Rankine Cycle Analysis

- Process 1 → 2, **isentropic pressure increase** by **ideal pump** (compression)



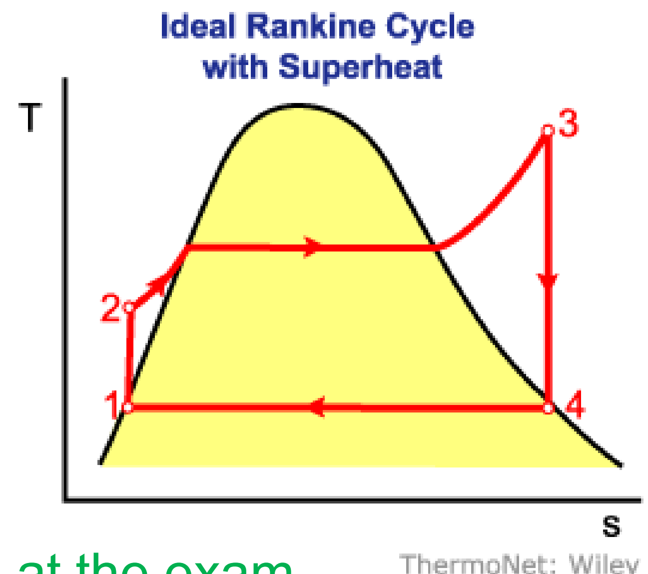
- Apply the energy balance to the pump

$$(\cancel{q_{in}} + w_{in}) - (\cancel{q_{out}} + \cancel{w_{out}}) = \Delta h$$
$$w_{pump,in} = h_{out} - h_{in} = h_2 - h_1$$



- Recalling: dh = Tds + vdP = vdP as for an isentropic process ds = 0
- For an incompressible liquid v = constant so integrating dh = vdP gives $\Delta h = v\Delta P$
- Resulting in

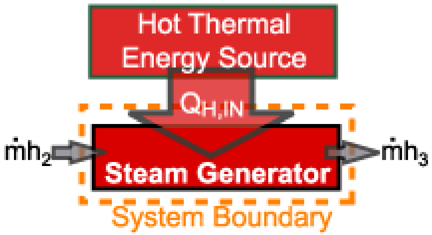
$$w_{pump,in} = v(P_{out} - P_{in})$$
$$w_{pump,in} = v(P_2 - P_1) \quad [kJ/kg]$$



The formula for the pump work is often forgotten at the exam

Ideal Rankine Cycle Analysis

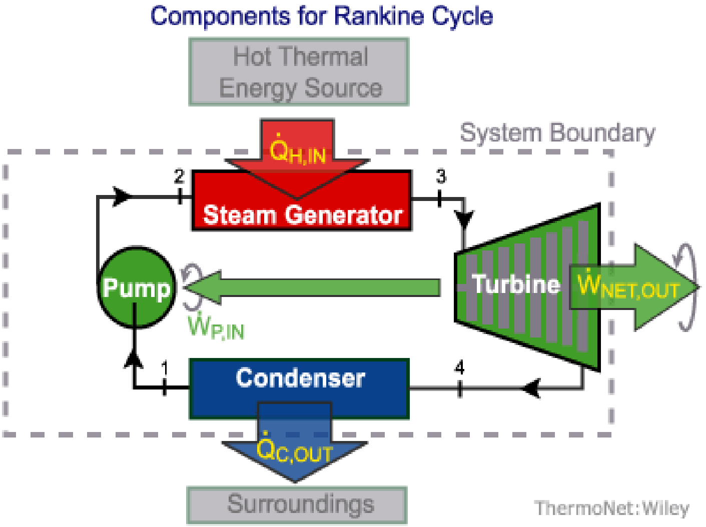
- Process 2 → 3, **isobaric heat transfer in boiler**

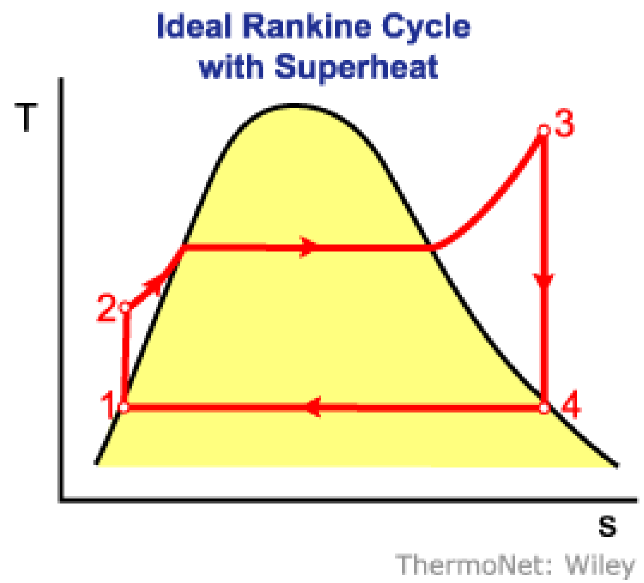


- Apply the energy balance to the boiler

$$(q_{in} + \cancel{w_{in}}) - (\cancel{q_{out}} + \cancel{w_{out}}) = \Delta h$$

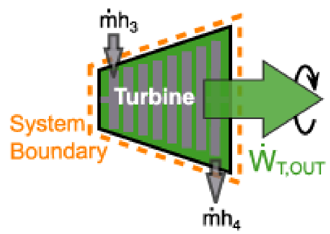
$$q_{in,boiler} = h_{out} - h_{in} = h_3 - h_2$$



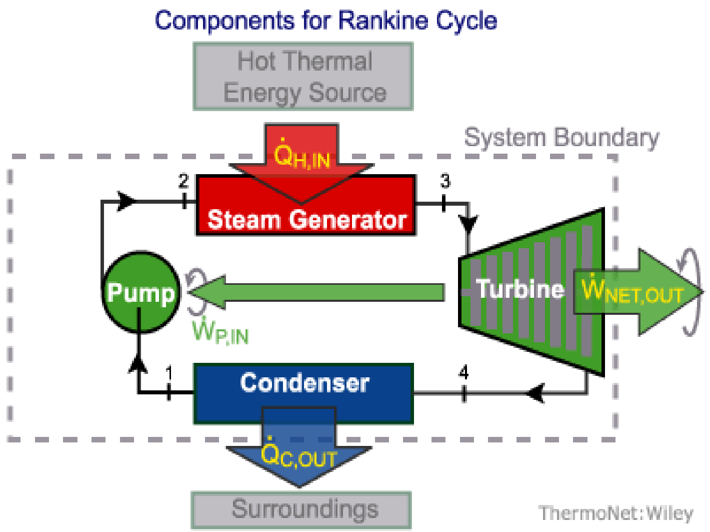


Ideal Rankine Cycle Analysis

- Process 3 → 4, **isentropic pressure decrease** in **ideal turbine** (expansion)



- Apply the energy balance to the turbine



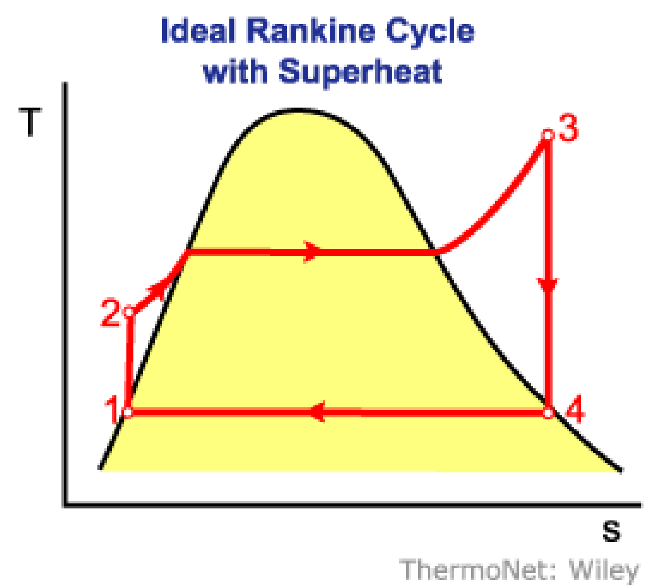
$$(q_{in} + \cancel{w_{in}}) - (\cancel{q_{out}} + \cancel{w_{out}}) = \Delta h$$

$$w_{out,turbine} = h_{in} - h_{iut} = h_3 - h_4$$

- The pump need work the compress the fluid, considering that the pump consumes some of the work the net work leaving the system is

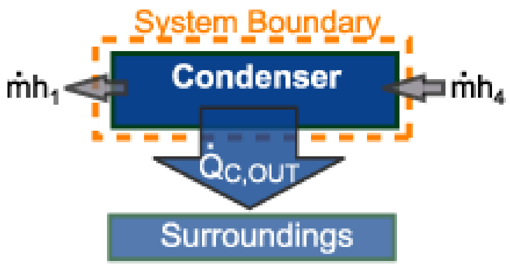
$$w_{net} = w_{out,turbine} - w_{pump,in}$$

$$w_{net} = (h_3 - h_4) - (h_2 - h_1)$$



Ideal Rankine Cycle Analysis

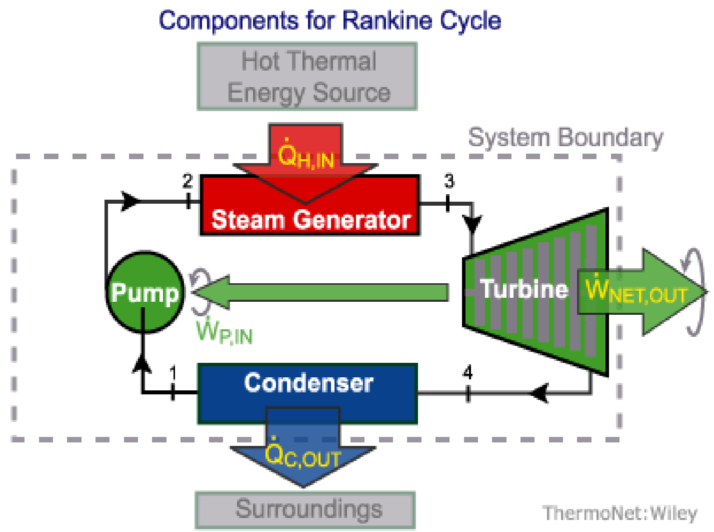
- Process 4 → 1, **isobaric heat transfer in condenser**

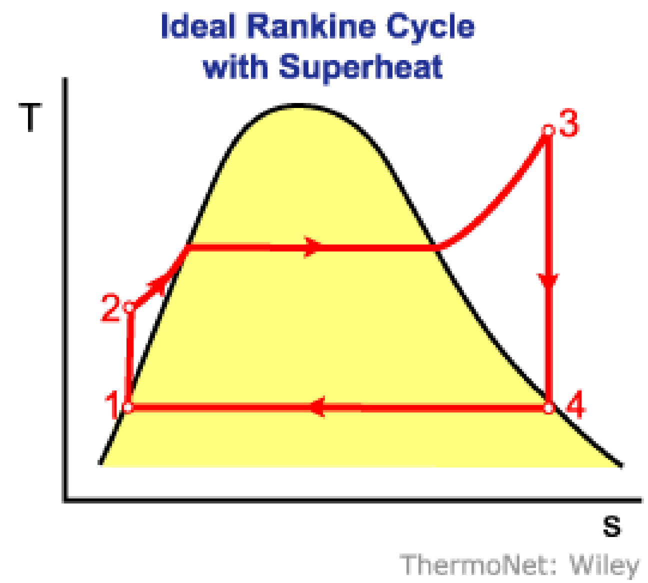


- Apply the energy balance to the condenser

$$(q_{in} + \cancel{w_{in}}) - (\cancel{q_{out}} + \cancel{w_{out}}) = \Delta h$$

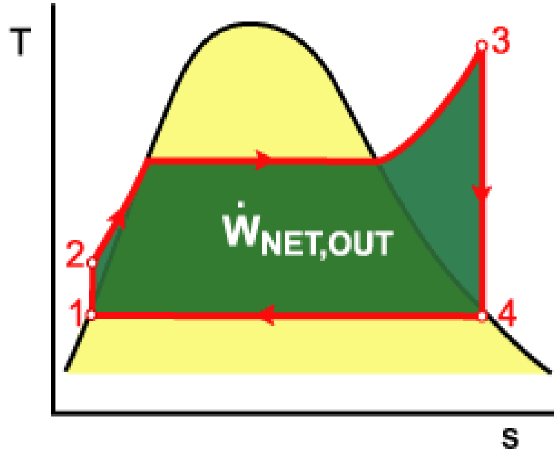
$$q_{out,condenser} = h_{in} - h_{out} = h_4 - h_1$$

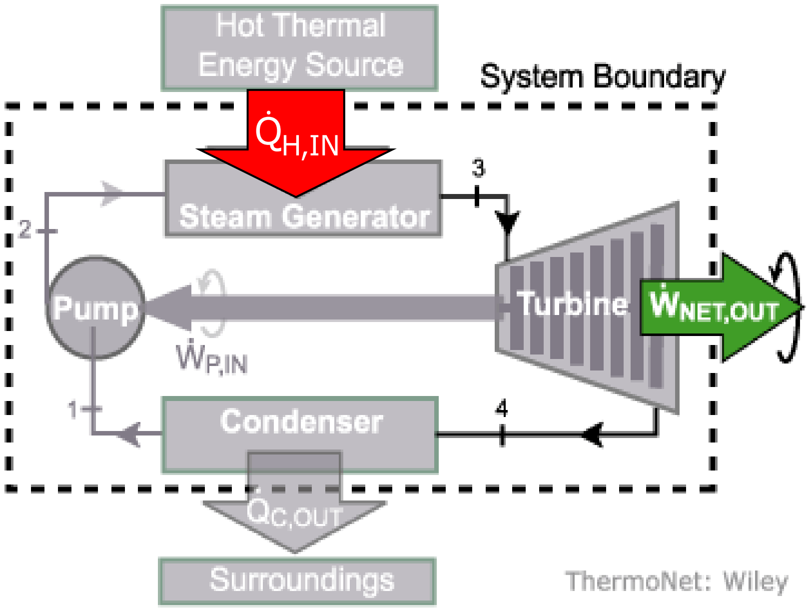




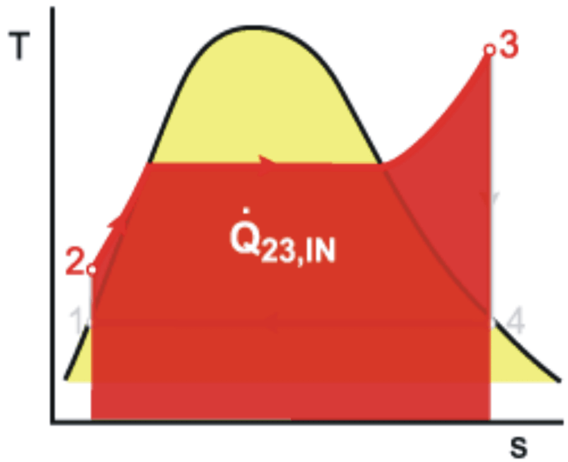
Rankine Cycle Efficiency

- Net work output





- Heat added



$$\eta_{Rankine} = \frac{w_{out,turbine} - w_{pump,in}}{q_{in}}$$

$$= \frac{w_{net}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

BREAK

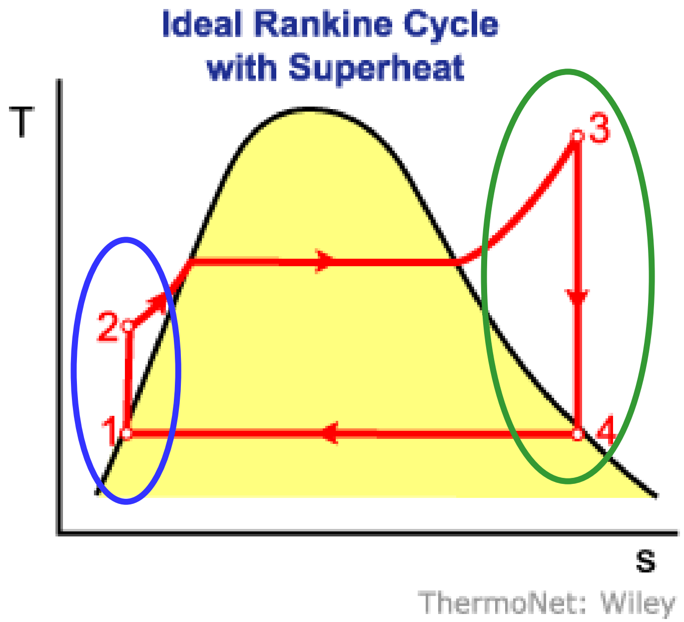
https://www.cafepress.com/+thermodynamics+mugs

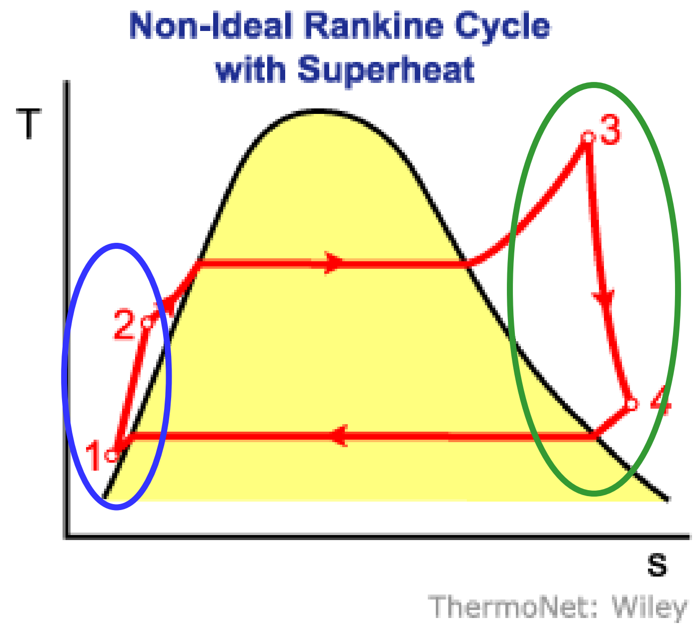
Non-Ideal Rankine Cycle

- For a real (non-ideal) Rankine cycle isentropic efficiencies for the pump and the turbine must be included

$$\eta_{s,pump} = \frac{h_{out,s} - h_{in}}{h_{out,a} - h_{in}} = \frac{v_{ICL}(P_{out} - P_{in})}{h_{out,a} - h_{in}} \qquad and \qquad \eta_{s,turbine} = \frac{h_{in} - h_{out,a}}{h_{in} - h_{out,s}}$$

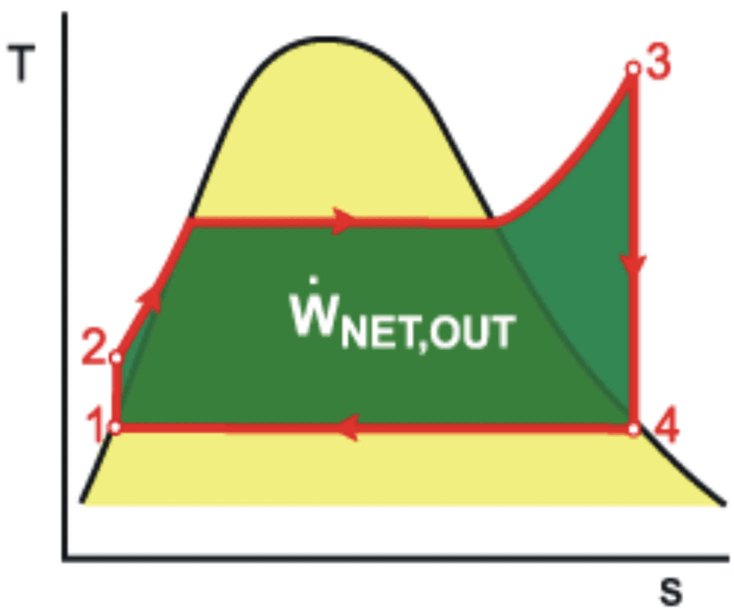
- The entropy in the pump and the turbine increases, resulting in shifting point 2 and 4 to the right

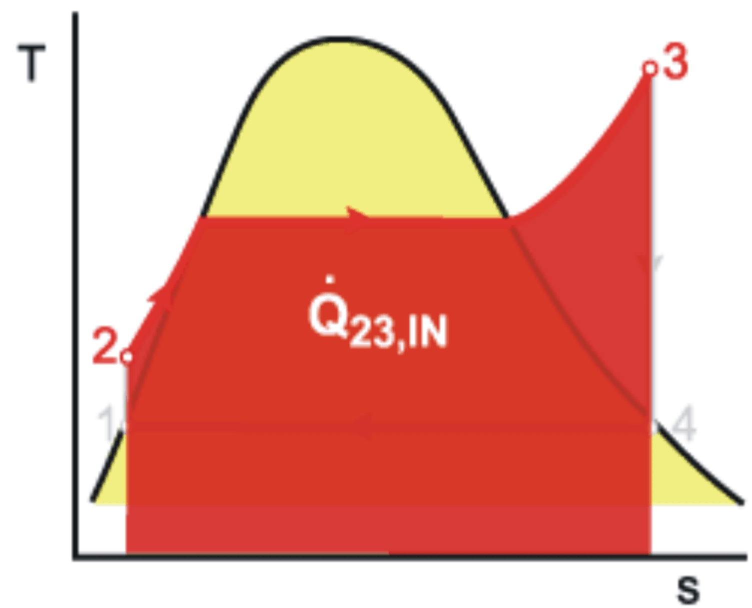




Design parameters Rankine Cycle

- How can the efficiency of the basic Rankine cycle be increased?
- Remember the net work output is the area enclosed in the graph, the net heat input is the area below the curve 2 – 3
- The area can be enlarged by
  - Changing the turbine input pressure
  - Changing the turbine inlet temperature
  - Changing the condenser temperature/pressure



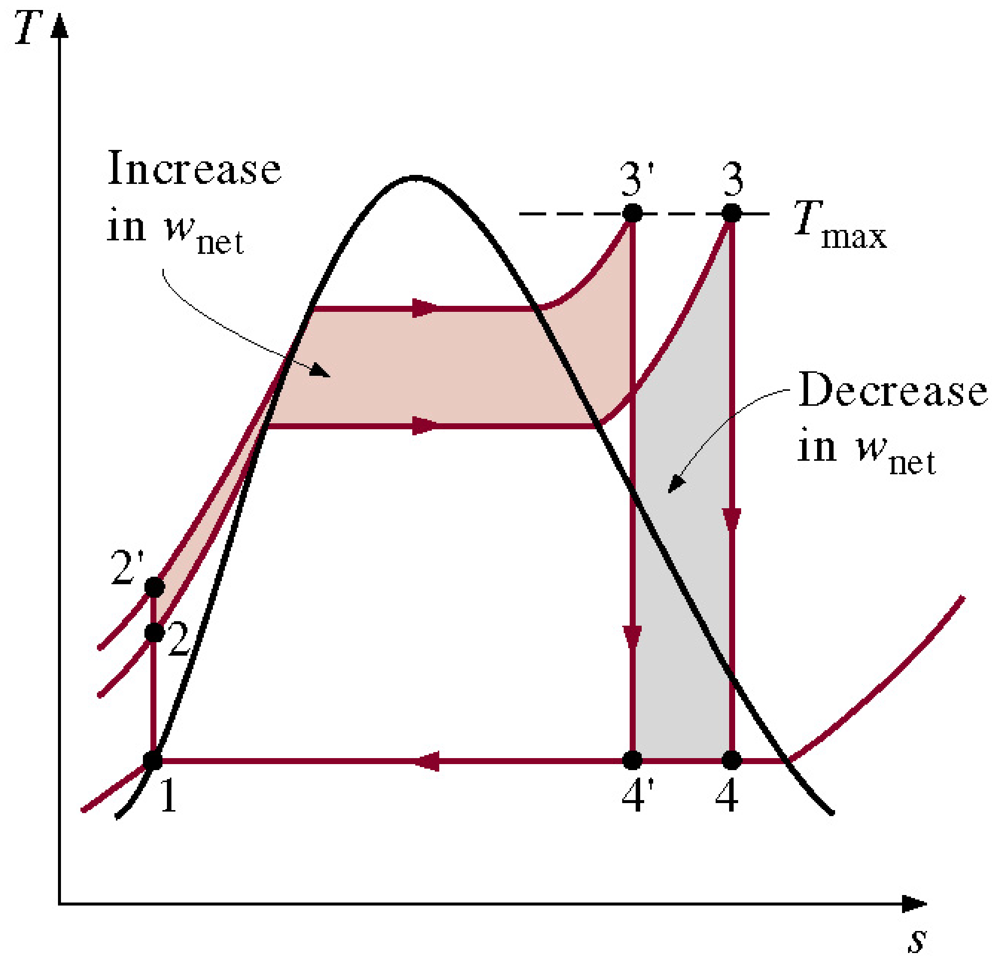


Design parameters Rankine Cycle

- The effect of increasing the boiler pressure on the ideal Rankine cycle

- **Power output:** hardly any change
- **Heat input:** hardly any change but a large part of the heat is added at a higher temperature
- **Efficiency:** increases (because the heat is added at a higher temperature)

- The **quality** of the saturated mixture at the turbine exit decreases (more liquid, less vapor), this is unfavorable for the turbine



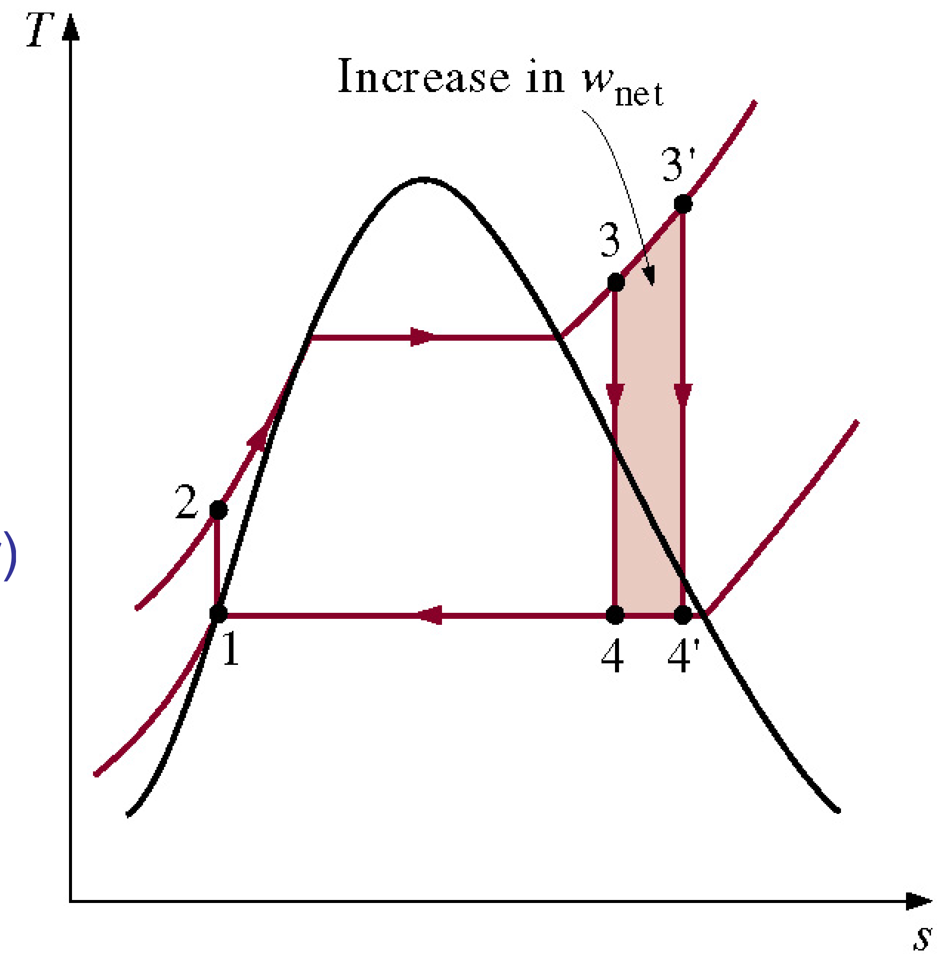
Design parameters Rankine Cycle

- The effect of superheating the vapor to higher temperatures on the ideal Rankine cycle

- **Power output:** increases
- **Heat input:** increases but it is an advantage that this extra heat is added at a high temperature
- **Efficiency:** increases

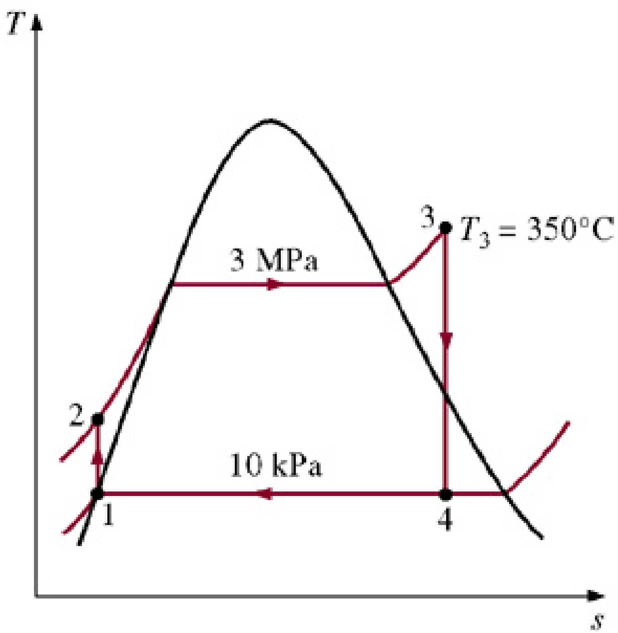
- The **quality** of the saturated mixture at the turbine exit increases (less liquid, more vapor) this is favorable for the turbine

- Note: the temperature in the system is limited to about 620°C by the material properties (see Material Sciences)



Design parameters Rankine Cycle

- The effect of increasing the boiler pressure and superheating the vapor to higher temperatures on the ideal Rankine cycle
  - Pressure 3 Mpa → 15 MPa
  - Temperature 350°C → 600°C

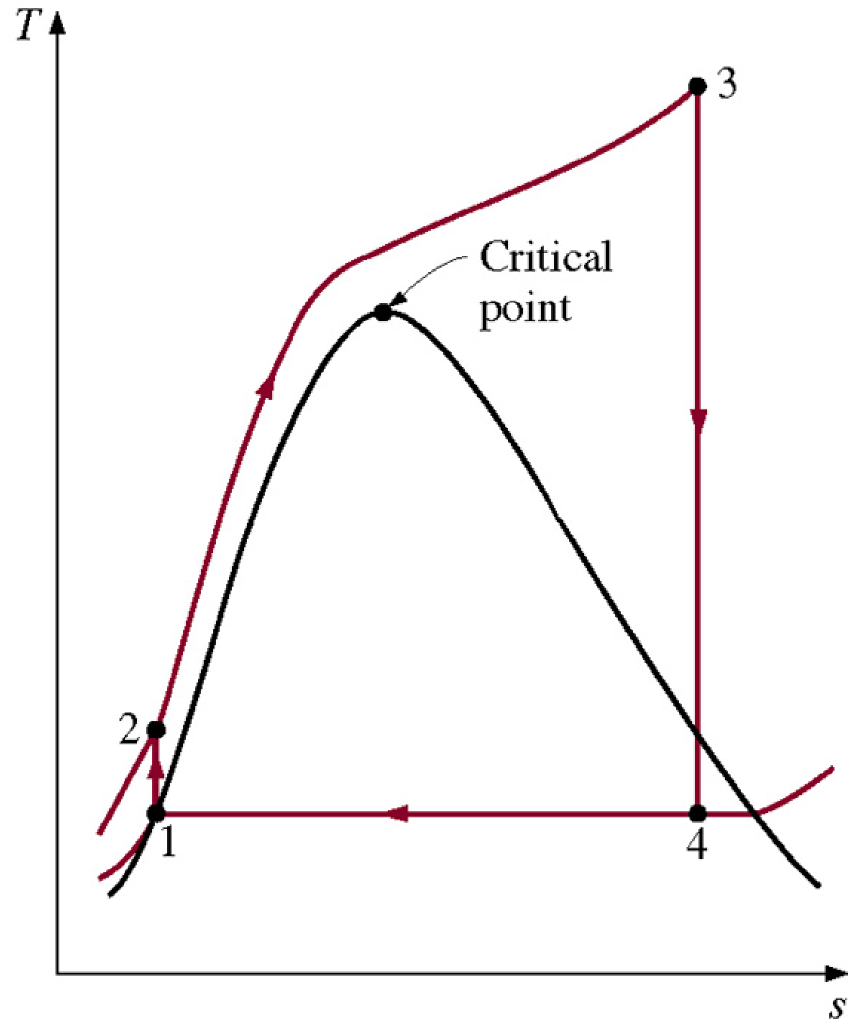


- The combination of the pressure and temperature at the turbine inlet determines the quality of the mixture at the turbine outlet
- To find the best design both must be considered

Design parameters Rankine Cycle

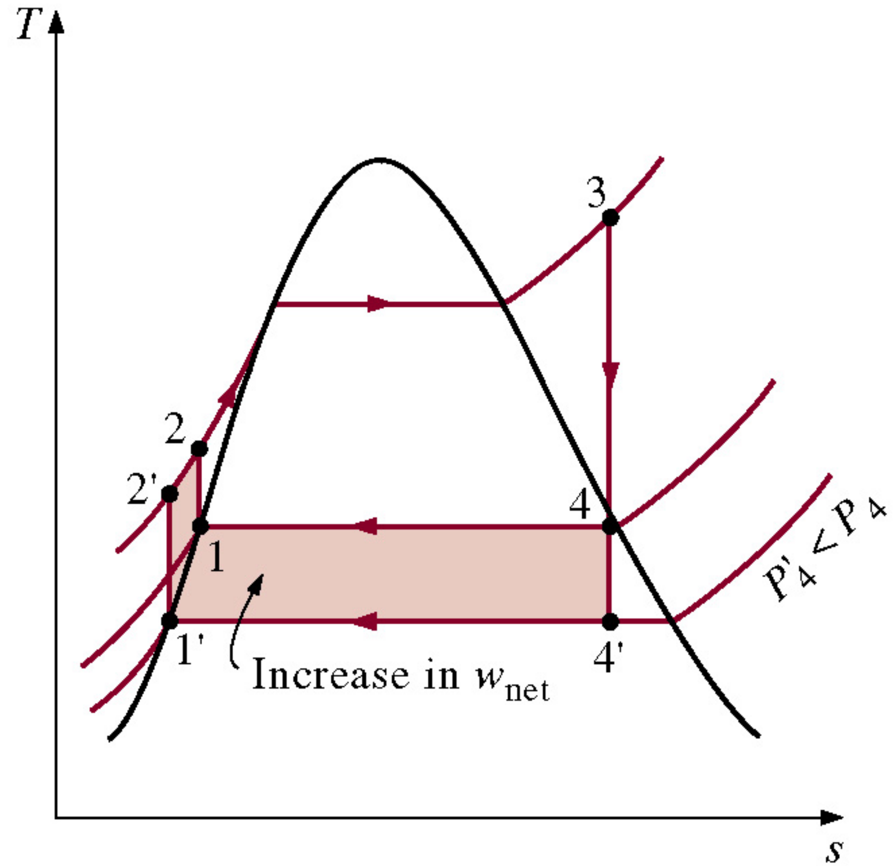
- **The supercritical Rankine cycle**

- An extreme situation, the boiler pressure goes to supercritical pressures, the curve rises above the critical point
- This results in high efficiencies as the temperature at which the heat is added is high
- On the ohter hand the requirements for the materials are higher



Design parameters Rankine Cycle

- The effect of lowering the condenser pressure on the ideal Rankine cycle



- **Power output:** increases
- **Heat input:** no change
- **Efficiency:** increases as the power output increases and the heat output decreases while the heat input does not change

$$\eta_{th} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{Q}_{in}} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}}$$

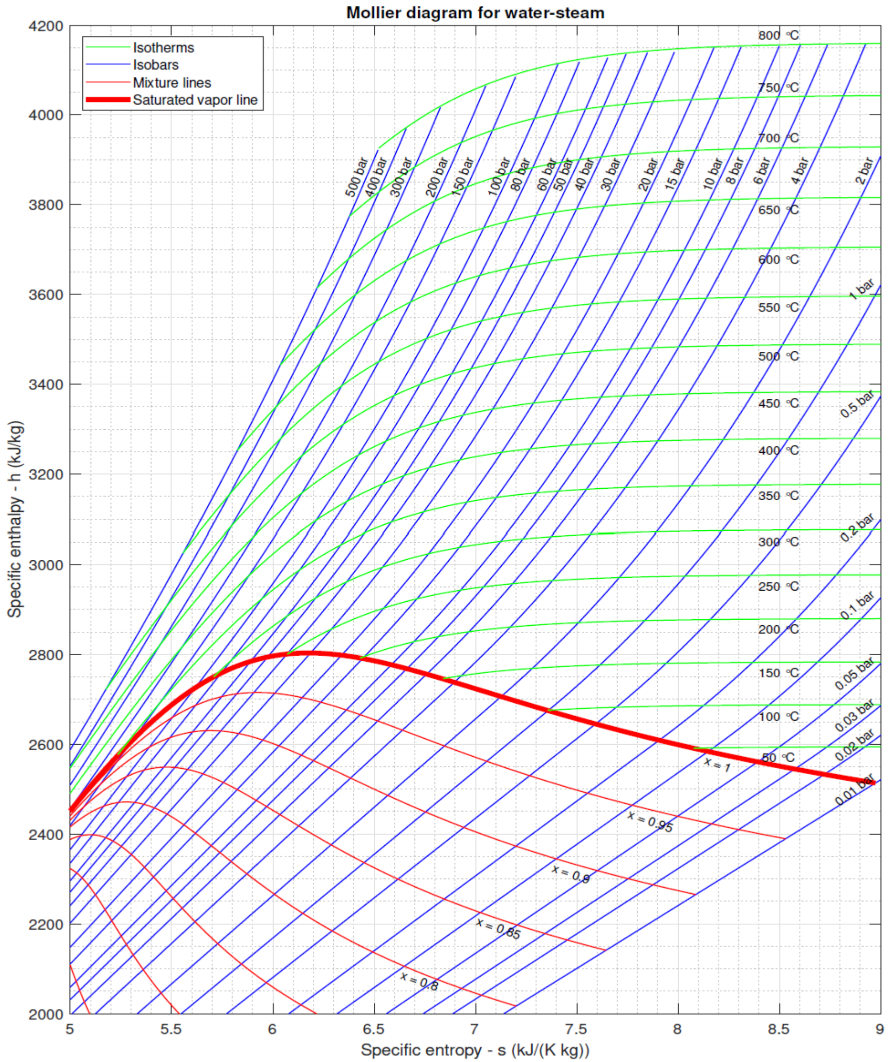
- The **quality** of the saturated mixture at the turbine exit decreases (more liquid, less vapor), which is unfavorable for the turbine

- Note: the condenser pressure is related to the condenser temperature which always must be higher than the temperature of the environment

Mollier Diagram Water for Rankine Cycle

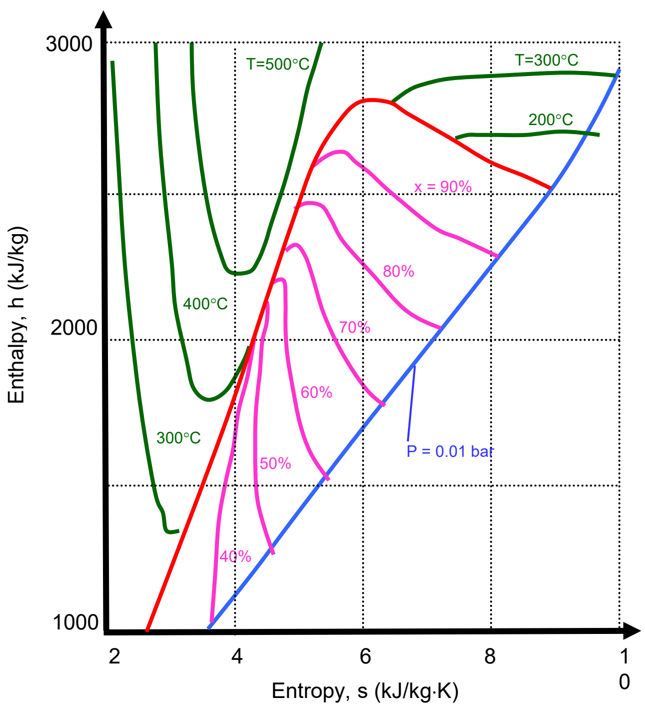
- The hs - diagram of water, the enthalpy on the y-axis and the entropy on the x-axis
- **Mollier Diagram** named, after Professor Richard Mollier who recognized the importance of the combination u + Pv = h in the analysis of steam turbines and in the representation of properties of steam in tables and diagrams
- The Mollier diagram is used to analyze the Rankine cycle
- The advantage over the table is that values in the mixture region can be found faster

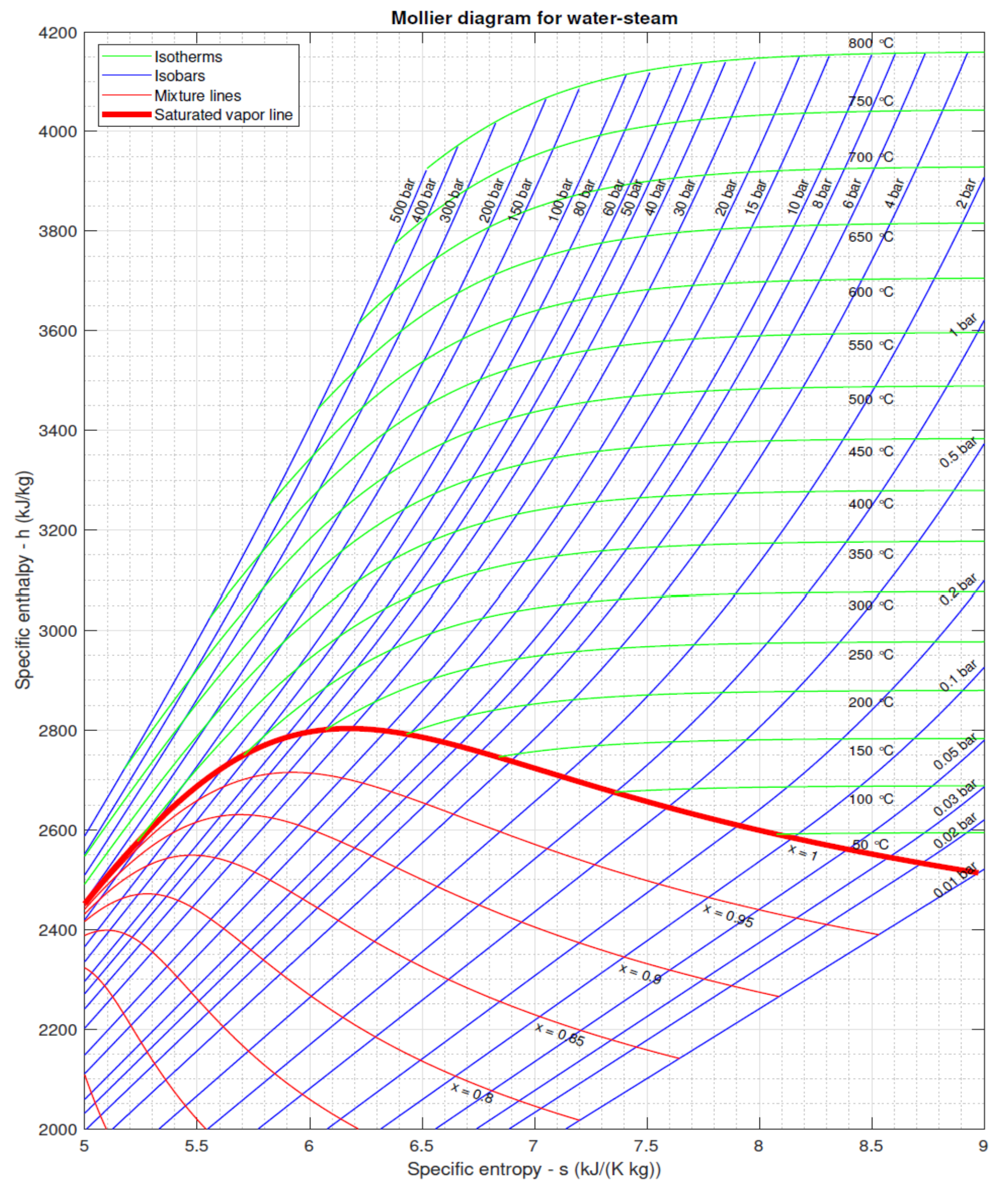
- Do you recognize the vapor dome (bold red line), isobars in Bar (blue), isotherms (green), vapor mass fraction (red)?



Mollier Diagram Water for Rankine Cycle

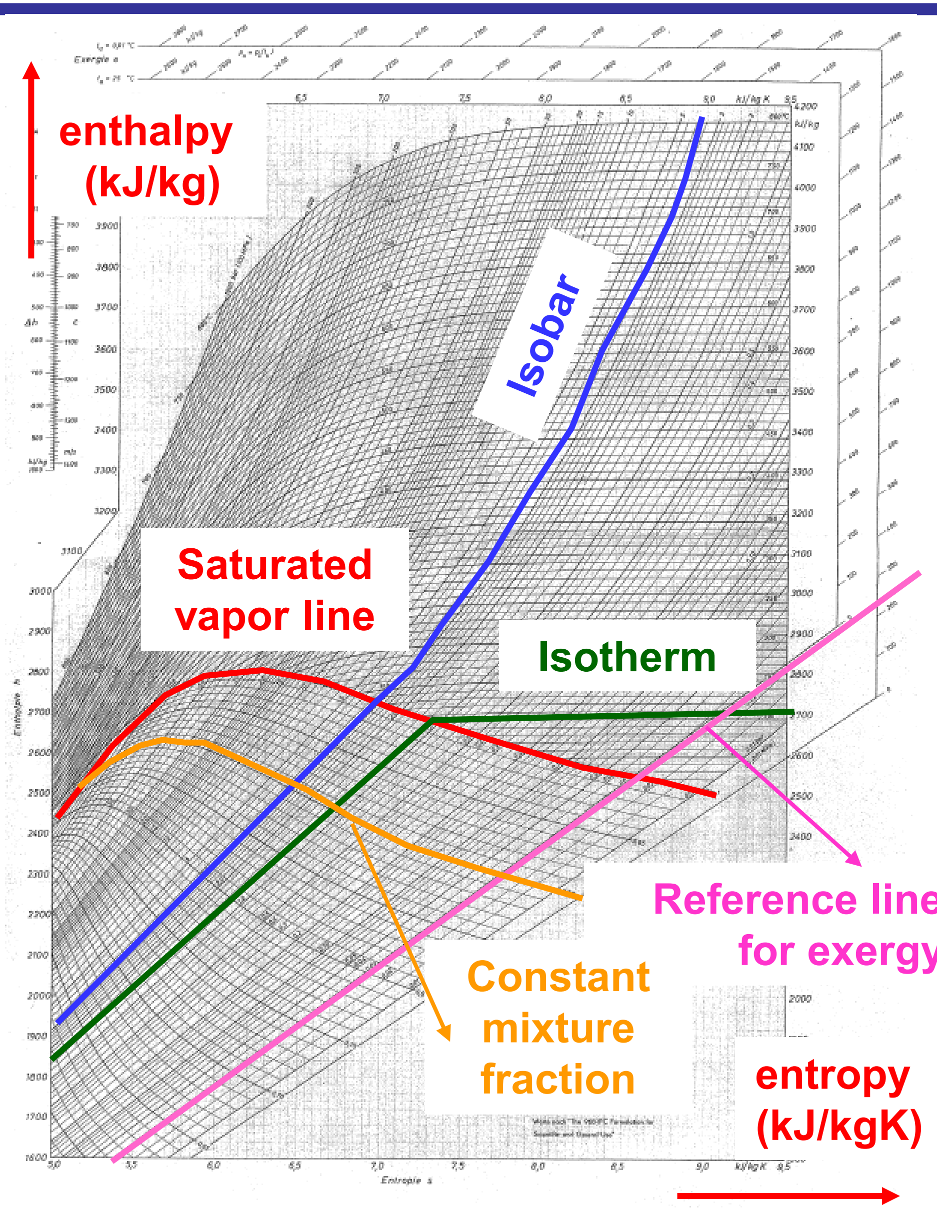
- Only the superheated region and part of the vaper dome is shown, however this is the part where the expansion process takes place
- The compressed liquid region is not shown, isobars are too close to each other





Mollier Diagram Water for Rankine Cycle

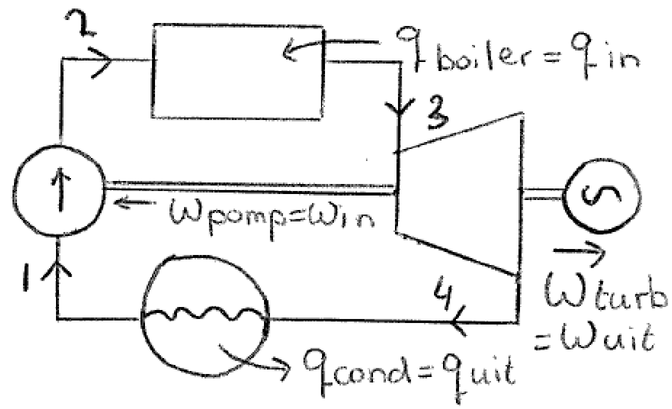
- Scanned version of the Mollier diagram for water used to analyze the Rankine cycle
  - Enthalpy (kJ/kg) on the y-axis, horizontal line → dh = 0
  - Entropy (kJ/kgK) on the x-axis, vertical line → ds = 0
  - Saturated vapor line divides superheated vapor and mixture region
  - Isobars (in **Bar** !!)
  - Isotherms (in degree Celsius)
  - Constant mixture fraction lines
  - Reference line for exergy
- Compressed liquid area not shown, lines are to close to each other → diagram is not usable, use tables
- This diagram is used in the solutions of the assignment bundle

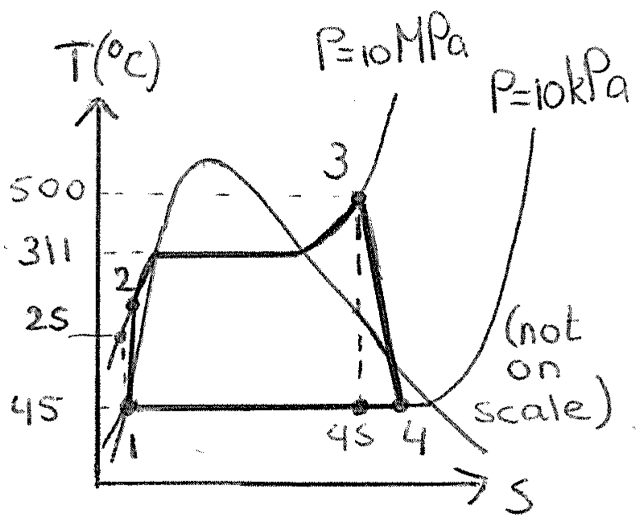


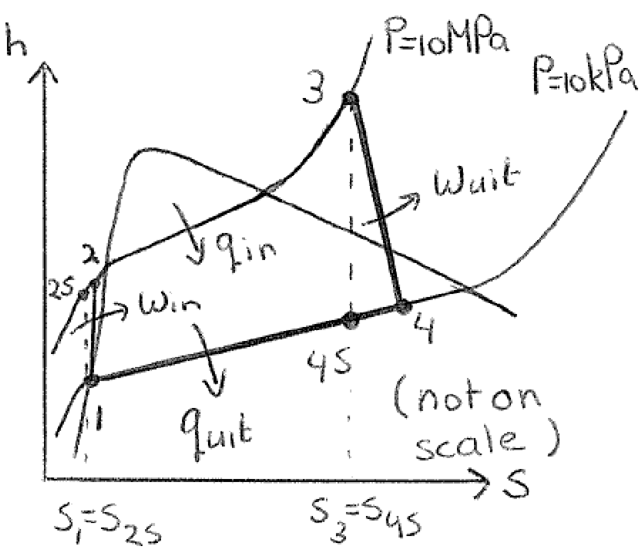
Example analysis Rankine Cycle

- Steam power plant on Rankine cycle between P_3=10MPa and P_4=10kPa
- Temperature of the steam at the turbine inlet is T_3=500°C
- Isentropic efficiencies of the pump and the turbine are 0.8, mass flow is 5 kg/s

- Draw schematically the set up of the cycle
- Draw the T-s and h-s diagram
- Give for every point two characteristics
  (with two characteristics the point can be found)
- Calculate heat and work in- and output
- Calculate the net power output and the efficiency



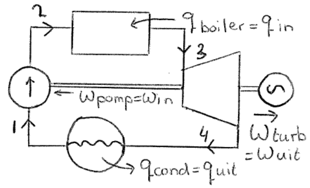


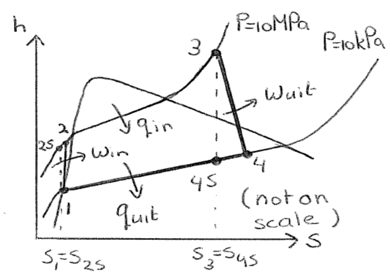


	First	Second
1	10kPa	$T_{sat@10kPa}$
2s	10MPa	$s_{2s}=s_1$
2	10MPa	η = 0.8
3	10MPa	500°C
4s	10kPa	$s_{4s}=s_3$
4	10kPa	η = 0.8

Example analysis Rankine Cycle

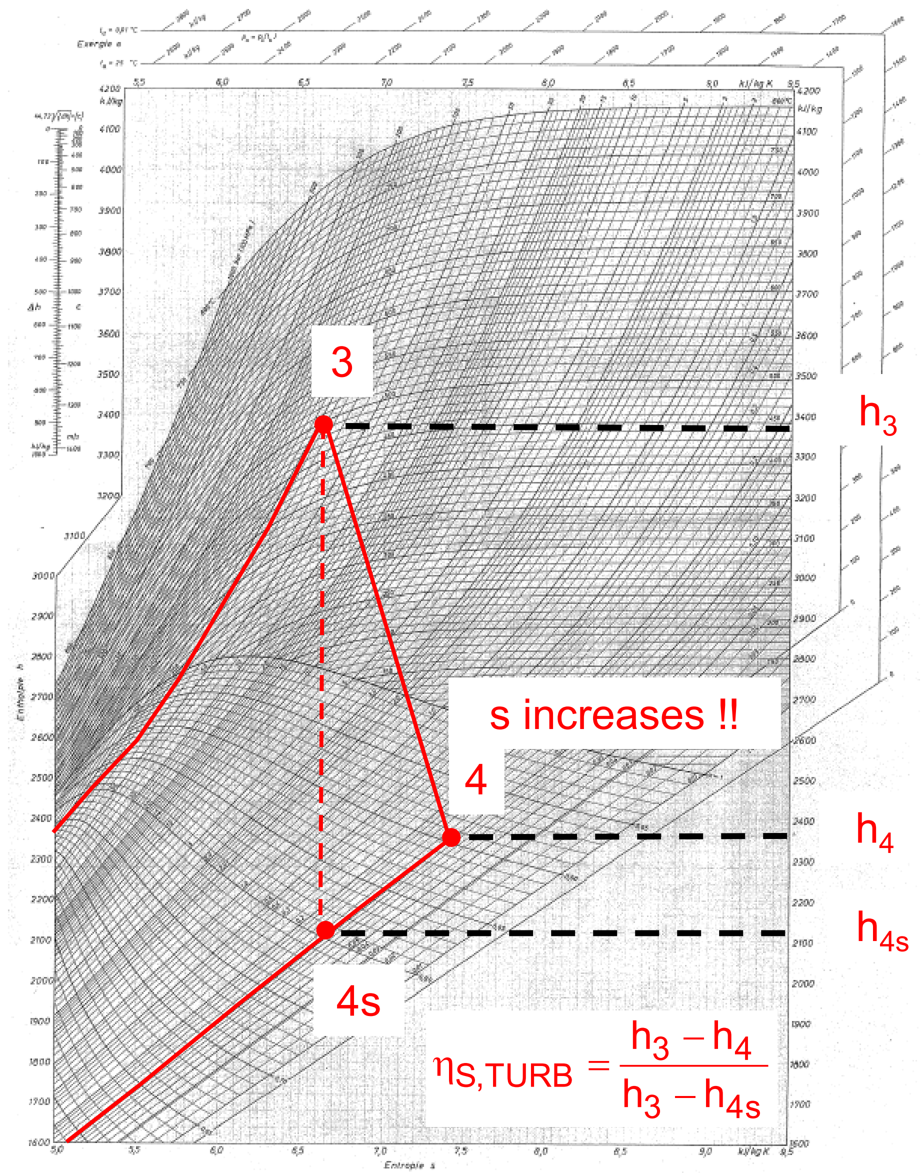
- **Rankine cycle**





	First	Second
1	10kPa	$T_{sat@10kPa}$
2s	10MPa	$s_{2s}=s_1$
2	10MPa	$\eta = 0.8$
3	10MPa	500°C
4s	10kPa	$s_{4s}=s_3$
4	10kPa	$\eta = 0.8$

- Point 1: h_1 from tables at P=10kPa and $T_{sat@10kPa}$
- Point 2s: h_{2s} from $h_{2s} - h_1 = v(P_2 - P_1)$
- Point 2: h_2 from $\eta_{S,PUMP} = \frac{h_{2S}-h_1}{h_2-h_1}$
- Point 3: h_3 from diagram
- Point 4s: h_{4s} from diagram
- Point 4: h_4 from $\eta_{S,TURB} = \frac{h_3-h_4}{h_3-h_{4s}}$



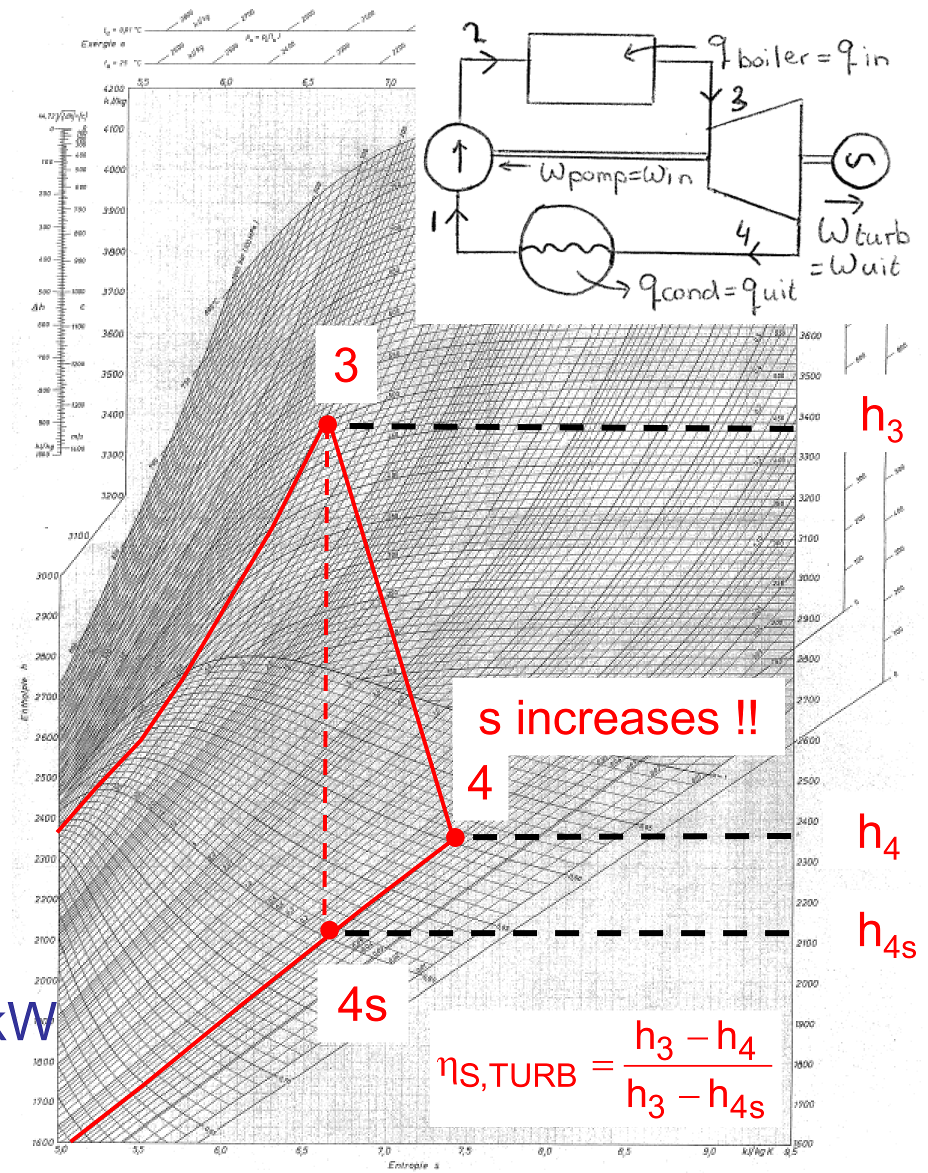
Example analysis Rankine Cycle

- Find the h value of every point

	P (kPa)	T (°C)	h (kJ/kg)	phase
1	10	45	192	Sat L
2s	10000		193	Com L
2	10000		193.3	Com L
3	10000	500	3375	Sup V
4s	10	45	2125	X=0.81
4	10	45	2375	X=0.91

- $w_{in} = h_2 - h_1 = 1.3$ kJ/kg
- $q_{in} = h_3 - h_2 = 3181.7$ kJ/kg
- $w_{out} = h_3 - h_4 = 1000$ kJ/kg
- $q_{out} = h_4 - h_1 = 2183$ kJ/kg
- See $w_{in} + q_{in} = w_{out} + q_{out}$ (first law)
- $\dot{W}_{net} = \dot{m}(w_{out} - w_{in}) = 5 \cdot 998.7 = 4993.5$ kW

$$\eta_{RANKINE} = \frac{w_{out} - w_{in}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} = 31\%$$



Example analysis Rankine Cycle

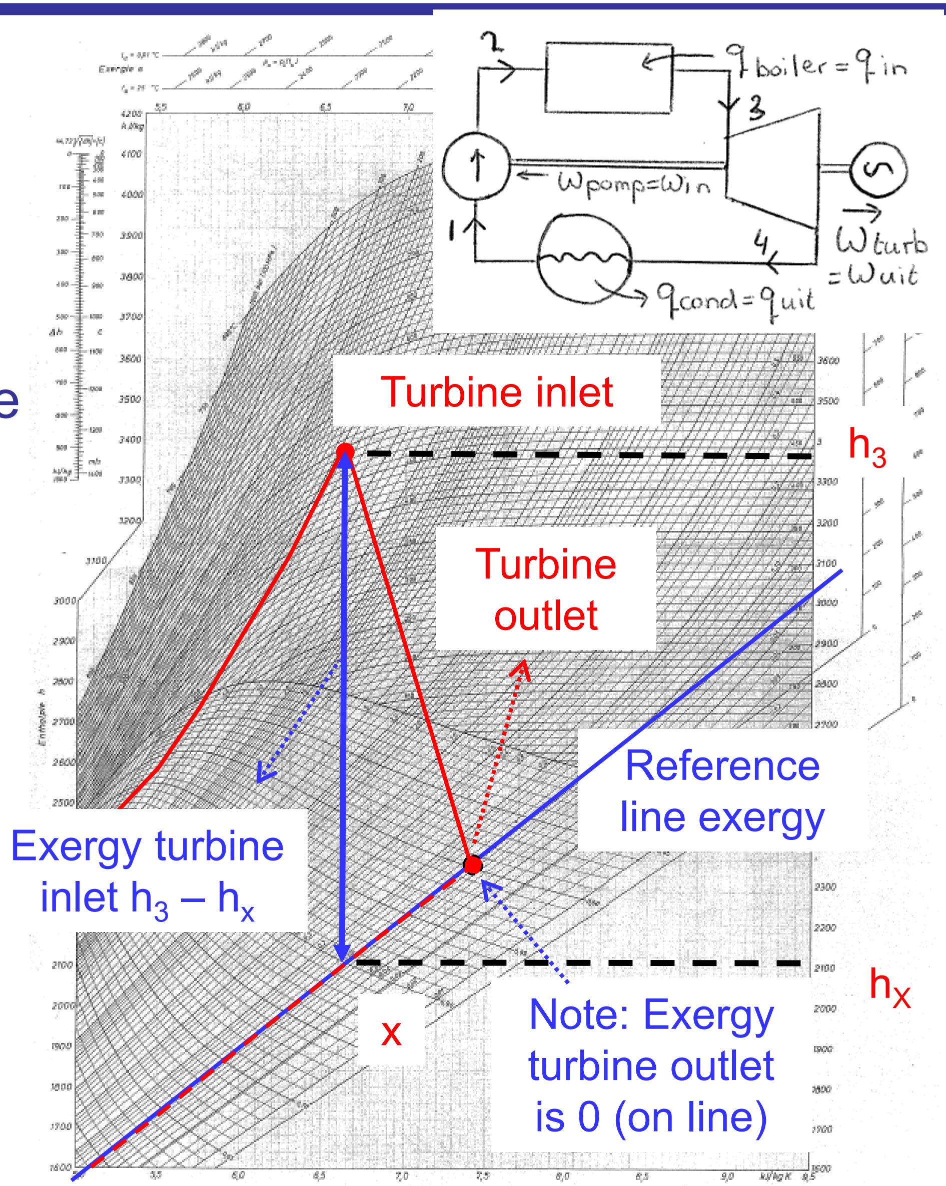
- Consider the Rankine cycle from the previous example and analyze it using second law analysis (exergy analysis)
- What is the second law efficiency?
- What is the exergy of the steam at the turbine outlet and the turbine inlet as determined from the diagram?

$$\eta_{SECOND\ LAW} = \frac{\eta_{RANKINE}}{\eta_{CARNOT}} \qquad \eta_{RANKINE} = 0.31$$

$$\eta_{CARNOT} = 1 - \frac{T_{COLD}}{T_{HOT}} = 1 - \frac{45 + 273}{500 + 273} = 0.59$$

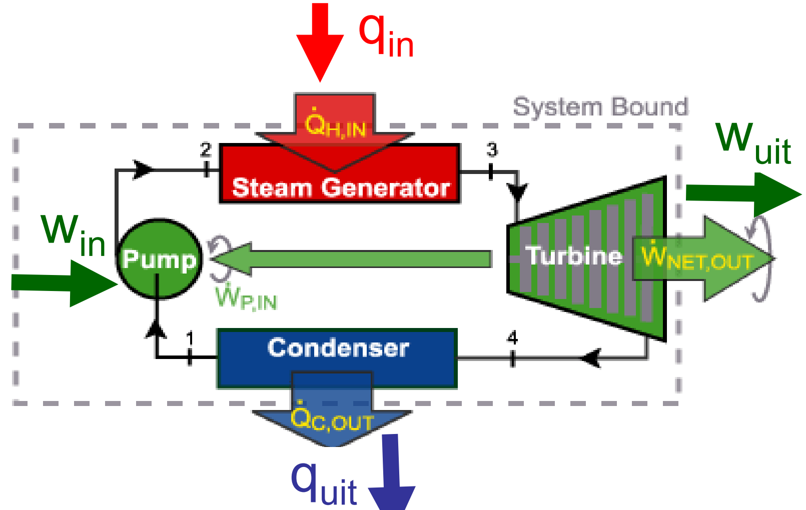
$$\eta_{SECOND\ LAW} = \frac{0.31}{0.59} = 0.52 \rightarrow 52\%$$

- Exergy inlet: $\Psi_{in} = h_3 - h_x =$
  $3375 - 2100 = 1275$ kJ/kg
- Exergy outlet: $\Psi_{out} = 0$ kJ/kg



Exergy and second law analysis is is not part of the exam, this is material for the project

Example: Rankine Cycle, check 1st & 2nd law



- Consider the steam cycle
- Energies in and out
  - w_{in} = 1 kJ/kg
  - q_{in} = 3182 kJ/kg at T_{in} = 311°C
  - w_{out} = 1000 kJ/kg
  - q_{out} = 2183 kJ/kg at T_{uit} = 45°C
- Check the first law: $q_{in} - q_{out} = w_{out} - w_{in} \rightarrow q_{net} = w_{net}$

$$\left.\begin{array}{l} q_{net} = q_{in} - q_{out} = 3182 - 2183 = 999 \text{ kJ/kg} \\ w_{net} = w_{out} - w_{in} = 1000 - 1 = 999 \text{ kJ/kg} \end{array}\right\} \rightarrow q_{net} = w_{net} \quad \text{Correct !}$$

- Check the second law: $\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} \leq 0$ (Clausius inequality: $\frac{\delta q_{net}}{T} \leq ds$)

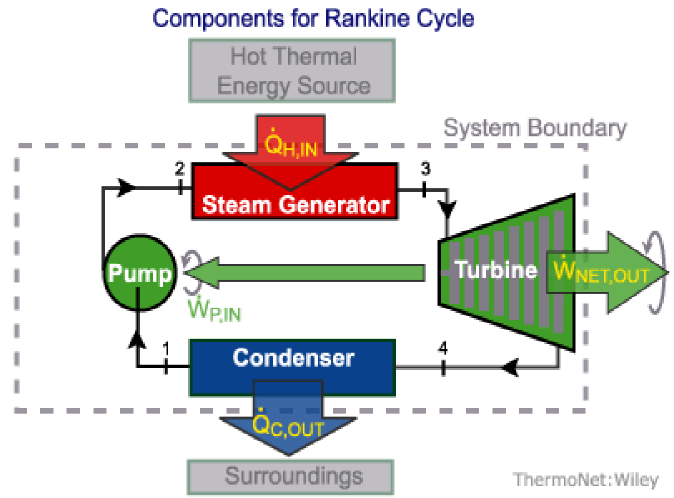
$$\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} = \underbrace{\frac{q_{in}}{T_{in}} - \frac{q_{out}}{T_{out}}}_{ds_{in} - ds_{out}} = \frac{3185}{584} - \frac{2183}{318} = 5.45 - 6.86 = -1.41\ kJ/kgK \leq 0\ kJ/kgK \rightarrow \text{Right !}$$

- Both laws are valid for this cycle 1: energy is conserved ($e_{in} = e_{out}$)
  2: entropy is created ($ds_{out} > ds_{in}$)

Recapitulate class 7

- **Vapor power cycles (Rankine cycles):** cycles using a working fluid that changes phase throughout the cycle
  - Piston steam engine & steam turbine
  - Ideal and real Rankine cycles
    - Heat and power in- and output:

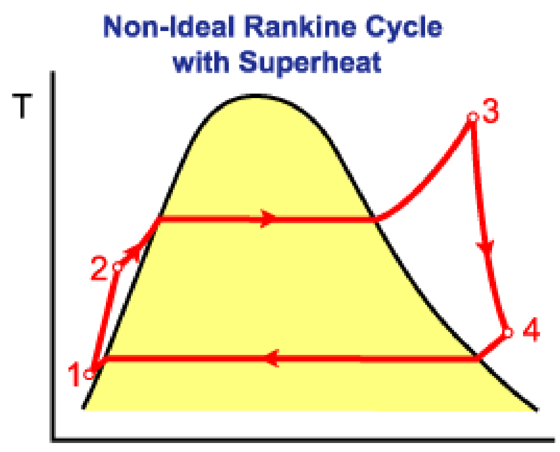
$$w_{pump,in} = v(P_{out} - P_{in}) = v(P_2 - P_1)$$
$$q_{in,boiler} = h_{out} - h_{in} = h_3 - h_2$$
$$w_{out,turbine} = h_{in} - h_{iut} = h_3 - h_4$$
$$q_{out,condenser} = h_{in} - h_{out} = h_4 - h_1$$
$$w_{net} = w_{out,turbine} - w_{pump,in} = (h_3 - h_4) - (h_2 - h_1)$$



- Thermal efficiency:

$$\eta_{Rankine} = \frac{w_{turbine,out} - w_{pump,in}}{q_{in,boiler}} = \frac{w_{net,out}}{q_{in,boiler}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

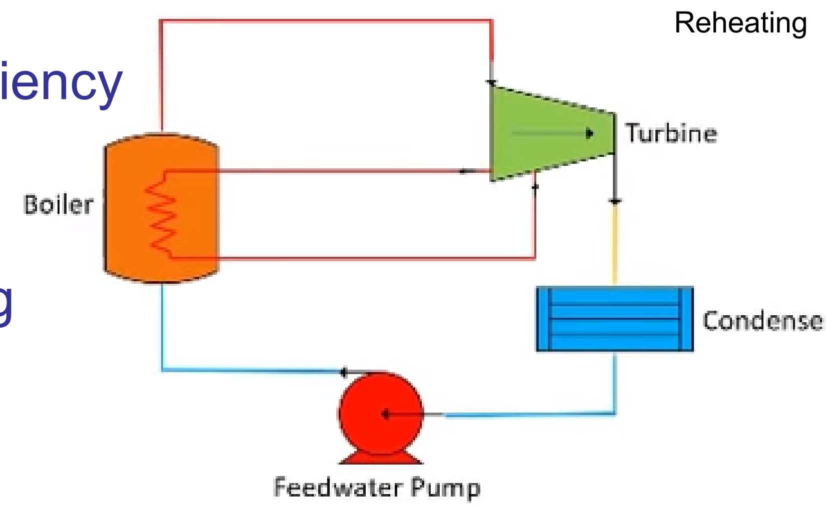
- Design parameters
  - Turbine inlet pressure and temperature
  - Condenser pressure and temperature
- Mollier diagram for water

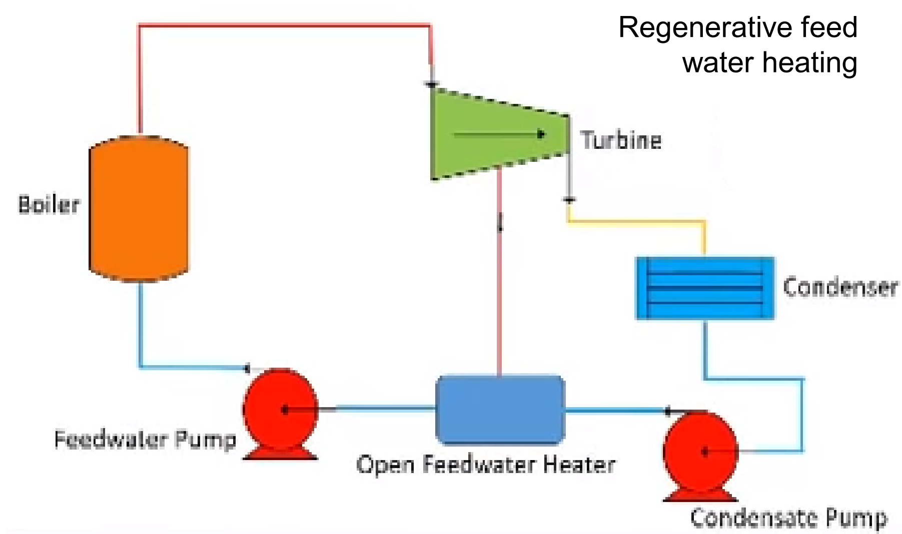


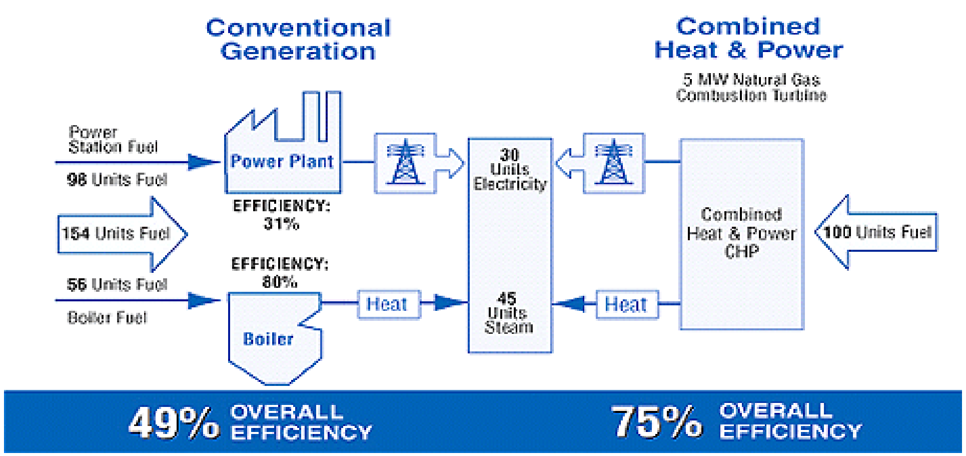
T-s diagrams showing the real Rankine cycle

Next class 8: Vapor Power Cycles - Advanced

- Designing a simple Rankine cycle
- Adding extra devices → improves efficiency
    - Extra heater → reheating
    - Open & closed feedwater heater
      → regenerative feedwater heating
- Combined heat & power generation
- Examples of real power plants







Combined heat and power reduces the energy loss

Types or Rankine cycles
https://www.youtube.com/watch?v=QFZN71MY71o&t=1s

Keep in mind: Important Formulas

- Specific volume $v = V/m$ [m³/kg] and density $\rho = 1/v = m/V$ [kg/m³]
- Volume work $\delta w = Pdv$
- Enthalpy $h = u + Pv$, (u internal energy, P pressure, v volume)
- Thermal efficiency $\eta_{thermal} = \frac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$
- Mixture fraction $x = \frac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
- Conservation of mass $m_{in} = m_{out}$, 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 $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$
- S increases, second law $ds_{total} = ds_{system} + ds_{surroundings} = \delta s_{gen} \geq 0$
- Inequality of Clausius $ds \geq \frac{\delta q_{net}}{T_{res}}$ (= for reversible process)
- Reversible heat transfer $\delta q_{net,rev} = Tds$, irreversible $\delta q_{net,irrev} < Tds$
- Gibbs equations $Tds = du + Pdv$ and $Tds = dh - vdP$
- Isentropic efficiencies $\eta_{INPUT,S} = \frac{w_{IN,S}}{w_{IN,A}}$, $\eta_{OUTPUT,S} = \frac{w_{OUT,A}}{w_{OUT,S}}$
- Thermal efficiency power cycles $\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$
- Carnot efficiency $\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$
- Coefficient of performance $(COP)_{HP} = \frac{q_{HOT,OUT}}{w_{IN}}$ and $(COP)_{REF} = \frac{q_{COLD,IN}}{w_{IN}}$

- Phase diagrams