Class 8
Vapor power cycles, advanced

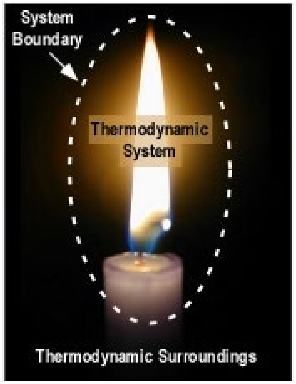
Steam rising from the Nesjavellir geothermal power station, the largest geothermal power plant in Iceland.
It uses geothermal energy that has absorbed inside the earth's magma.

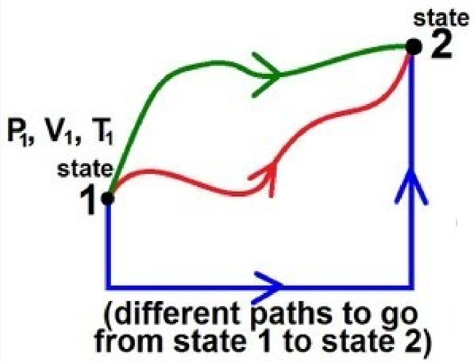
Roadmap Engineering Thermodynamics

- Using thermodynamics for practical applications requires knowledge of:

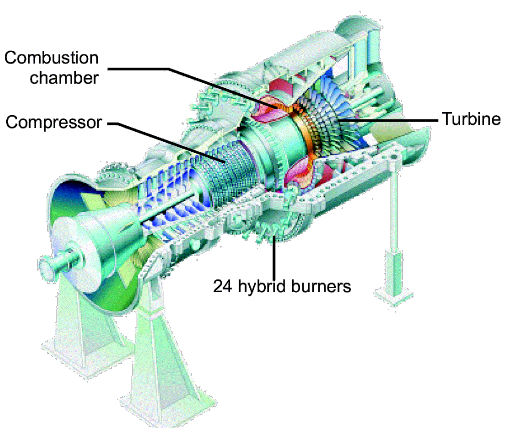
Concepts and definitions (Class 1)

Various forms of energy (Class 2)

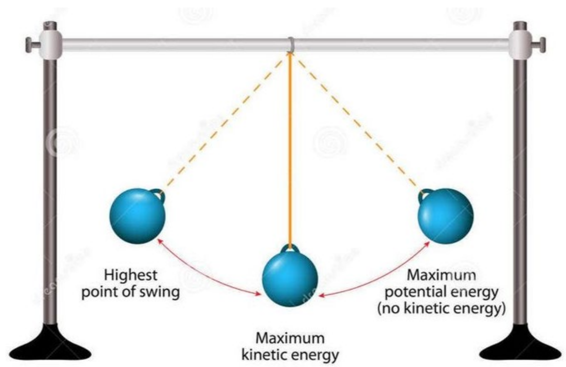




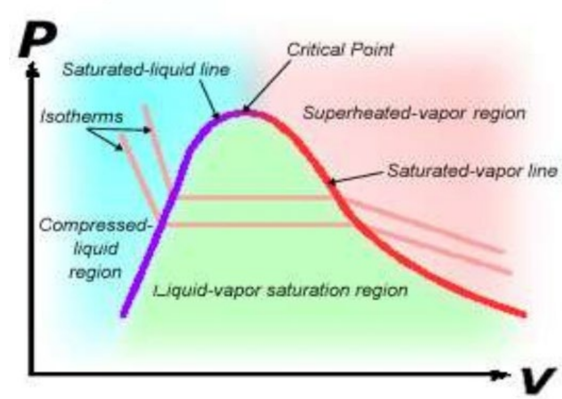
Power cycles
(Class 6 – 11)



Laws of Thermo
(Class 4 and 5)

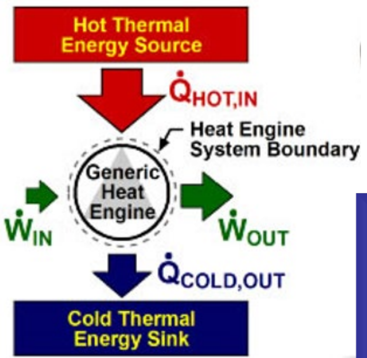


Properties of Substances
(Class 3, 9)

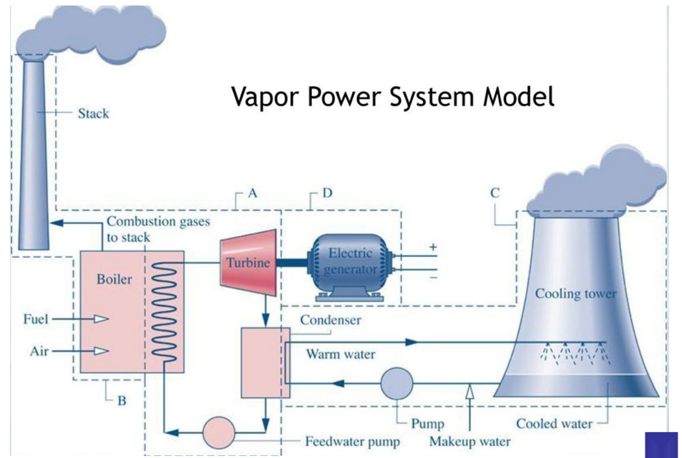


Roadmap Engineering Thermodynamics

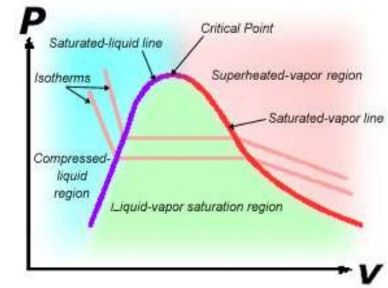
Thermodynamic cycles (Class 6)

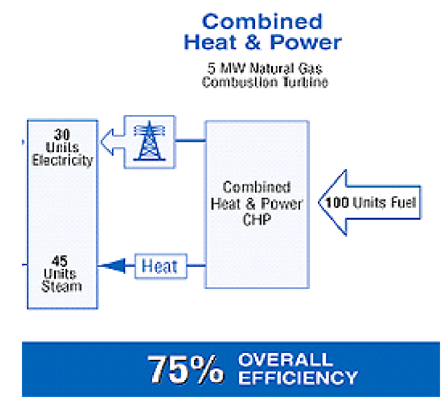


Vapor power cycles – Rankine cycle (Class 7, 8)

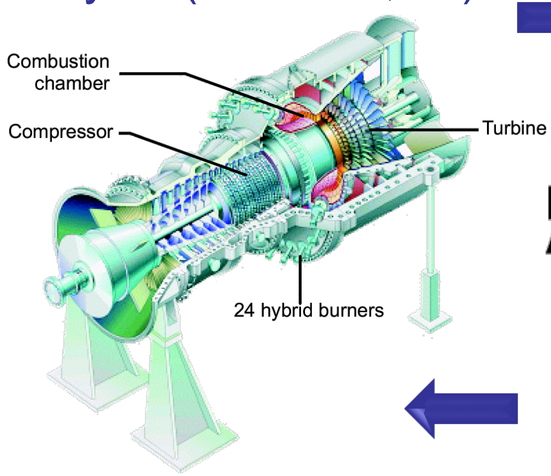


Properties of water (Class 3)

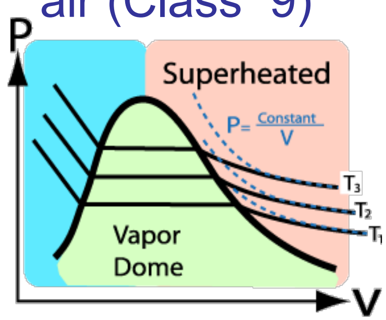




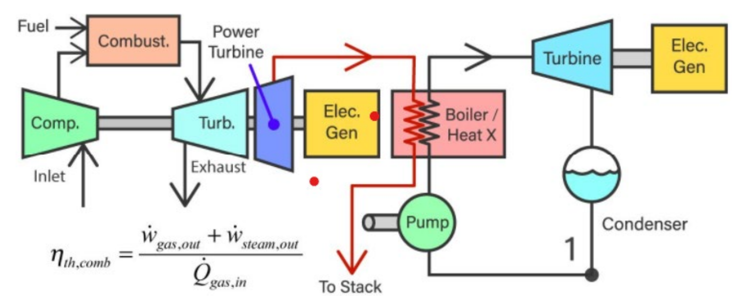
Gas power cycles – Brayton cycle (Class 10, 11)



Properties of air (Class 9)



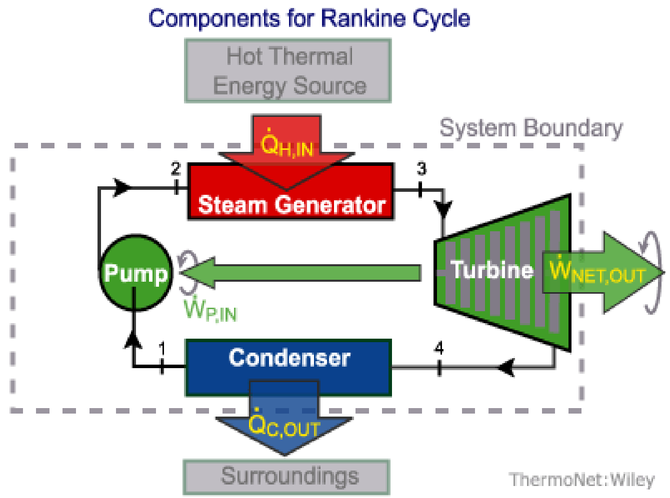
Combined cycles Combined heat & power (Class 8, 11)



Recapitulate Class 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:

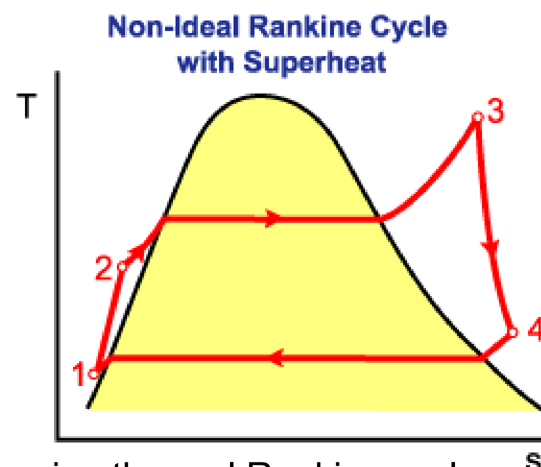
$$w_{pump,in} = v(P_{out} - P_{in}) = v(P_2 - P_1)$$
$$q_{in,boiler} = h_{out} - h_{in} = h_3 - h_2$$
$$w_{out,turbine} = h_{in} - h_{iut} = h_3 - h_4$$
$$q_{out,condenser} = h_{in} - h_{out} = h_4 - h_1$$
$$w_{net} = w_{out,turbine} - w_{pump,in} = (h_3 - h_4) - (h_2 - h_1)$$



    - 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

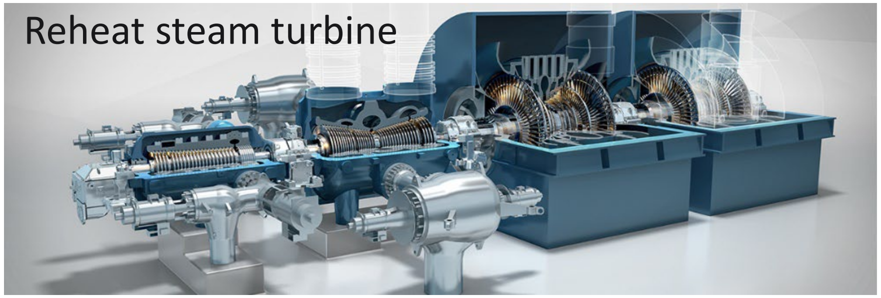


T-s diagrams showing the real Rankine cycle

Content Class 8

- **Vapor power cycles – Rankine 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



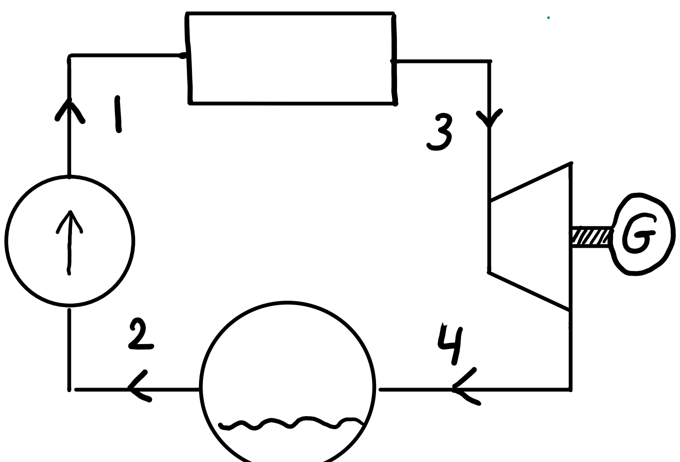
Feedwater heater tubes

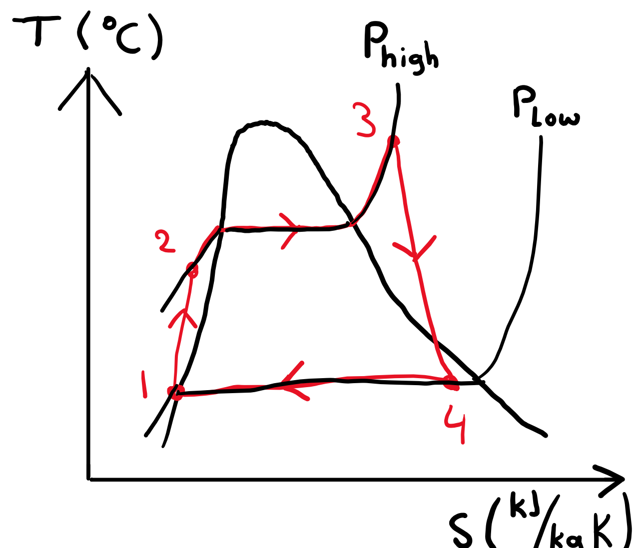
- **Learning goal:** recognize a **complicated** thermodynamic system to produce work, explain the configuration, analyse the thermodynamic aspects from the viewpoint of the first law of thermodynamics, interpret and evaluate the results and suggest improvements

How to design a simple Rankine power cycle

- In class 7 we learned how a vapor power cycle looks like, how it works and how to analyse the cycle
- The next step is to design your own cycle for a given power requirement
- How do you do that?

- The simple Rankine cycle consists of four components: pump, boiler or heat exchanger, turbine and condenser
- Draw the flow diagram with the 4 components and sketch a Ts - diagram
- Make a table and determine 2 properties needed to find the energies (h-values) for every point



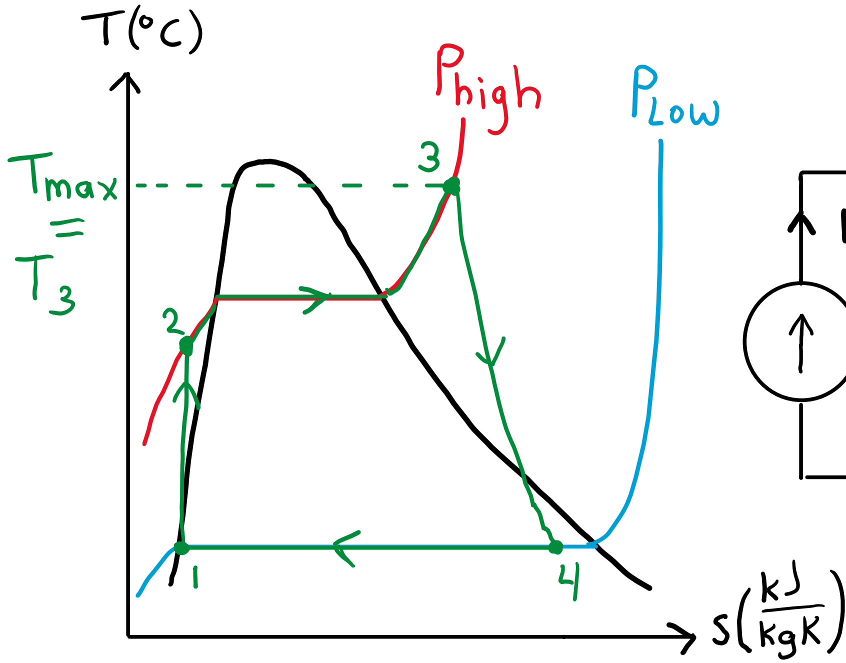


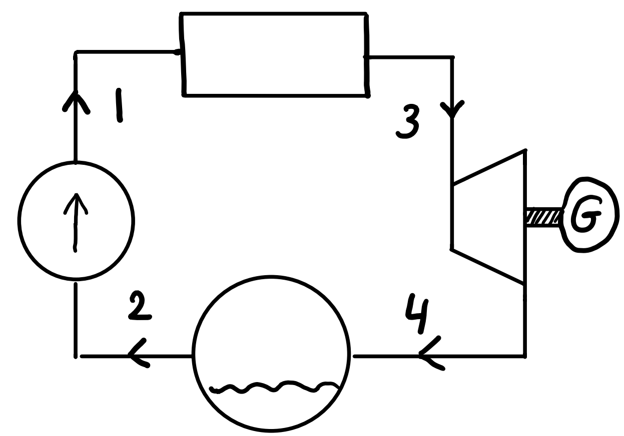
	1st	2nd
1		
2s		
2		
3		
4s		
4		

How to design a simple Rankine power cycle

- For the two properties it is common to choose / assume
  - Isentropic efficiencies for the pump and the turbine (point 2 and 4)
  - A high pressure for the cycle (point 2 and 3)
  - A low pressure for the cycle (point 1 and 4)
  - A maximum temperature in the cycle (at the turbine inlet, point 3)
  - Saturated liquid at the condenser outlet (point 1)
- Add data to the table and the Ts - diagram

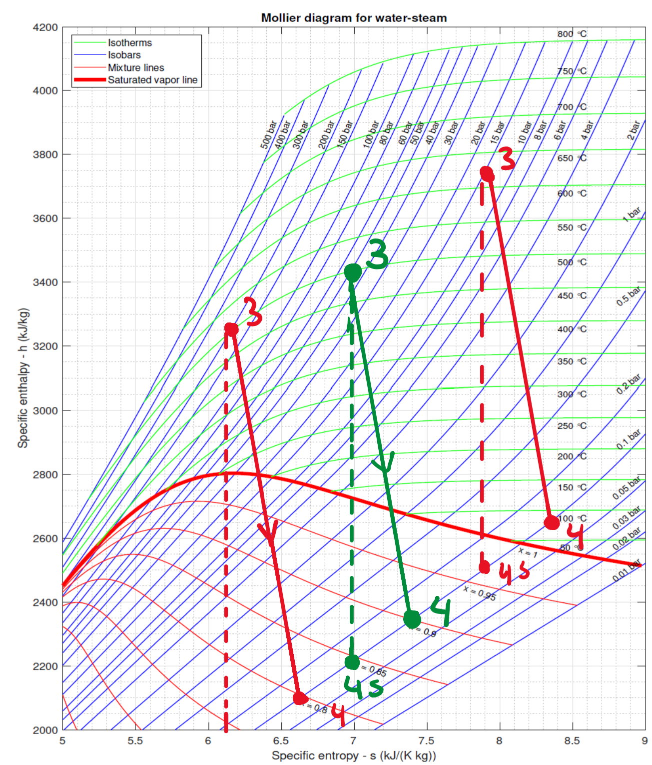
	1st	2nd
1	P_L	$x=0$
2s	P_H	$s_{2s}=s_1$
2	P_H	$\eta_{s,p}$
3	P_H	T_{max}
4s	P_L	$s_{4s}=s_3$
4	P_L	$\eta_{s,t}$





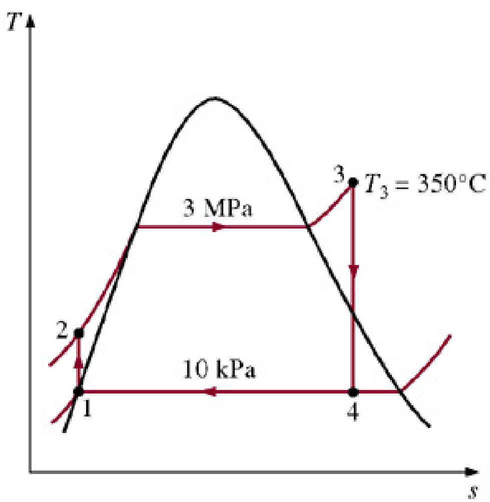
How to design a simple Rankine power cycle

- Isentropic efficiencies depend on how good the pump and the turbine are manufactured, cannot be changed they come with the device and are in the order of 70 to 90%
- The low pressure should be such that the temperature in the condenser is higher than the temperature of the environment to which the heat of the condensation process is rejected (note: the pressure in the condenser determines the temperature, saturation P & T)
- The combination of the pressures and the turbine inlet temperature should be such that the quality of the fluid at the turbine outlet is acceptable
- This can be trial and error but sketching in a hs - diagram makes it much easier to see
- The line 3 – 4 can be shifted left – right
- The green line is a good combination of P & T, the red ones are less good as the quality at the outlet is too low or T is too high



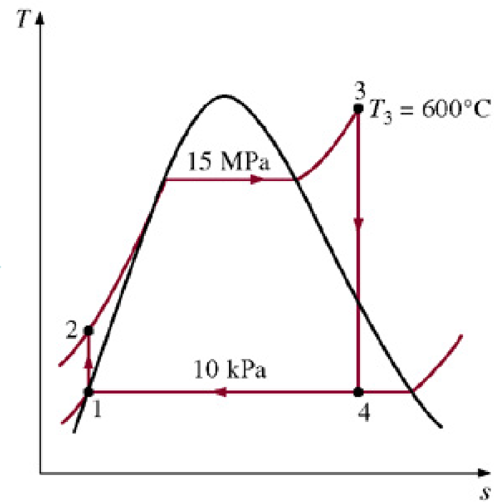
How to design a simple Rankine power cycle

- Choosing the turbine inlet temperature and the low and high pressures is the most challenging part
- You can use these parameters to optimize the output and / or the efficiency
- We have seen (class 7) that the efficiency of the simple cycle can be improved by
  - Increasing the turbine inlet pressure
  - Increasing the turbine inlet temperature
  - Decreasing the condenser temperature / pressure



3 Mpa → 15 Mpa
350°C → 600°C

Efficiency ↑

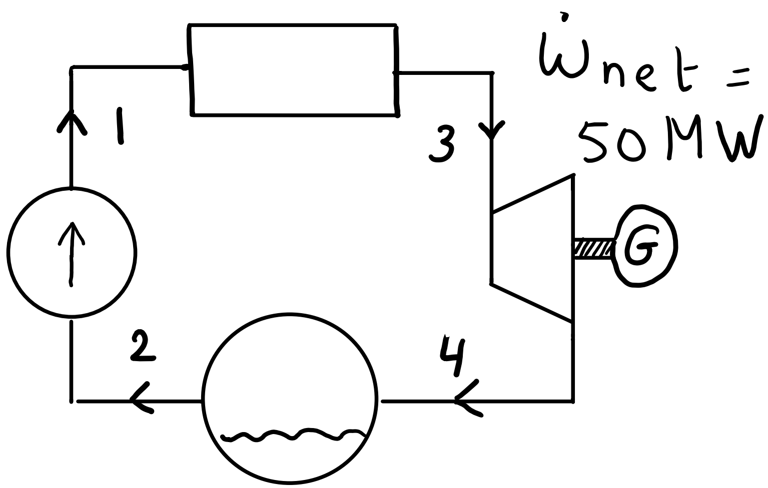


Pressure and temperature both are changed so that the quality of the mixture at the outlet of the turbine stays acceptable

How to design a simple Rankine power cycle

- **Example: design a cycle that delivers 50 MW net power output**

- Isentropic efficiencies are assumed to be 80%
- Low pressure is 0.1 bar = 100 kPa, saturation temperature for 100 kPa is 45 degrees C, this is high enough to be able to transfer the heat of the condensation process to the environment (assumed to be 20 degree C)
- High pressure is 50 bar = 5000 kPa
- Turbine inlet temperature is 500 Degree C
- Put a values in the table and check if you have two properties for every point



	first	second
1	P = 10 kPa	$x = 0$
2s	P = 5 MPa	$s_{2s} = s$
2	P = 5 MPa	$\eta_p = 80\%$
3	P = 5 MPa	$T = 500\,^\circ C$
4s	P = 10 kPa	$s_{4s} = s_3$
4	P = 10 kPa	$\eta_t = 80\%$

How to design a simple Rankine power cycle

- Next step is to determine the enthalpy, h-values for every point

Point 1: $x_1 = 0$, $P_1 = 10\,kPa$: table A5, $h_1 = 191.8\ \frac{kJ}{kg}$

Point 2s: s & v constant $\rightarrow dh = T\cancel{ds}^{\,0} + v\,dP$ constant

$h_{2s} - h_1 = v(P_{2s} - P_1) = 191.8 + 0.001(5000 - 10)$

$h_{2s} = 196.8\ \frac{kJ}{kg}$

Point 2: $\eta_{s,p} = \dfrac{h_{2s} - h_1}{h_2 - h_1} \rightarrow h_2 = h_1 + \dfrac{h_{2s} - h_1}{\eta_{s,p}}$

$h_2 = 198.0\ \frac{kJ}{kg}$

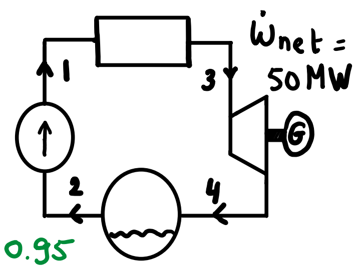
Point 3: Mollier diagram $\rightarrow h_3 = 3450\ \frac{kJ}{kg}$

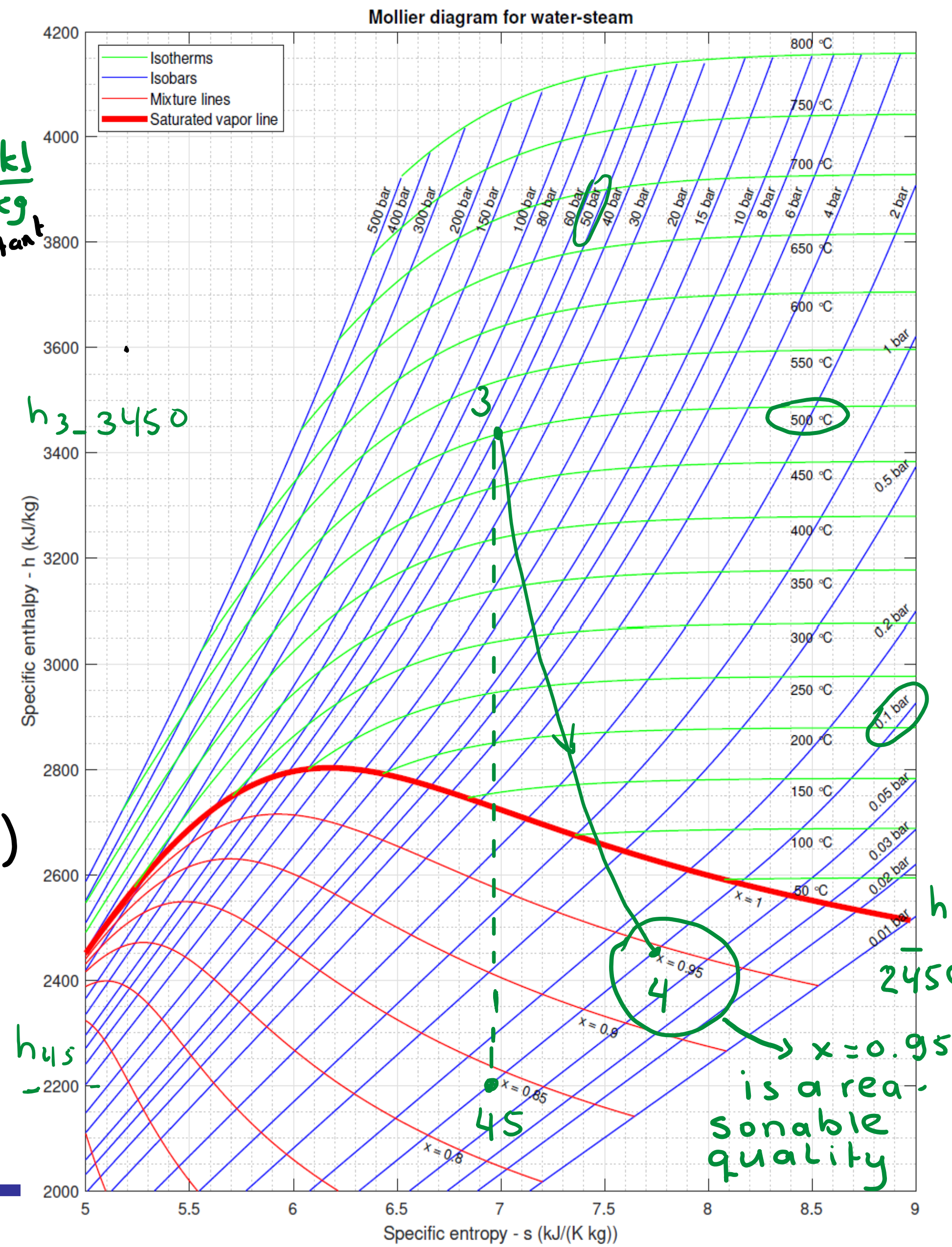
Point 4s: Same entropy as 3, vertical below 3 on Mollier diagram on th 10kPa isobar $h_{4s} = 2200\ \frac{kJ}{kg}$

Point 4: $\eta_{s,t} = \dfrac{h_3 - h_4}{h_3 - h_{4s}} \rightarrow h_4 = h_3 - \eta_{s,t}(h_3 - h_{4s})$

$h_4 = 2450\ \frac{kJ}{kg}$

Add point 4 to the Mollier diagram, check if the entropy increases and check the qualty at the turbine exit $\rightarrow 0.95$

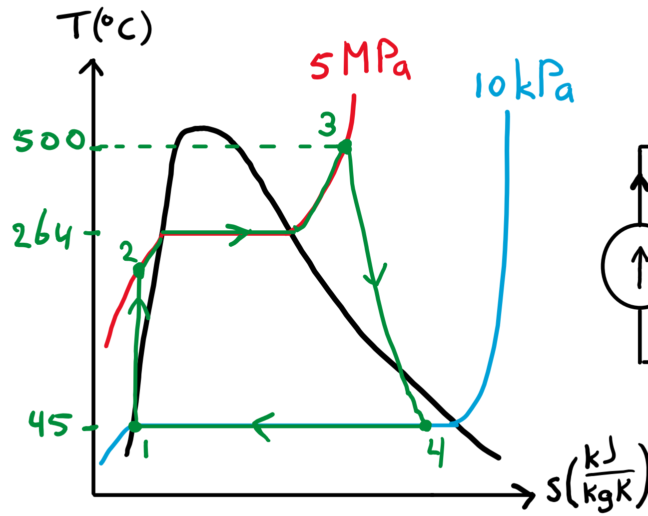


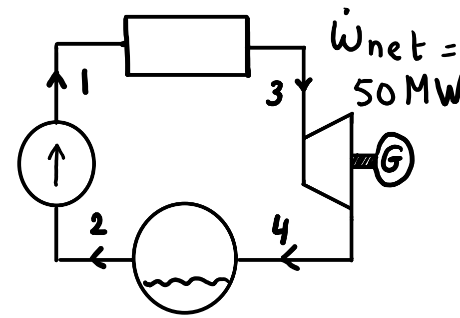


How to design a simple Rankine power cycle

- Add the h-values to the table and complete the Ts-diagram

	First property	Second property	$h\left(\frac{kJ}{kg}\right)$
1	$P_1 = 10 kPa$	$x_1 = 0$	191.8
2s	$P_{2s} = 5 MPa$	$s_{2s} = s_1$	196.8
2	$P_2 = 5 MPa$	$\eta_{s,p} = 80\%$	198.0
3	$P_3 = 5 MPa$	$T_3 = 500°C$	3450
4s	$P_{4s} = 10 kPa$	$s_{4s} = s_3$	2200
4	$P_4 = 10 kPa$	$\eta_{s,t} = 80\%$	2450





- Analyse the cycle

Specific work/heat in/outputs

$w_{in} = h_2 - h_1 = 6 \frac{kJ}{kg}$

$w_{out} = h_4 - h_3 = 1000 \frac{kJ}{kg}$

$q_{in} = h_3 - h_2 = 3250 \frac{kJ}{kg}$

$q_{out} = h_4 - h_1 = 2258 \frac{kJ}{kg}$

$w_{net} = w_{out} - w_{in}$

$w_{net} = 994 \frac{kJ}{kg}$

Net power output should be 50 MW

$\dot{W}_{net} = \dot{m}\, w_{net} \rightarrow \dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{50\,000}{994}$

$\dot{m} = 50.3 \frac{kg}{s}$

Thermal efficiency : $\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{m}\, w_{net}}{\dot{m}\, q_{net}}$

$\eta_{th} = 0.306 \rightarrow 31\%$

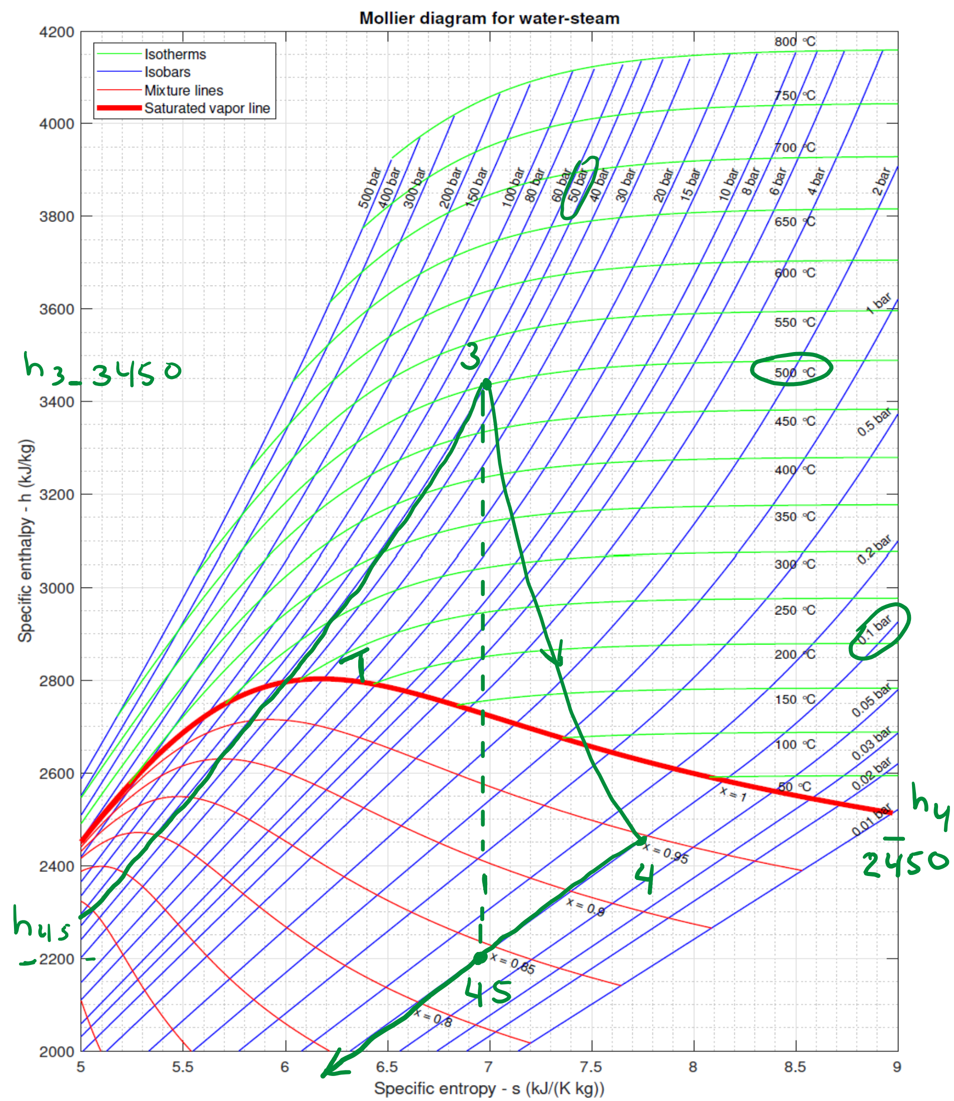
Total heat input $\rightarrow \dot{Q}_{in} = \dot{m} . q_{in} = 163.5 MW$

How to design a simple Rankine power cycle

- Discussion of the results

- Net power output is 50 MW
- Mass flow is 50.3 kg/s
- Total power input is 163.5 MW
- Thermal efficiency is 31%

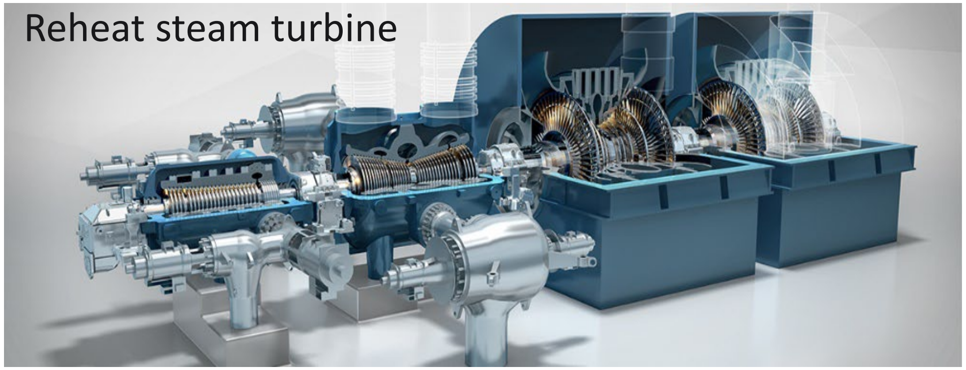
- The cycle meets the requirements
- 31% efficiency is good for a simple Rankine cycle so this seems to be a good design
- If you program the cycle in Matlab you can try different combinations of pressures and temperatures to optimize the cycle
- Realize that the power output can easily be changed by adjusting the mass flow, 100 kg/s gives 99.4 MW



- We designed the cycle!

Increasing the Rankine Cycle Performance

- The efficiency of a simple Rankine cycle is not very high
- It can be optimized by playing with the turbine inlet temperature and the pressures
- However the efficiency can be improved further by adding extra devices
- Means to **improve the efficiency of the simple Rankine cycle** are the use of
  - Extra heaters → reheating
  - Open & closed feedwater heaters → regenerative feed water heating



Feedwater heater tubes

- The idea behind these improvements is to higher the average temperature at which heat is added, why ?

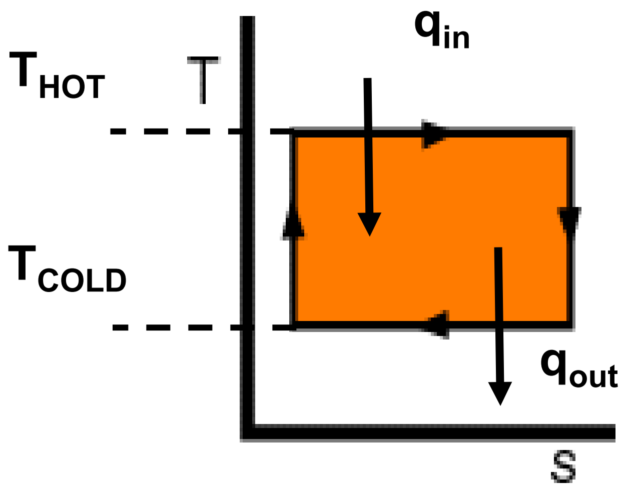
Increasing the Rankine Cycle Performance

- **Why do we want a higher average temperature for adding heat?**

- Recapitulate Carnot engine, ideal engine with the highest possible efficiency
- This is achieved by adding the heat isothermal and isentropic pressure increase and decrease
- The efficiency is determined by the highest and lowest temperature
- The larger the temperature difference the higher the efficiency

$\rightarrow$ Carnot efficiency = $1 - \frac{T_{COLD}}{T_{HOT}}$

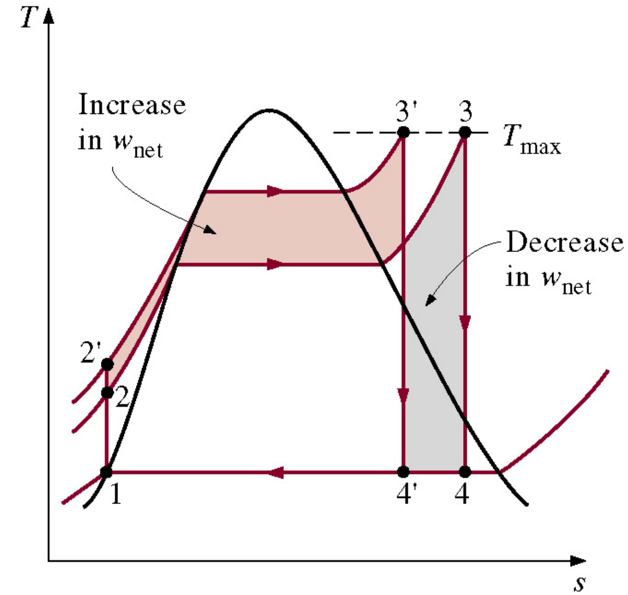
- Therefore the higher the average temperature at which the heat is added the higher the efficiency



Improvement Rankine Cycle: Reheating

- A higher boiler pressure increases the efficiency of a Rankine cycle as the heat on average is added at a higher temperature (3 → 3')

- However the moisture content in the turbine outlet increases to unacceptable levels (4 → 4')

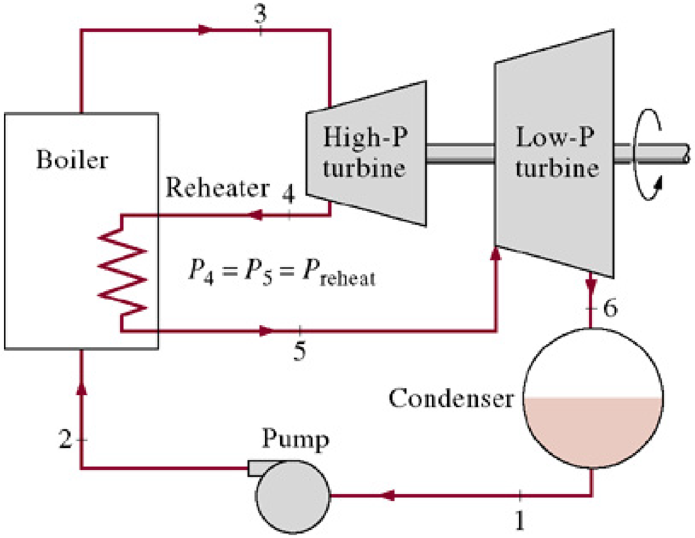


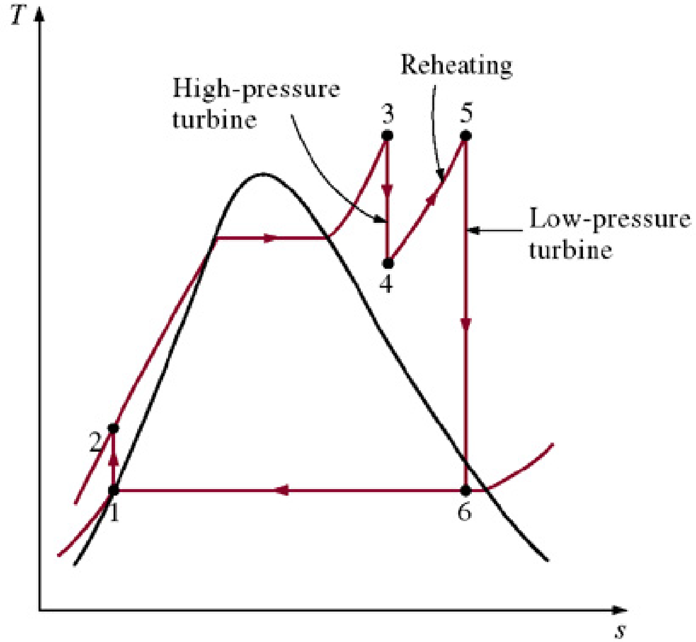
- How can we take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture content at the final stage of the turbine?

  - Superheat the steam to higher temperatures, however the temperature is limited by the material properties of the boiler and turbine, T_{max} around 620°C (important which material to choose)
  - Reheating

Improvement Rankine Cycle: Reheating

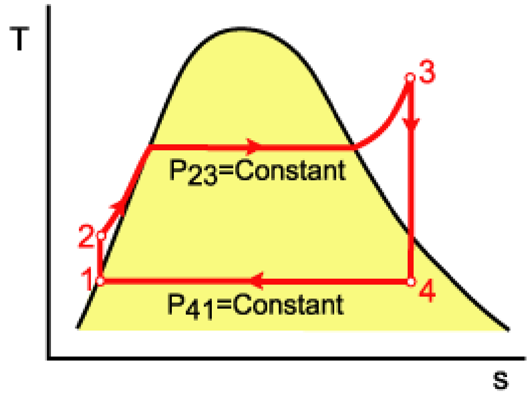
- For reheating a second turbine is added and the expansion process takes place in two steps
  - The steam is expanded to an intermediate pressure and sent back to the boiler (the optimum reheat pressure is about one-fourth of the maximum)
  - It is reheated at constant pressure usually to the inlet temperature of the first turbine
  - Steam expands in the second stage to the condenser pressure



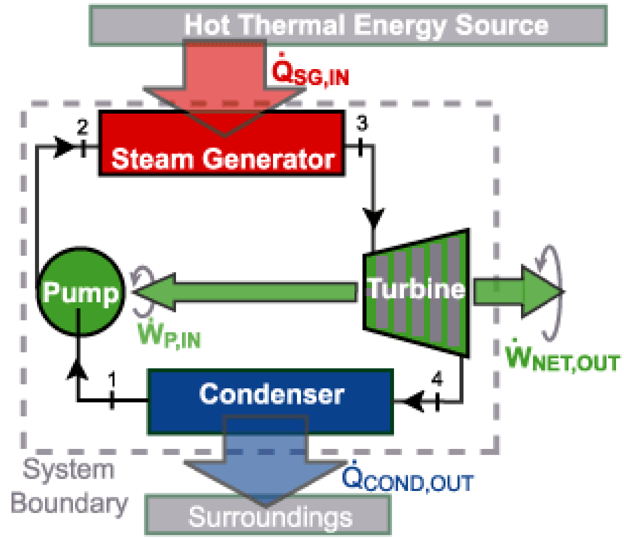


Improvement Rankine Cycle: Reheating

- Without reheat

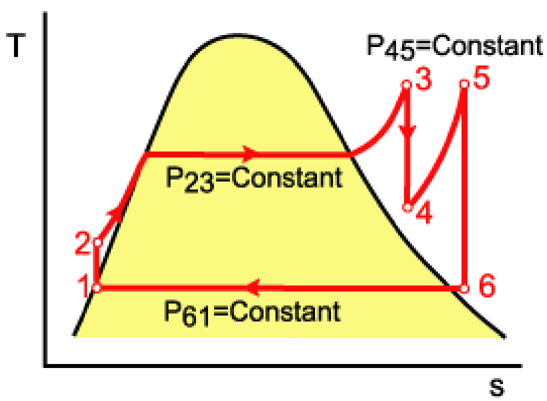


ThermoNet: Wiley

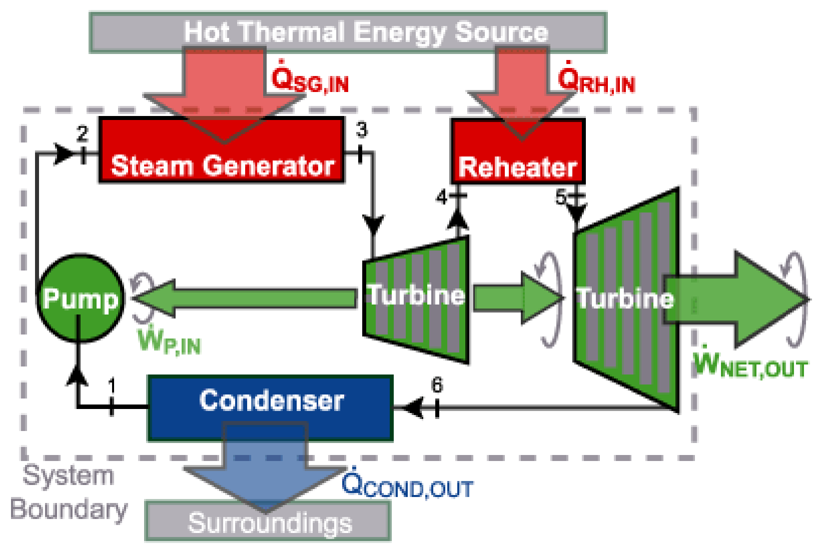


- The efficiency of a Rankine cycle can be improved by reheating as the heat is added to the steam at a higher average temperature

- With reheat



ThermoNet: Wiley

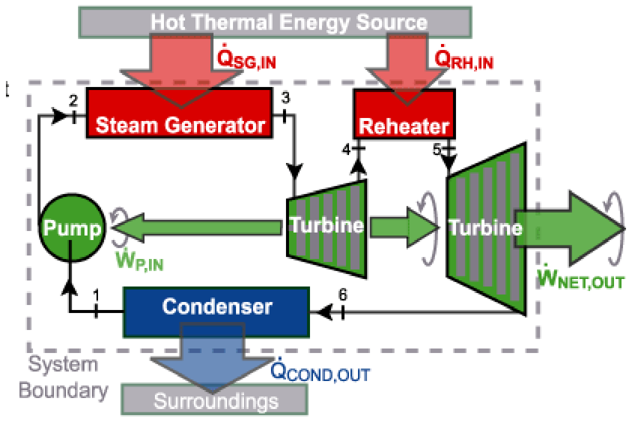


- Reheating decreases the liquid fraction in the turbine → better reliability

Improvement Rankine Cycle: Reheating

- The total heat input is the sum of the heat input in the steam generator and the reheater

$$q_{in,total} = q_{in,sg} + q_{in,rh}$$
$$= (h_3 - h_2) + (h_5 - h_4)$$

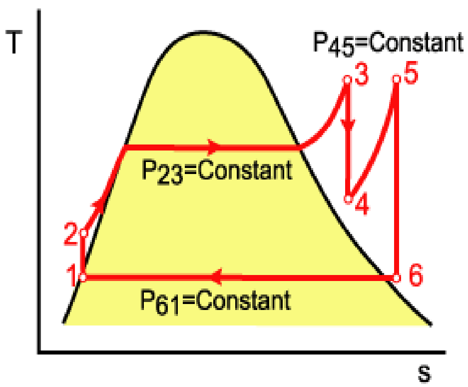


- The total work produced is the sum of the work of both turbines

$$w_{out,total} = w_{out,\ turb1} + w_{out,turb2} = (h_3 - h_4) + (h_5 - h_6)$$

- The net work output of the reheat Rankine cycle is

$$w_{net} = w_{out,\ total} - w_{in,pump} = (h_3 - h_4) + (h_5 - h_6) - (h_2 - h_1)$$



- The efficiency therefore becomes

$$\eta_{RANKINE} = \frac{w_{NET,OUT}}{q_{IN}} = \frac{(h_3 - h_4) + (h_5 - h_6) - (h_2 - h_1)}{(h_3 - h_2) + (h_5 - h_4)}$$

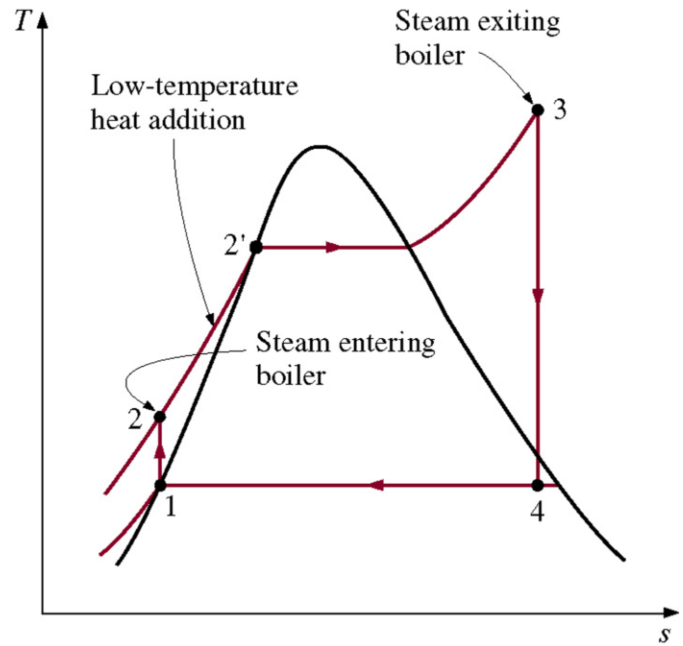
Improvement Rankine Cycle: Feed Water Heating

- The first part of the heat-addition process in the boiler takes place at relatively low temperatures

- This lowers the average temperature at which the heat is added to the steam which decreases the efficiency

  (remember Carnot: $\eta_{Carnot} = 1 - \frac{T_{COLD}}{T_{HOT}}$)

- To avoid this the liquid should leave the pump at a higher temperature



- Use a part of the steam to preheat the feed water

  → regenerative feed water heating

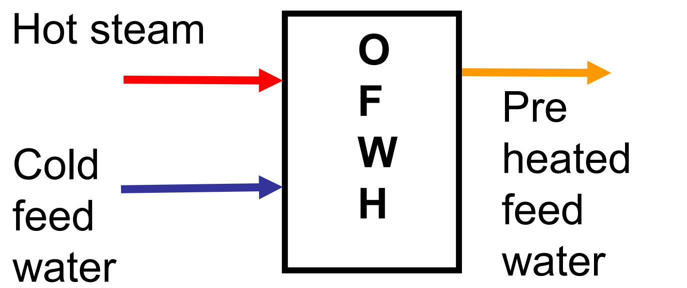
- The device where the feed water is heated is called a feed water heater, basically this is a heat exchanger where heat is transferred from the steam to the feed water, there are

  → open and closed feed water heaters

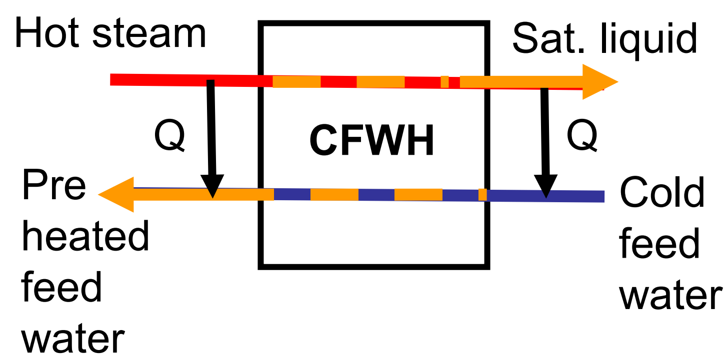
Improvement Rankine Cycle: Feed water Heating

- There are two types of feedwater heaters, open and closed

- In an open feed water heater (OFWH) heat is transferred from the steam to the feed water by mixing the two streams (this is called a mixing chamber)



- In a closed feed water heater (CFWH) heat is transferred from the steam to the feed water without mixing them but by using a closed heat exchanger

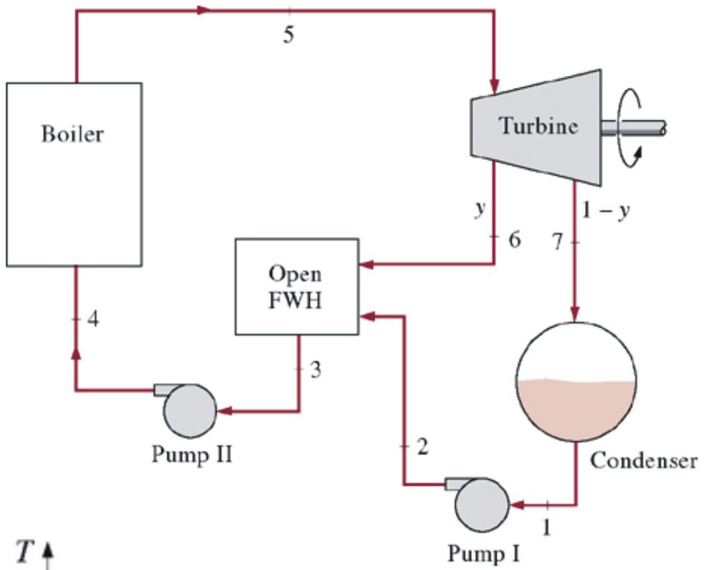


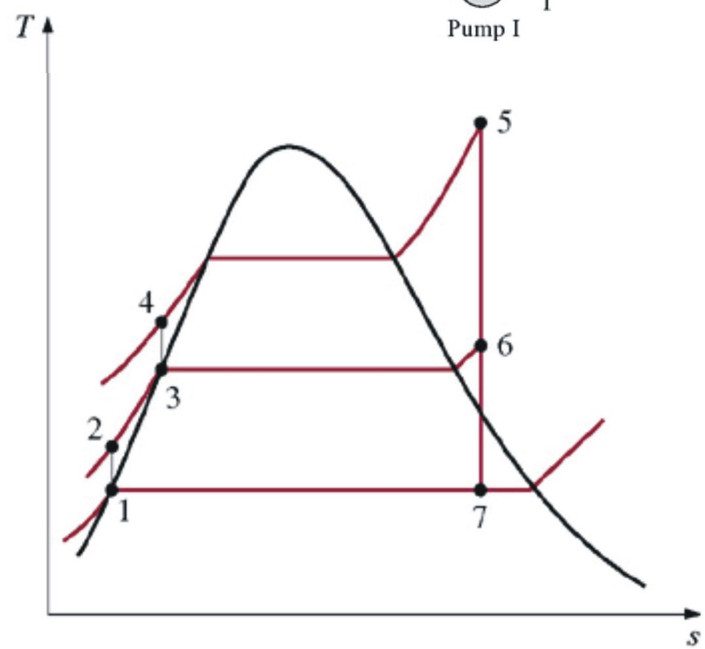
Improvement Rankine Cycle: Feed Water Heating

- Regenerative feed water heating: steam bled from turbine is used to heat feed water entering boiler

- However extracting steam from the turbine reduces the mass flow rate through
  - The lower pressure turbine stages
    $\rightarrow$ reduces $w_{NET,OUT}$
  - The condenser
    $\rightarrow$ reduces q_{OUT}

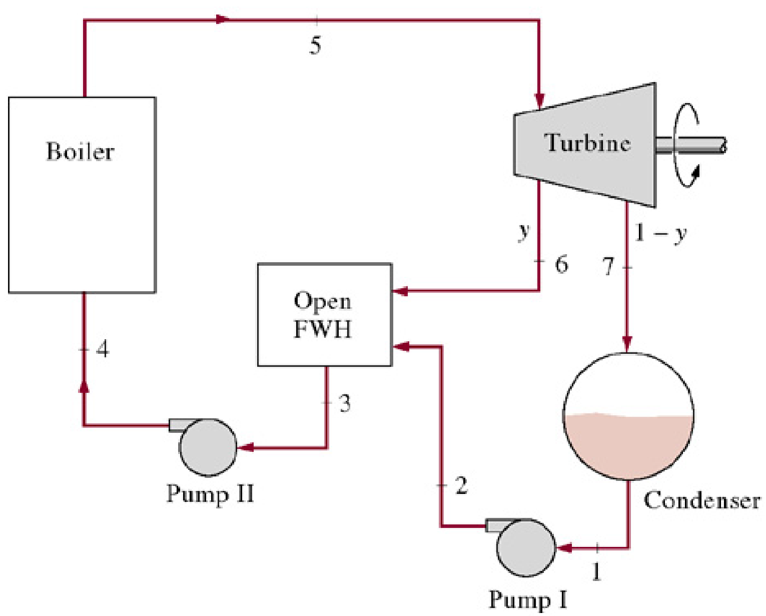
- However preheating the feed water
  $\rightarrow$ **reduces q_{IN}**
- The **net effect** is
  - An increase in η_{TH}
  - A reduction of $w_{NET,OUT}$



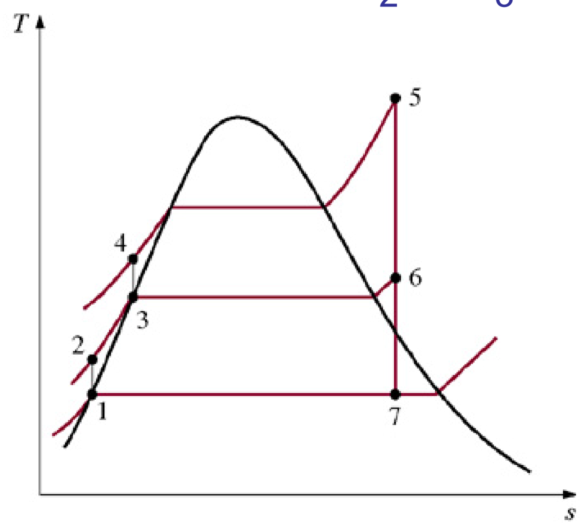


Rankine Cycle with Open Feed Water Heater

- The **open feed water heater** is a mixing chamber in which the steam extracted from the turbine mixes with the feed water exiting the first pump
- Ideally the mixture leaves the heater as a saturated liquid
  $\rightarrow h_3 = h_{sat\text{-}liquid@P3}$ (to find in table 5)
- The fraction of the steam extracted is such that the mixture leaves the open feed water heater as a saturated liquid (in the ideal situation)

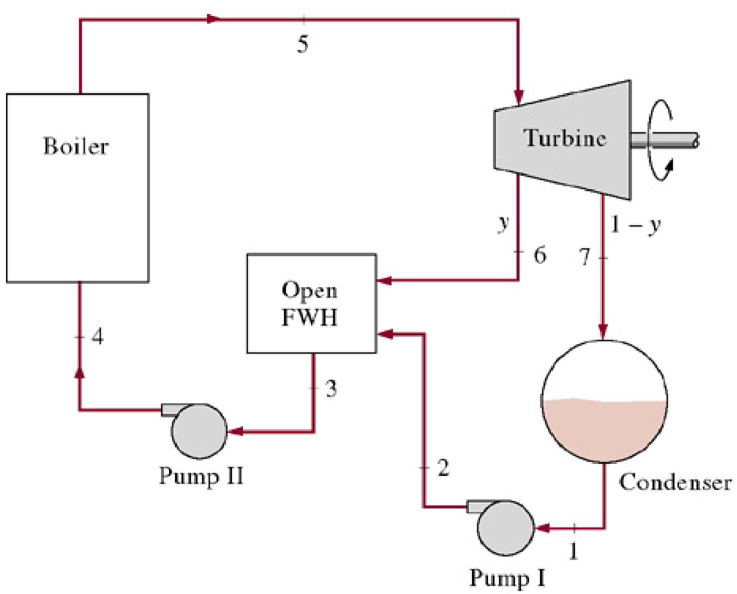


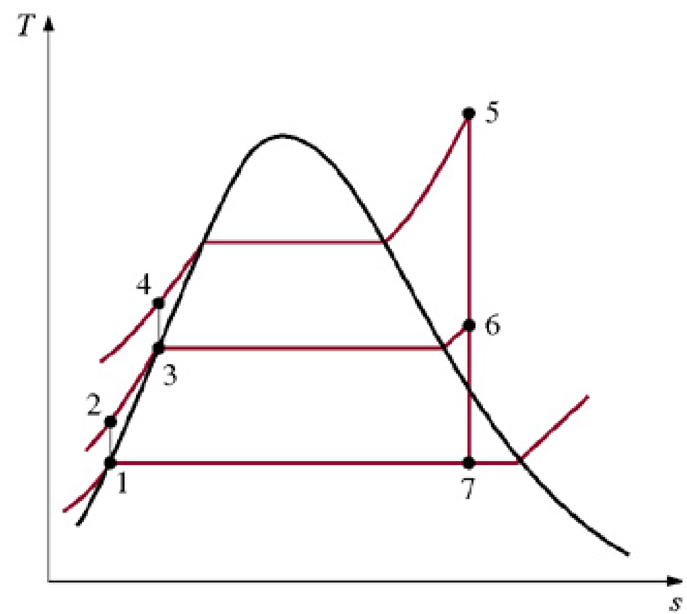
- Note $P_2 = P_3 = P_6$



Rankine Cycle with Open Feed Water Heater

- Analyzing the Rankine cycle with an **open feed water heater**
- The mass flow changes throughout the cycle
- Three different mass flows: $\dot{m}_7 = \dot{m}_1 = \dot{m}_2$ & $\dot{m}_3 = \dot{m}_4 = \dot{m}_5$ & $\dot{m}_6$
- Extra relations are required
    - Mass balance mixing chamber: $\dot{m}_6 + \dot{m}_2 = \dot{m}_3$
    - Energy balance mixing chamber: $\dot{m}_6\, h_6 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

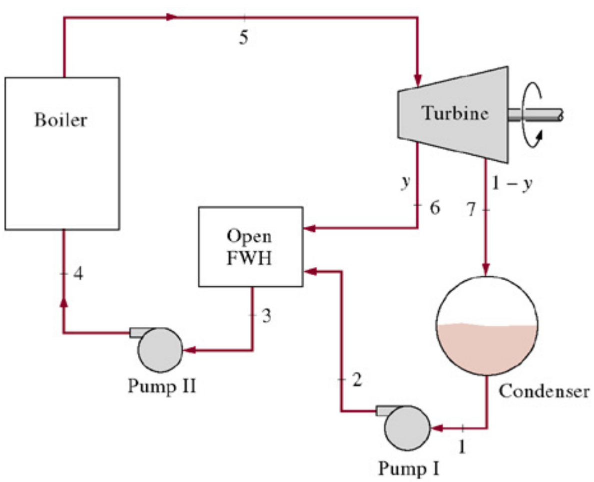


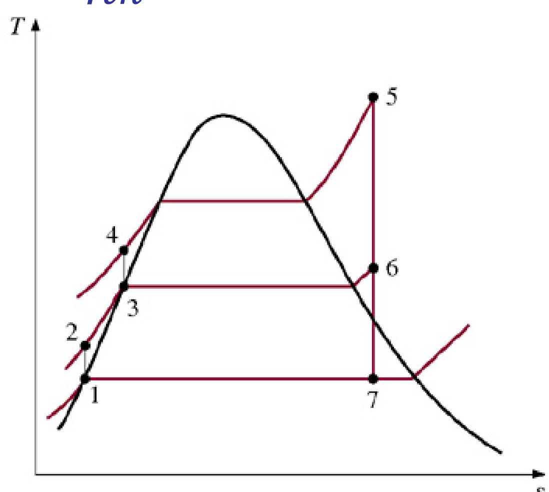


Rankine Cycle with Open Feed Water Heater

- Three different mass flows: $\dot{m}_7 = \dot{m}_1 = \dot{m}_2$ and $\dot{m}_3 = \dot{m}_4 = \dot{m}_5$ and $\dot{m}_6$
- Mass balance mixing chamber: $\dot{m}_6 + \dot{m}_2 = \dot{m}_3$
- Energy balance mixing chamber: $\dot{m}_6 \, h_6 + \dot{m}_2 h_2 = \dot{m}_3 h_3$
  - Power heat in- and output: $\dot{Q}_{\text{in}} = \dot{m}_3 \, (h_5 - h_4)$ and $\dot{Q}_{\text{out}} = \dot{m}_7 \, (h_7 - h_1)$
  - Power work output: $\dot{W}_{\text{out}} = \dot{m}_3 \, (h_5 - h_6) + \dot{m}_7 (h_6 - h_7)$
  - Power work input: $\dot{W}_{\text{in}} = \dot{m}_7 \, (h_2 - h_1) + \dot{m}_3 (h_4 - h_3)$
- Thermal efficiency: $\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{Q}_{in}} =$

$$\eta_{th} = \frac{\dot{m}_3 \, (h_5 - h_6) + \dot{m}_7 (h_6 - h_7) - \dot{m}_7 \, (h_2 - h_1) - \dot{m}_3 (h_4 - h_3)}{\dot{m}_3 \, (h_5 - h_4)}$$



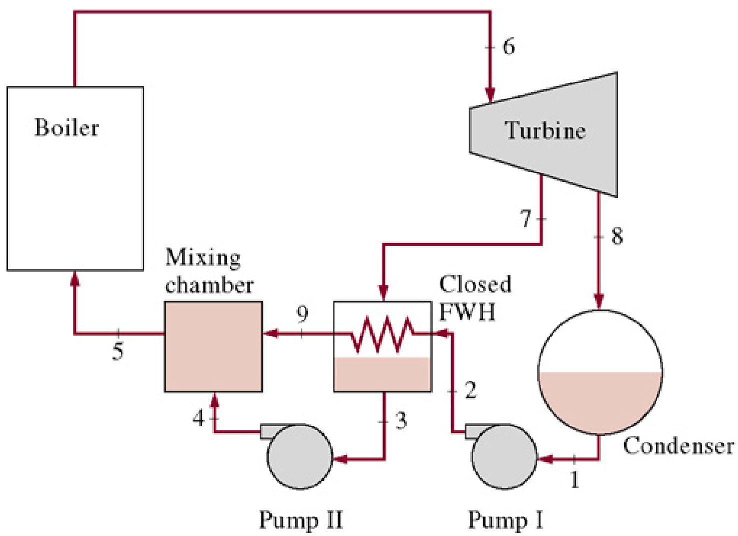


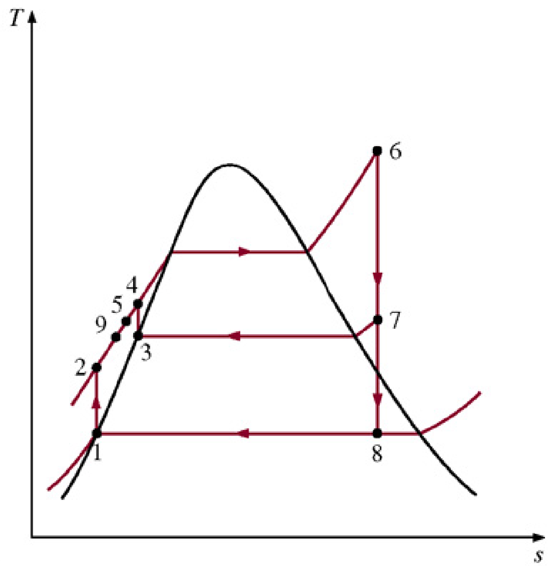
BREAK

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

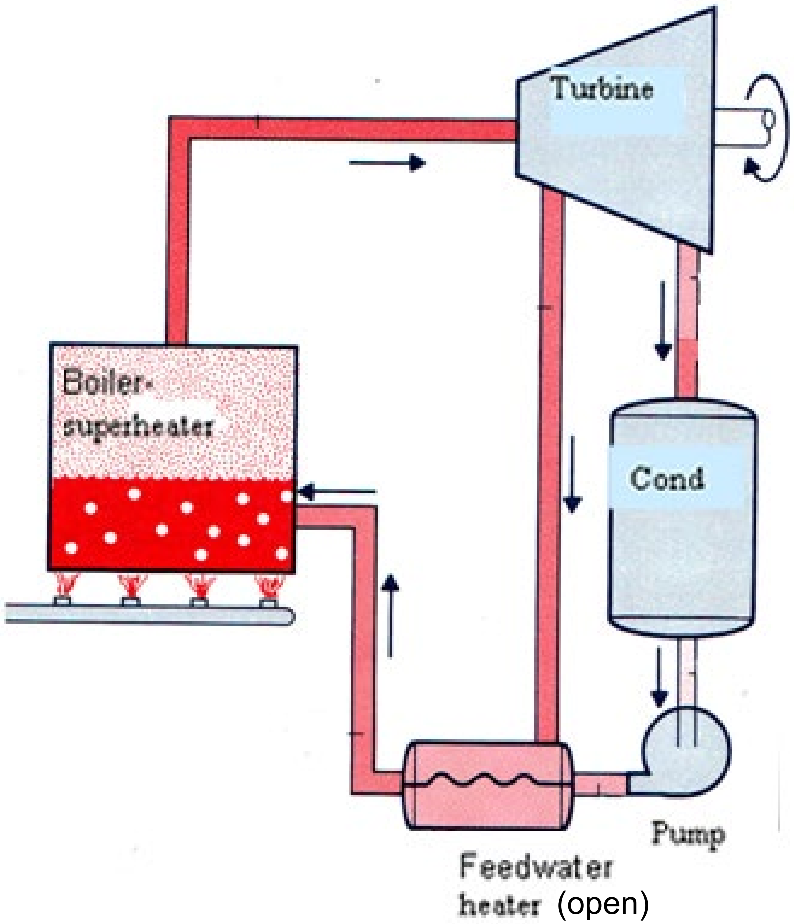
Rankine Cycle with Closed Feed Water Heater

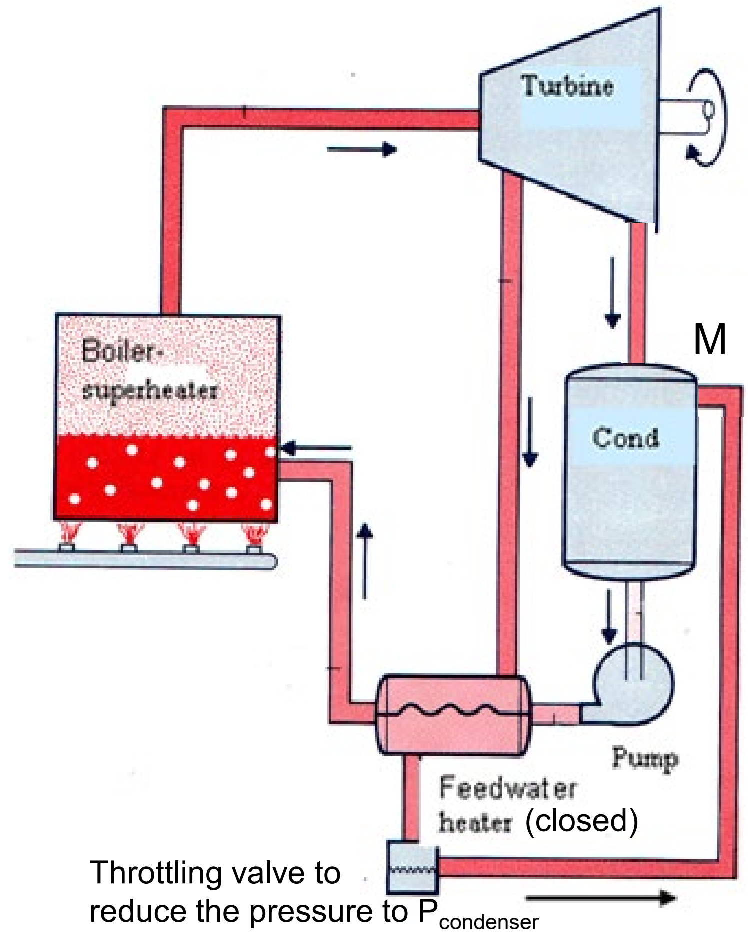
- The **closed feed water heater** is a heat exchanger in which the heat of the steam extracted from the turbine is transferred to the feed water exiting the first pump
- In an **ideal** closed feed water heater the feed water is heated to the exit temperature of the extracted steam ($T_9 = T_3$) and the steam leaves the heater as a saturated liquid at the extraction pressure → $h_3 = h_{sat\text{-}liquid@P7}$ (table 5)
- Both streams are mixed in a mixing chamber (in this figure) or the saturated steam is rerouted to the condenser via a throttling valve (see next slide)





Improvement Rankine Cycle: feed water heater



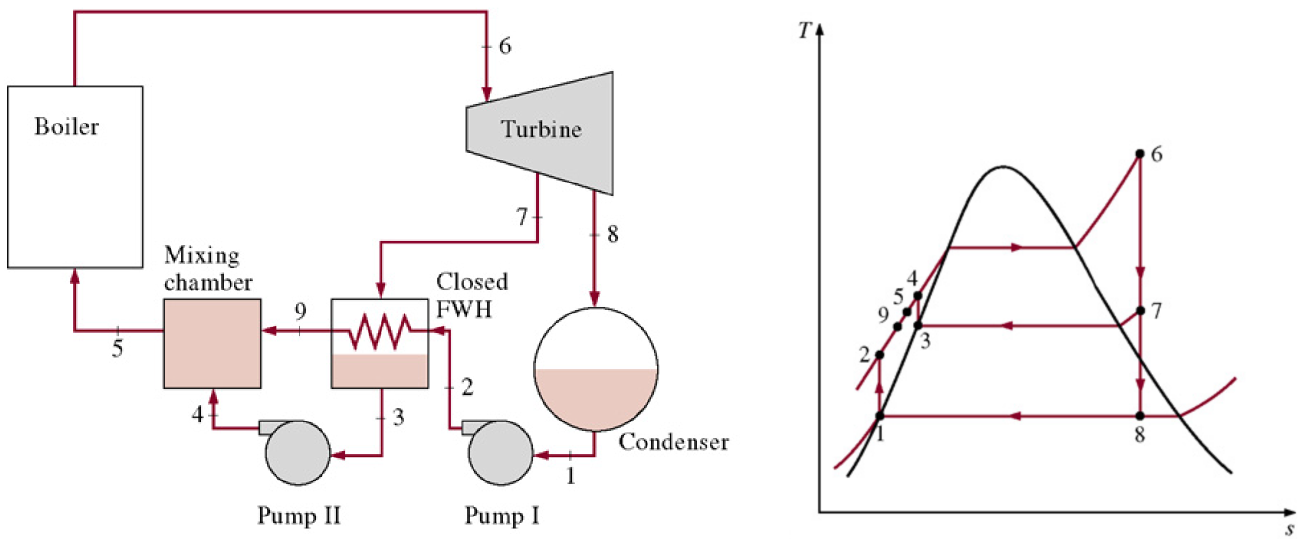


Open feed water heater, mixing is performed in the open feed water heater.

Closed feedwater heater with the steam rerouted to the condenser. Mixing is performed at point M. Note the pressures for mixing should be equal.

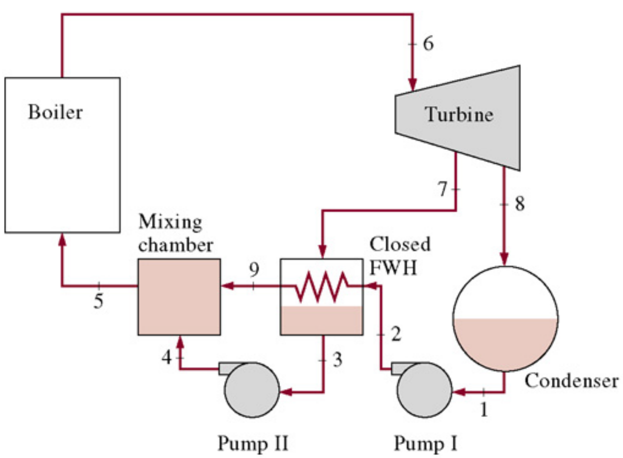
Rankine Cycle with Closed Feed Water Heater

- Analyzing the Rankine cycle with a **closed feed water heater**
- The mass flow changes throughout the cycle
- Three different mass flows: $\dot{m}_7 = \dot{m}_3 = \dot{m}_4$ & $\dot{m}_8 = \dot{m}_1 = \dot{m}_2 = \dot{m}_9$ & $\dot{m}_5 = \dot{m}_6$
- Extra relations are required
  - Energy balance closed feed water heater: $\dot{m}_7\,(h_7 - h_3) = \dot{m}_2(h_9 - h_2)$
  - Mixing chamber relations
    - Mass balance mixing chamber: $\dot{m}_5 = \dot{m}_4 + \dot{m}_9$
    - Energy balance mixing chamber: $\dot{m}_5\,h_5 = \dot{m}_4 h_4 + \dot{m}_9 h_9$

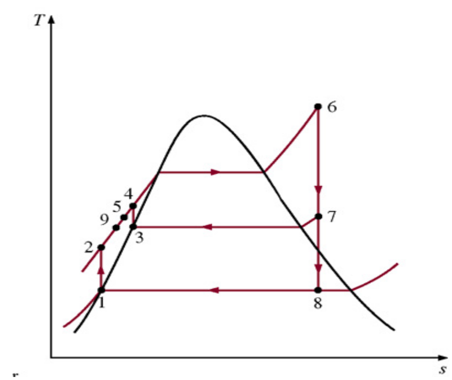


Rankine Cycle with Closed Feed Water Heater

- Energy balance closed feed water heater: $\dot{m}_7\,(h_7 - h_3) = \dot{m}_2(h_9 - h_2)$
- Energy balance mixing chamber: $\dot{m}_5\,h_5 = \dot{m}_4 h_4 + \dot{m}_9 h_9$
- Mass balance mixing chamber: $\dot{m}_5 = \dot{m}_4 + \dot{m}_9$
  - Power heat in- and output: $\dot{Q}_{\text{in}} = \dot{m}_5\,(h_6 - h_5)$ and $\dot{Q}_{\text{out}} = \dot{m}_8\,(h_8 - h_1)$
  - Power work output: $\dot{W}_{\text{out}} = \dot{m}_5\,(h_6 - h_7) + \dot{m}_8(h_7 - h_8)$
  - Power work input: $\dot{W}_{\text{in}} = \dot{m}_8\,(h_2 - h_1) + \dot{m}_3(h_4 - h_3)$
- Three different mass flows: $\dot{m}_7 = \dot{m}_3 = \dot{m}_4$ & $\dot{m}_8 = \dot{m}_1 = \dot{m}_2 = \dot{m}_9$ & $\dot{m}_5 = \dot{m}_6$
- Thermal efficiency: $\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{Q}_{in}} =$

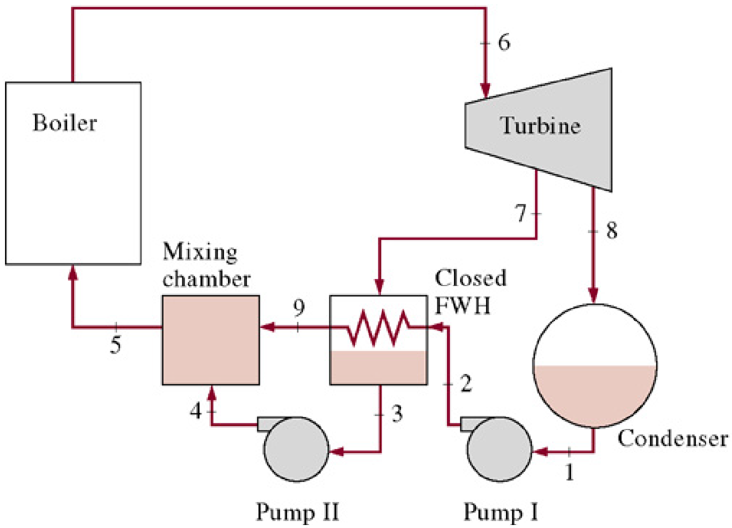


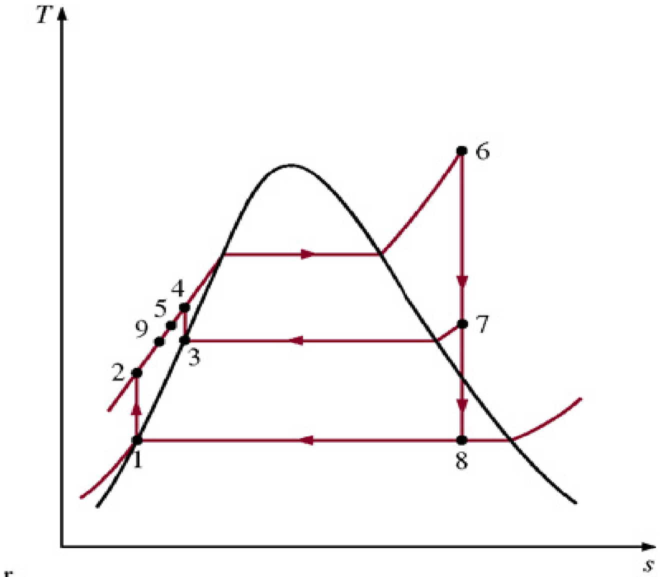
$$\eta_{th} = \frac{\dot{m}_5\,(h_6 - h_7) + \dot{m}_8(h_7 - h_8) - \dot{m}_8\,(h_2 - h_1) - \dot{m}_3(h_4 - h_3)}{\dot{m}_5\,(h_6 - h_5)}$$



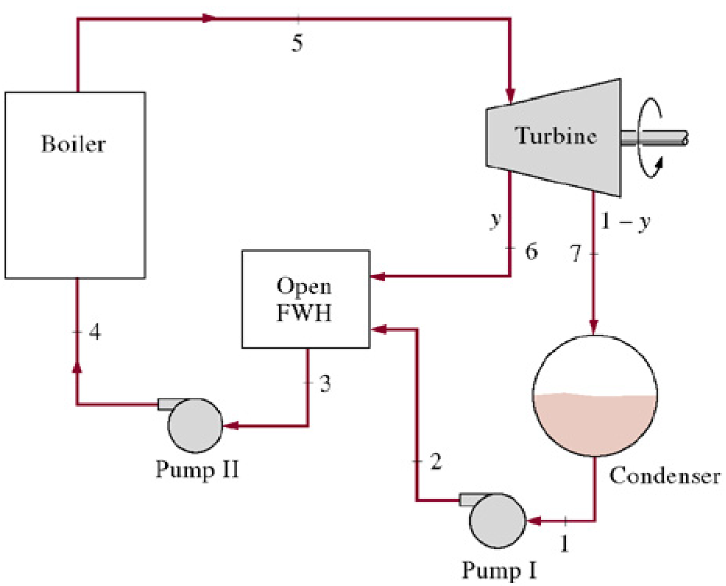
Open and closed feed water heaters

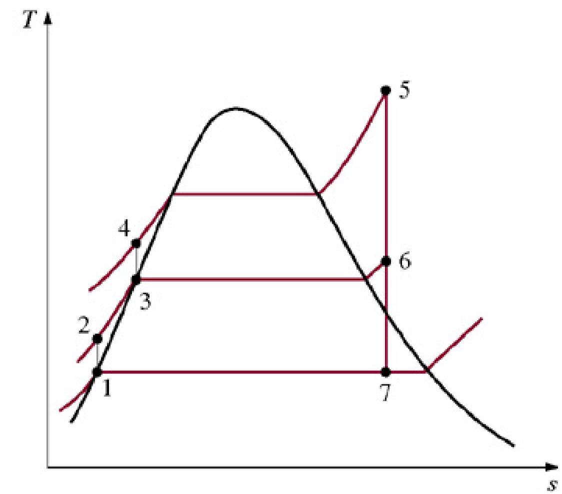
Closed feed water heater





Open feed water heater



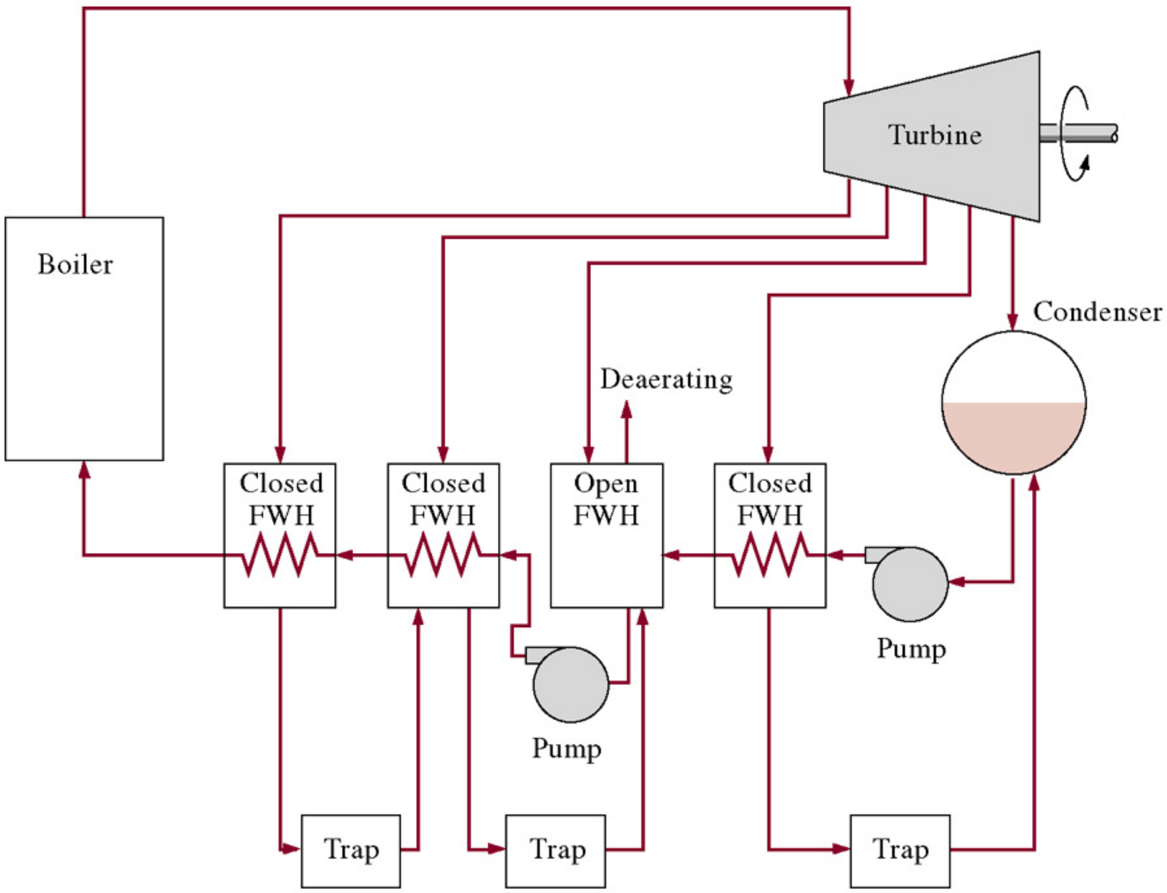


Combination of Open and Closed Heaters

- Most steam power plants use a combination of open and closed feed water heaters (often up to 8 feed water heaters are used)

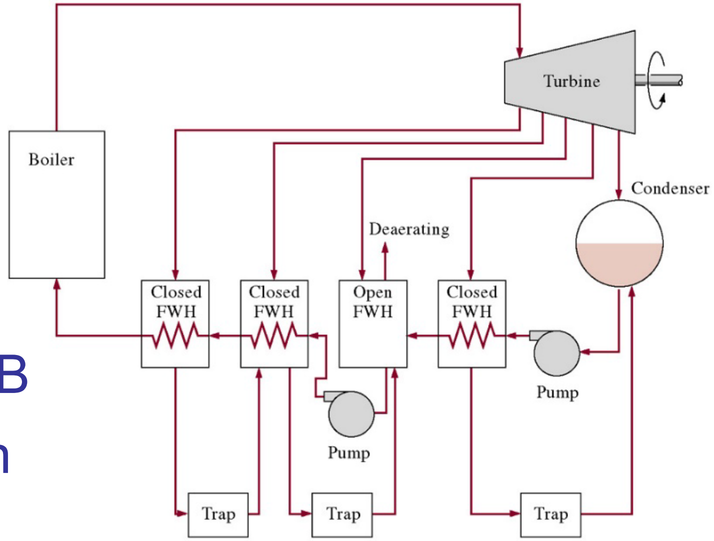
- **Open feed water heater:** simple, inexpensive, good heat transfer, however each heater requires a separate pump

- **Closed feed water heater:** more complex, more expensive, heat transfer is less, however not all of them need a pump

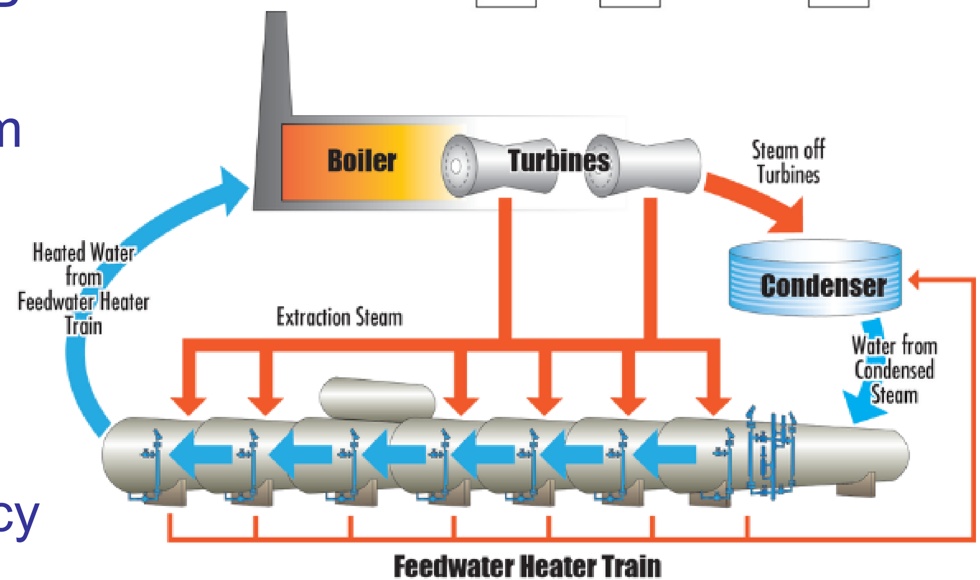


Combination of Open and Closed Heaters

- **Why so many feed water heaters are used?**
- The use of more than one feed water heater increases the efficiency as part of the steam is longer in the turbine, available to produce work
- In feed water heater A the steam can have a lower temperature than in feed water heater B
- Therefore the steam for A can be extracted in a later stage than the steam for B
- Feed water heater B needs relatively high temperature steam which is extracted in an early stage

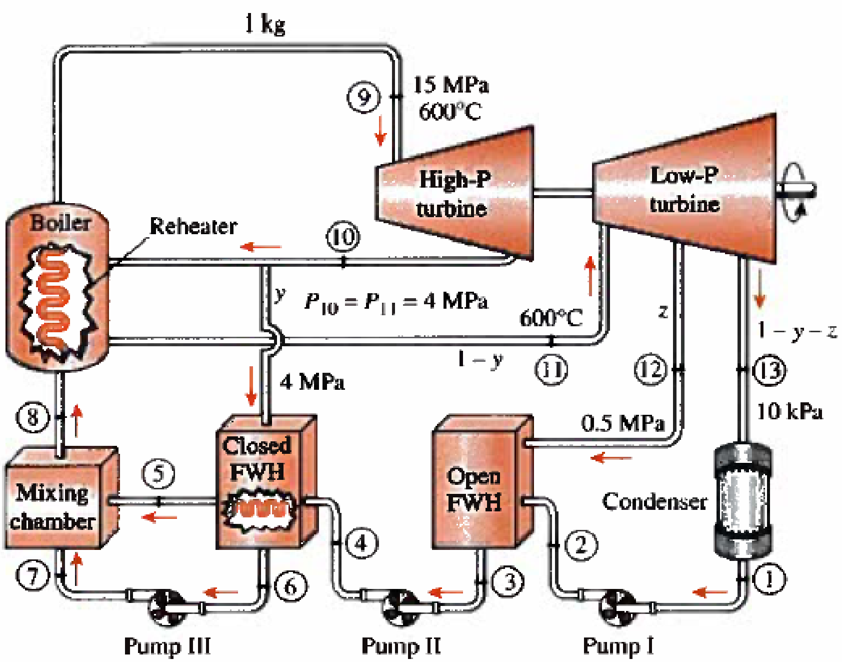


- A train of feedwater heaters is common in power plants, they significantly improve the efficiency

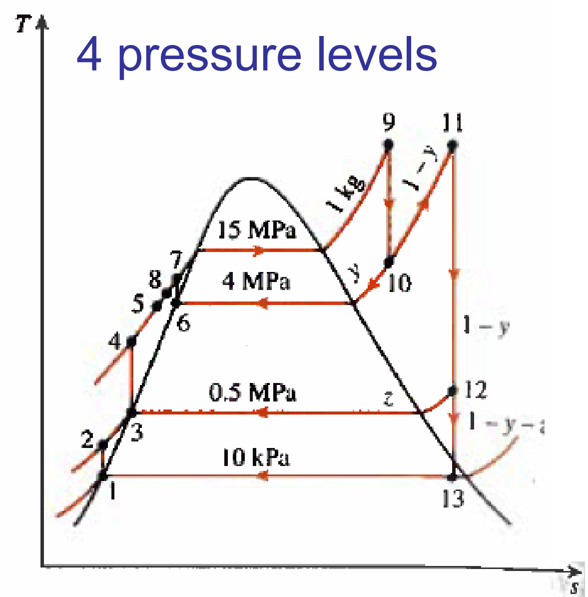


Combination of Reheater, Open and Closed FWH

- Most systems used for power generation are complicated systems combining two or more turbines with reheating and several open and closed feed water heaters
- To derive the thermal efficiency all power in- and outputs should be considered
- Thermal efficiency: $\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{out-HPT}+\dot{W}_{out-LPT}-\dot{W}_{in-p1}-\dot{W}_{in-p2}-\dot{W}_{in-p3}}{\dot{Q}_{in-boiler}+\dot{Q}_{in-reheater}}$



4 pressure levels



6 mass flows:

$\dot{m}_8 = \dot{m}_9 = \dot{m}_{10}$

$\dot{m}_{13} = \dot{m}_1 = \dot{m}_2$

$\dot{m}_3 = \dot{m}_4 = \dot{m}_5$

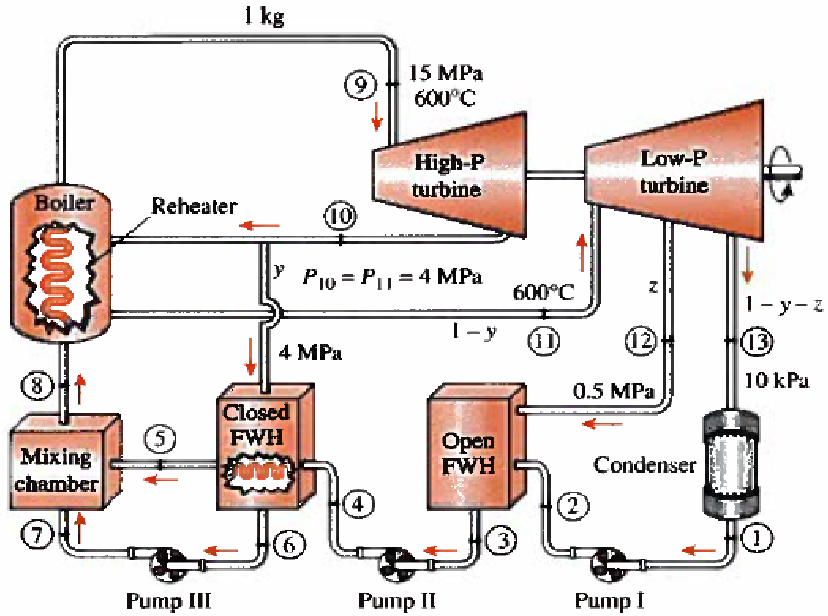
$\dot{m}_6 = \dot{m}_7$

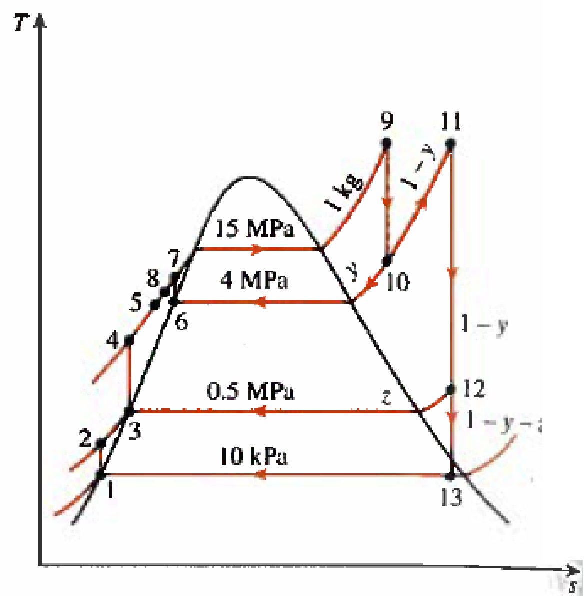
$\dot{m}_{12}$ & $\dot{m}_{11}$

Mass flows can be related using the mass balances and energy balances over the feedwater heaters

Combination of Reheater, Open and Closed FWH

$$\eta_{th} = \frac{\dot{m}_{10}(h_9 - h_{10}) + \dot{m}_{11}(h_{11} - h_{12}) + \dot{m}_{13}(h_{12} - h_{13}) - \dot{m}_{13}(h_2 - h_1) - \dot{m}_3(h_4 - h_3) - \dot{m}_6(h_7 - h_6)}{\dot{m}_{10}(h_9 - h_8) + \dot{m}_{11}(h_{11} - h_{10})}$$





6 mass flows:

$\dot{m}_8 = \dot{m}_9 = \dot{m}_{10}$

$\dot{m}_{13} = \dot{m}_1 = \dot{m}_2$

$\dot{m}_3 = \dot{m}_4 = \dot{m}_5$

$\dot{m}_6 = \dot{m}_7$

$\dot{m}_{12}$ & $\dot{m}_{11}$

Mass flows can be related using the mass balances and energy balances over the feedwater heaters

- 6 equations needed to find 6 mass flows
    1. Energy balances closed feed water heater: $\dot{m}_6(h_{10} - h_6) = \dot{m}_4(h_5 - h_4)$
    2. Energy balance open feed water heater: $\dot{m}_{12}h_{12} = \dot{m}_2 h_2 + \dot{m}_3 h_3$
    3. Mass balances open feed water heater: $\dot{m}_3 = \dot{m}_2 + \dot{m}_{12}$
    4. Energy balance mixing chamber: $\dot{m}_8 h_8 = \dot{m}_5 h_5 + \dot{m}_7 h_7$
    5. Mass balances mixing chamber: $\dot{m}_8 = \dot{m}_5 + \dot{m}_7$
    6. Finally a power input or output should be given to determine the main mass flow
- All h values can be found from the tables and / or diagrams

Co-generation / Combined heat and power

- So far, we have seen the simple Rankine cycle and we improved its efficiency by adding extra devices to build an as efficient as possible Rankine cycle
- These Rankine cycles are among the most commonly used vapor power cycles to generate electricity
- So far in all heat cycles discussed the **goal was to convert** an as large as possible portion of **the heat** transferred to the working fluid **into work** (the most valuable from of energy)
- However, some of the energy of the heat input, q_{in} can not be converted to work due to the restrictions of the second law, therefore heat, q_{out} from all heat cycles is "lost" to the surroundings (this represents significant energy losses)
- The loss of a heat cycle can be further reduced by using this rejected heat in a useful way

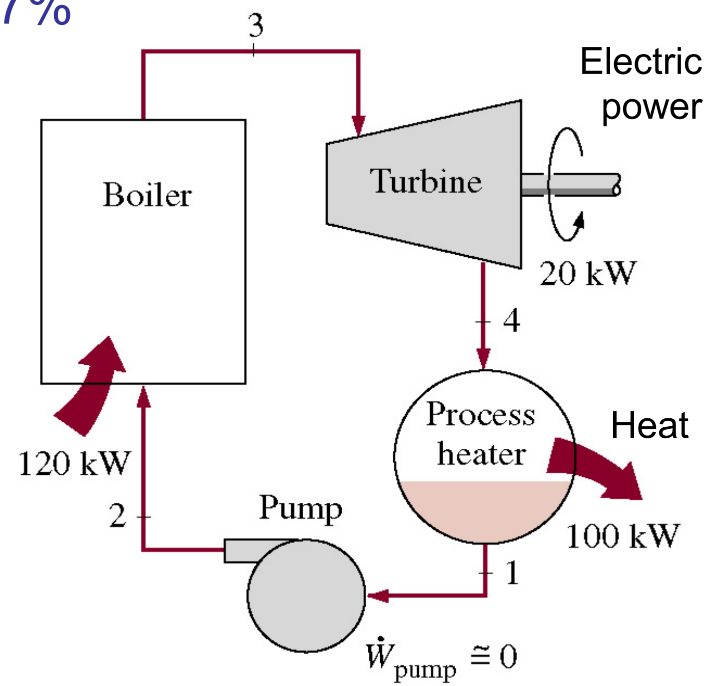
Co-generation / Combined heat and power

- To reduce the loss of a heat cycle the rejected heat should be used
- Sometimes a lot of heat (150 - 200°C) is needed for:
  - Process heating → E.g. desalination of seawater
  - Feedstock for chemical process
  - Local heating (city heating) → E.g. our university (need about 85°C)
  - Driving absorption air-conditioning cycle
- Bleed steam from the turbine and use it for heating, doing so more or even all energy from the input heat can be used
- **Co-generation** or **combined heat and power** (CHP) is the production of more than one useful form of energy (such as process heat and electric power) from the same energy source
- This way a power plant can produce electricity while meeting the process-heat requirements of certain industrial processes or heat for heating houses

Ideal co-generation Rankine Cycle Plant

- Consider a simple ideal co-generation power plant
- The thermal efficiency of this plant is only 17%

$$\eta_{HE} = \frac{w_{OUT} - w_{IN}}{q_{IN}} = \frac{20}{120} = 0.17$$

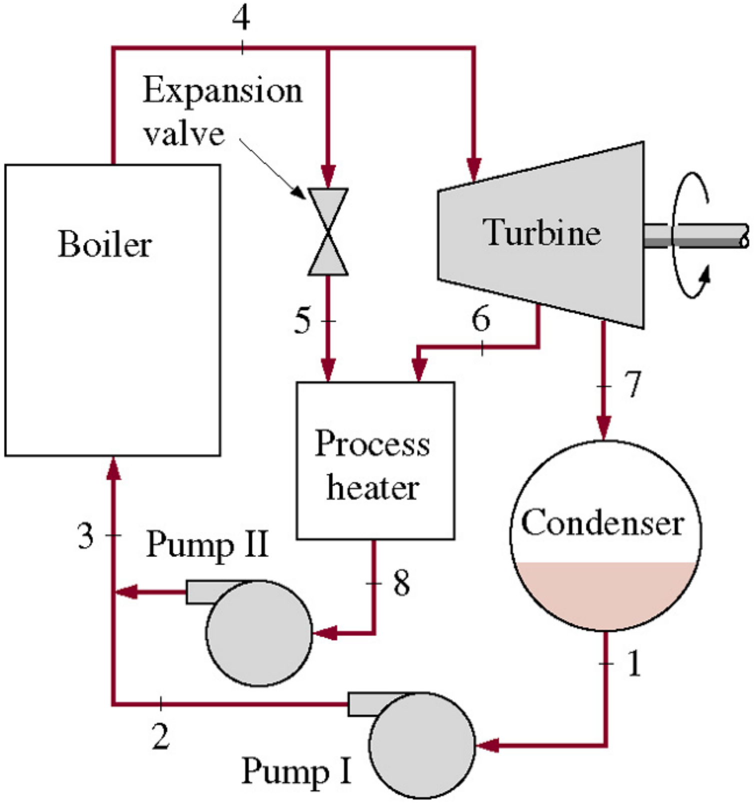


- However, in addition to the work delivered the heat rejected in, what is called, the process heater (100 kW) is also useful
- This reduces the energy loss
- As this is a different form of energy it is not considered in the thermal efficiency, but it is considered in a different number
- The **utilization factor**, ε_u is defined as: $\varepsilon_U = \dfrac{Network-output+Process-heat}{Total-heat-input}$
- For this ideal co-generation cycle: $\varepsilon_U = \dfrac{W_{NET} + Q_{PROCESS}}{Q_{IN}} = 1$

Co-generation plant with adjustable loads

- The ideal co-generation or CHP plant of the previous slide is not practical because it cannot adjust to variations in power and process-heat loads

- A more practical but more complex plant has the ability to adjust the heat and power by adjusting the mass flows through point 5, 6 and 7



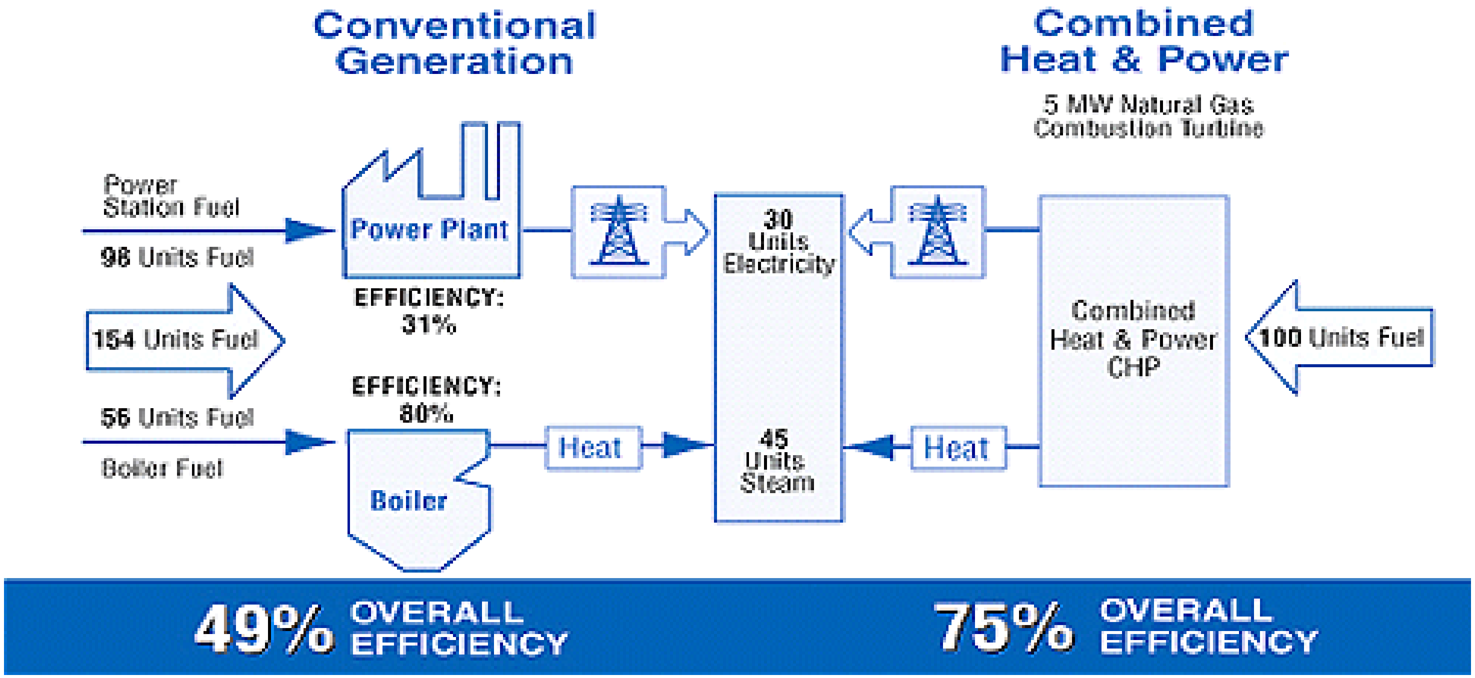
- No power and maximum heat is produced when $m_4 = m_5$ ($m_6 = m_7 = 0$)

- Maximum power and no heat is produced when $m_4 = m_7$ ($m_6 = m_5 = 0$)

- Under optimal conditions the plant simulates the ideal plant and all fluid goes via point 6 ($m_7 = m_5 = 0$)

Combined Heat and Power System

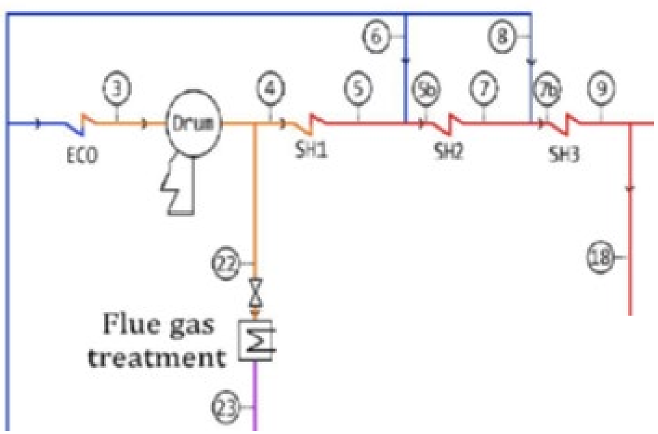
- The overall efficiency or utilization factor of conventional generation versus combined heat and power (CHP)



Example of a typical CHP system, to produce 75 units of useful energy (30 in the form of electricity and 45 in the form of steam), the conventional generation or separate heat and power systems use 154 units of energy—98 for electricity production and 56 to produce heat—resulting in an overall efficiency of 49 percent. However, the CHP system needs only 100 units of energy to produce the 75 units of useful energy from a single fuel source, resulting in a total system efficiency of 75 percent (http://epa.gov/chp/basic/efficiency.html)

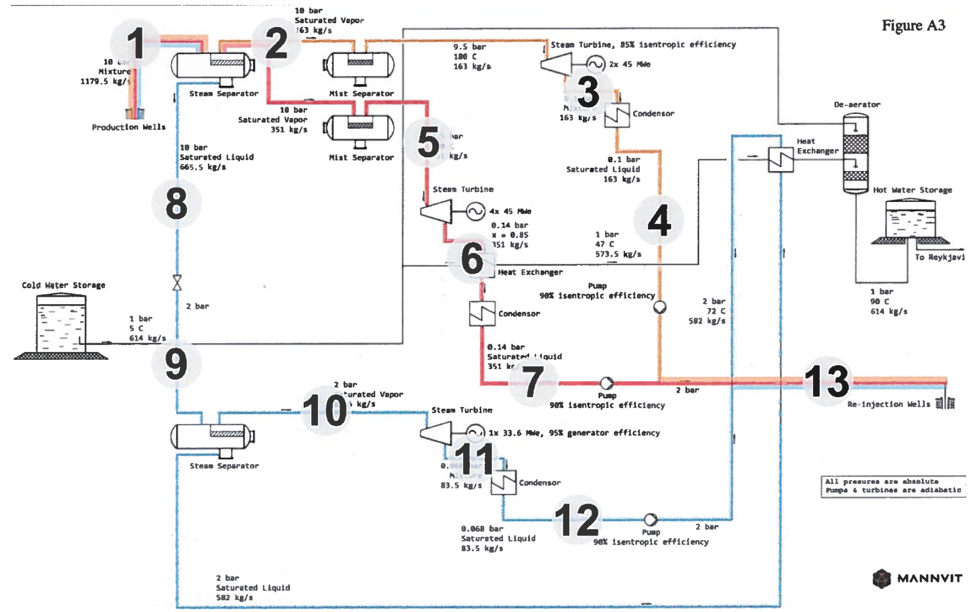
Example of real power systems

- The cycles we have seen so far are all simplified
- Real cycles are way more complicated
- They have a lot of additional devices, tubes and valves to control the flows
- Small additional flows and valves for regulation of the flow are present
- Heat losses in the pipes and tubes occur
- Pressure drops occur over the pipes and devices like boilers, condensers, heat exchangers
- Steam separators and deaerators are present to get rid of unwanted droplets or air in the working medium
- Additional devices to clean flue gasses can be present

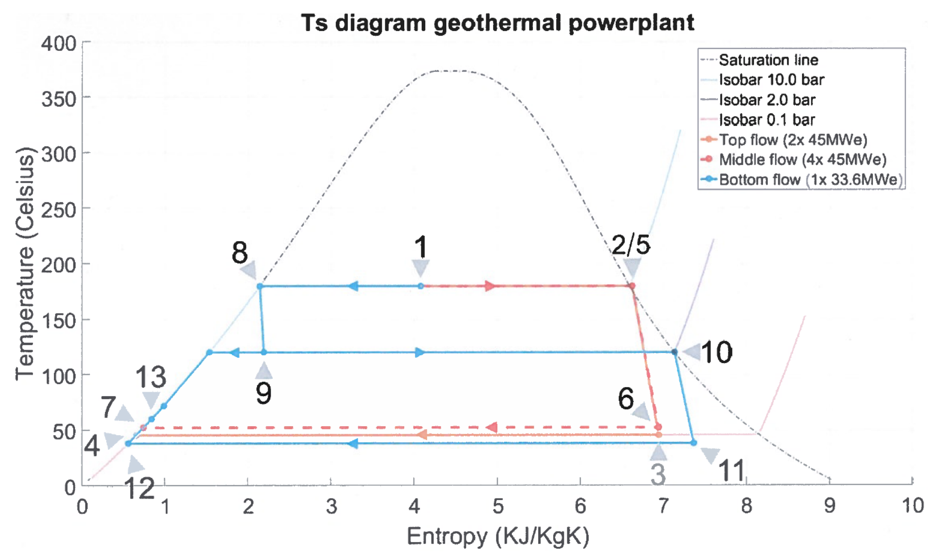


Boiler of a biomass power plant. Due to variations in the composition of biomass the temperature in the boiler can vary. The cold blue flows are used to control the temperature of the red hot flow going to the turbine. A little bit of the saturated steam is tapped and used to clean the flue gases.

Geothermal Power Plant, Hellisheiði, Iceland

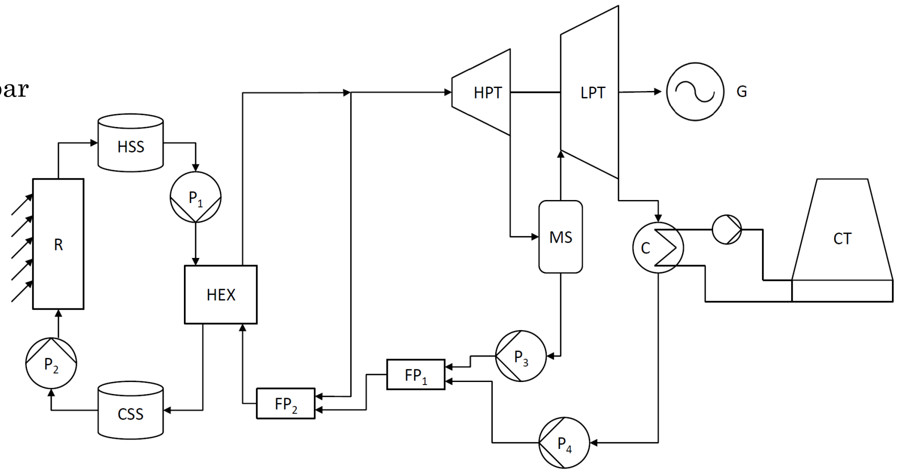


This power plant uses geothermal heat that has absorbed inside the thick layer of melted hot rock beneath the earth's crust, called magma.
The power plant generates electricity as well as heat for district heating.
The net power output is around 300 MW and the heat supplied to the city is in the order of 230 MW.
The thermal efficiency of the cycle is around 19% while the utilization factor is around 32%.
The main mass flow in the cycle is 1180 kg/s.

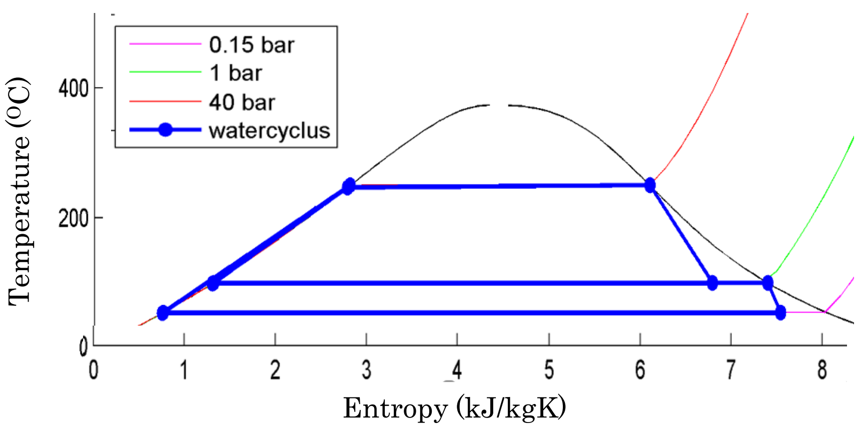


PS 10 Solar Power Plant, Seville, Spain

Temperature cold salt	247C
Temperature hot salt	565C
HEX steam outlet	x = 1 @ 40 bar
Net solar power absorption	50.8 MW_{th}
Efficiency salt system	94%
Efficency heat exchanger	100%
HPT exhaust pressure	1.0 bar
HPT exhaust moisture content	10 wt%
LPT exhaust pressure	0.15 bar
LPT exhaust moisture content	7 wt%
Generator nominal efficiency	95%
Pump 3 isentropic efficiency	91%
Pump 4 isentropic efficiency	88%
Feedwater preheater pressure	40 bar

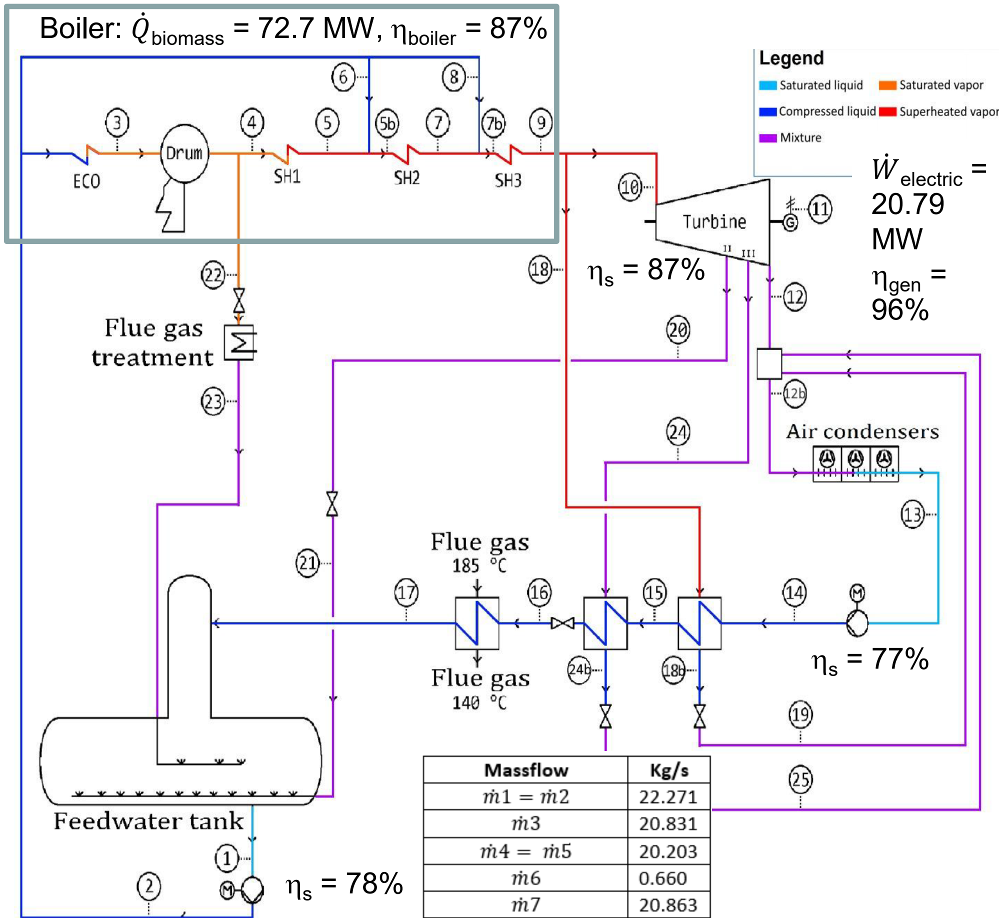


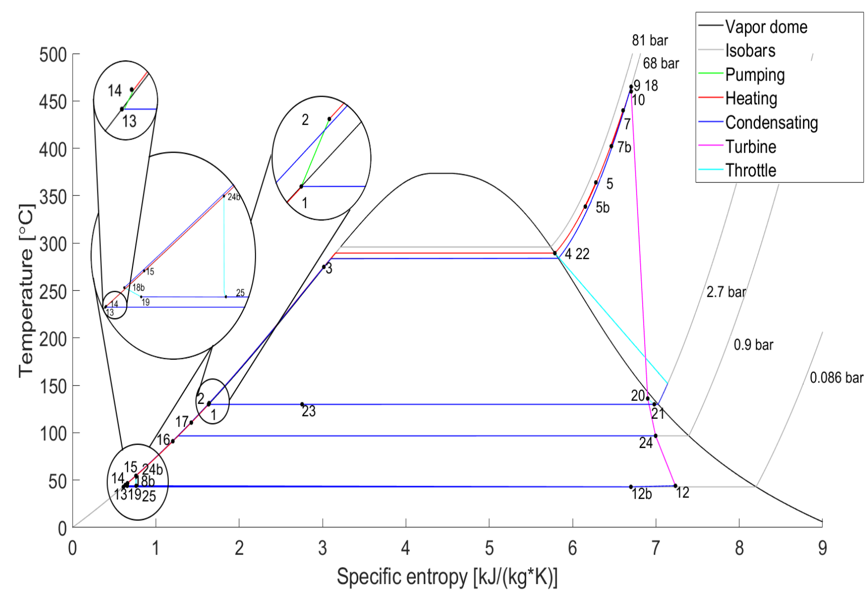
HPT	High pressure turbine
LPT	Low pressure turbine
HEX	Heat exchanger
CSS	Cold salt storage
HS	Hot salt storage
P1	Pump 1
P2	Pump 2
P3	Pump 3
P4	Pump 4
SS	Steam separator
FP1	Feedwater preheater 1
FP2	Feedwater preheater 2
R	Solar radiation receiver
C	Condenser
G	Generator
CT	Cooling tower



Simplified flow scheme with added salt storage and data of the PS10 solar power plant in Seville, Spain. Analysing the cycle results in a thermal efficiency of only 21%. The net power output is around 10 MW. The main mass flow of the water is 28 kg/s and of the salt 97 kg/s.

Twence Biomass Power Plant, Hengelo, NL

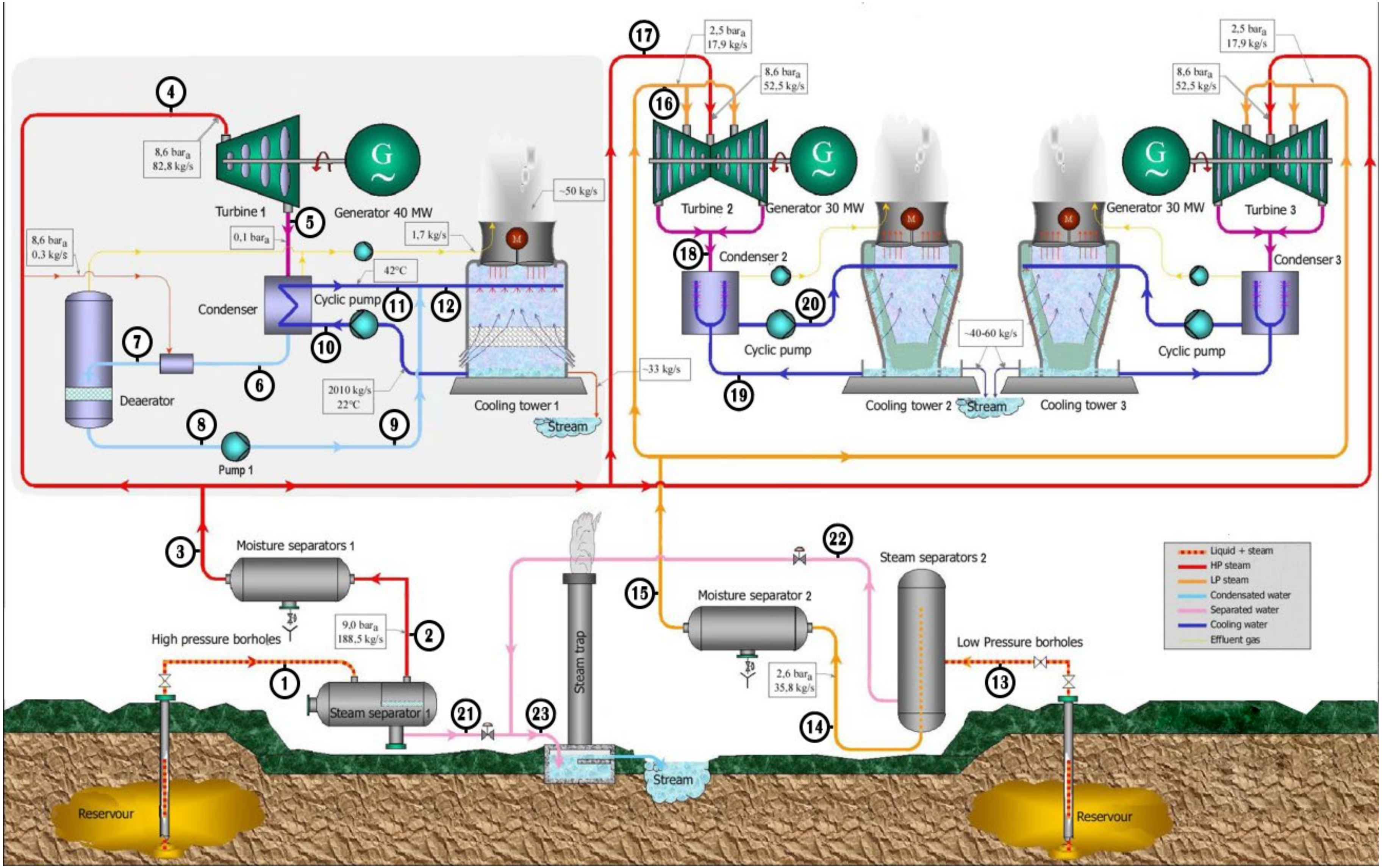




Massflow	Kg/s
$\dot{m}1 = \dot{m}2$	22.271
$\dot{m}3$	20.831
$\dot{m}4 = \dot{m}5$	20.203
$\dot{m}6$	0.660
$\dot{m}7$	20.863
$\dot{m}8$	0.780
$\dot{m}9$	21.643
$\dot{m}10$	21.539
$\dot{m}12$	19.180
$\dot{m}13 = \dot{m}14 = \dot{m}15 = \dot{m}16 = \dot{m}17$	20.979
$\dot{m}18 = \dot{m}19$	0.104
$\dot{m}20 = \dot{m}21$	0.664
$\dot{m}22 = \dot{m}23$	0.628
$\dot{m}24 = \dot{m}25$	1.695

Thermal efficiency 34%
Overall efficiency 29%

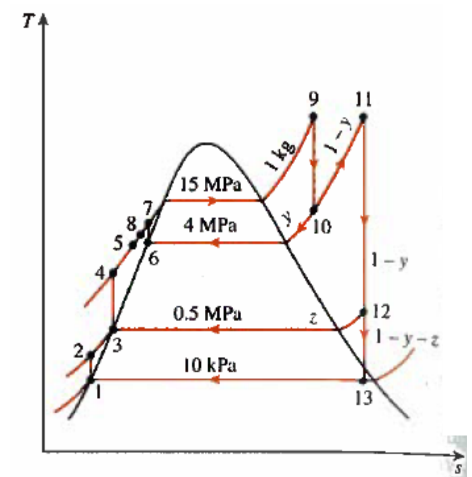
Landsvirkjun geothermal power plant, Iceland



Geothermal power plant to be analysed in this years project for first year BSc ME students

Recapitulate Class 8

- Designing a simple Rankine cycle
  - Design parameters: turbine inlet P & T, condenser P & T
- Improve the efficiency of the Rankine cycle by adding extra devices
  - Extra heater → reheating
  - Open & closed feedwater heater → regenerative feedwater heating
- Thermal efficiency: $\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{out-HPT}+\dot{W}_{out-LPT}-\dot{W}_{in-p1}-\dot{W}_{in-p2}-\dot{W}_{in-p3}}{\dot{Q}_{in-boiler}+\dot{Q}_{in-reheater}}$
- Take the mass flows into account and relate the mass flows using:
  - Energy balances closed feed water heater
  - Energy balances mixing chambers / OFWH'ers
  - Mass balances mixing chambers / OFWH'ers
- The energy loss can be reduced by combining heat & power generation (Co-generation)
- Examples of real power plants



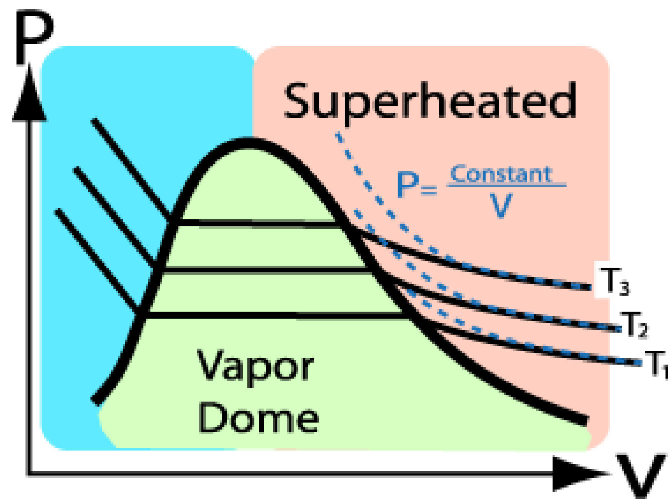
Ts-diagram Rankine cycle with reheating and feed water heating

Next Class 9: Properties of gases

- In class 7 & 8 we met the **vapor power cycle,** a cycle using **a working fluid that undergoes a phase transition** through the cycle (Rankine cycle)

- The subject of class 10 & 11 is the **gas power cycle**, a cycle using **gas as working** fluid through the whole cycle (Brayton cycle)

- In class 9 we will see how we can get energy values for air or other gases, like we learned in class 3 for water
  - Diagrams and tables
  - Ideal gas law, $Pv = RT$
- Internal energy for ideal gas
- Enthalpy for ideal gas
- Entropy changes for ideal gas
- Specific heat capacities for gases
  - C_p: for constant pressure
  - C_v for constant volume



Keep in mind: Important Formulas

- Specific volume $v = V/m$ [m^3/kg] and density $\rho = 1/v = m/V$ [kg/m^3]
- 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