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B-KUL-Z55337
Applied Thermodynamics

Sylvain Quoilin

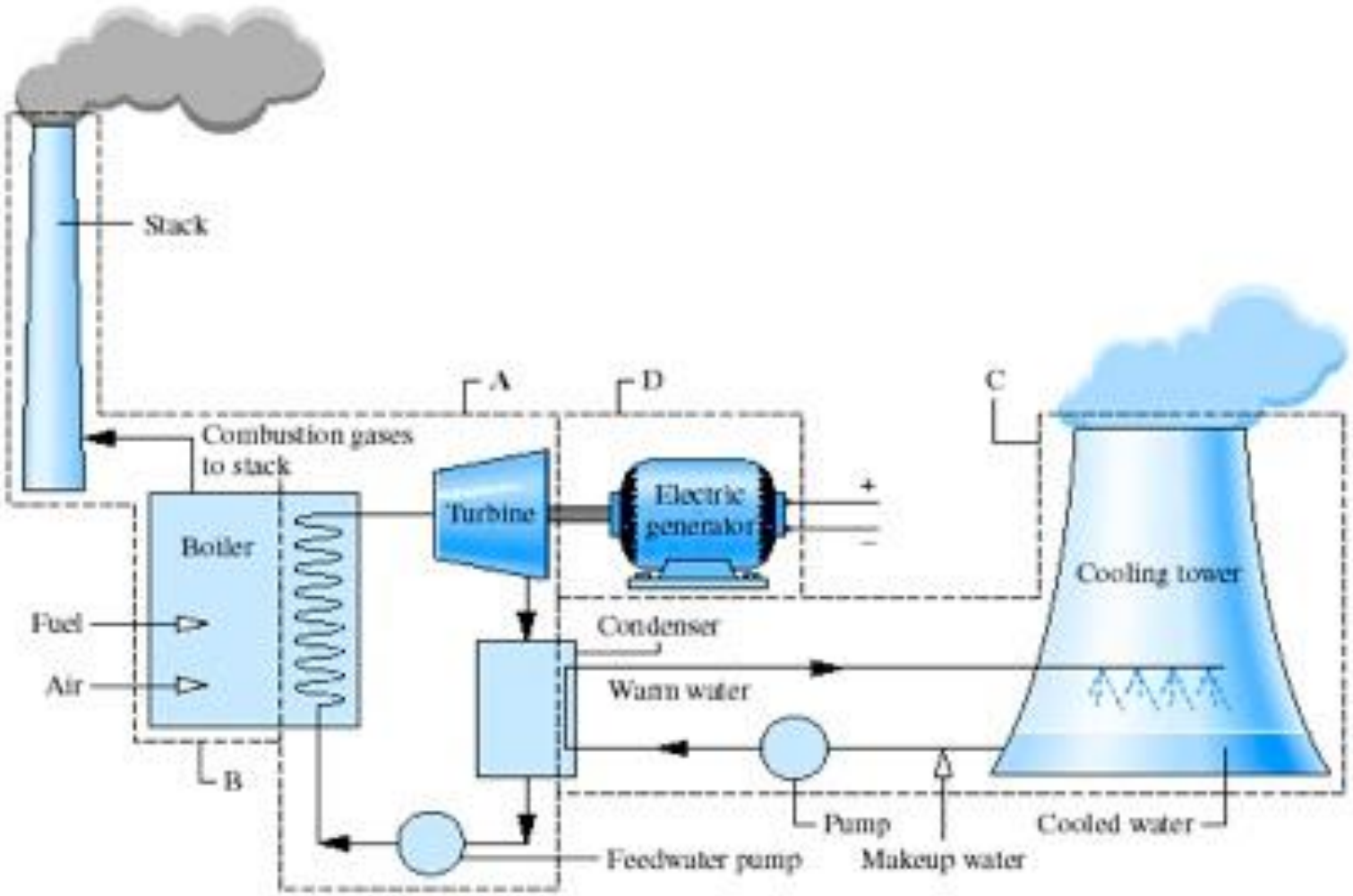
Adapted from: Y.A. Cengel, M. A. Boles, Thermodynamics – An Engineering Approach (5th Edition)

Chapter 9

Vapor and Combined Power Cycles

(NB: this corresponds to the Chapter 10 of the reference book)

Vapor power plants



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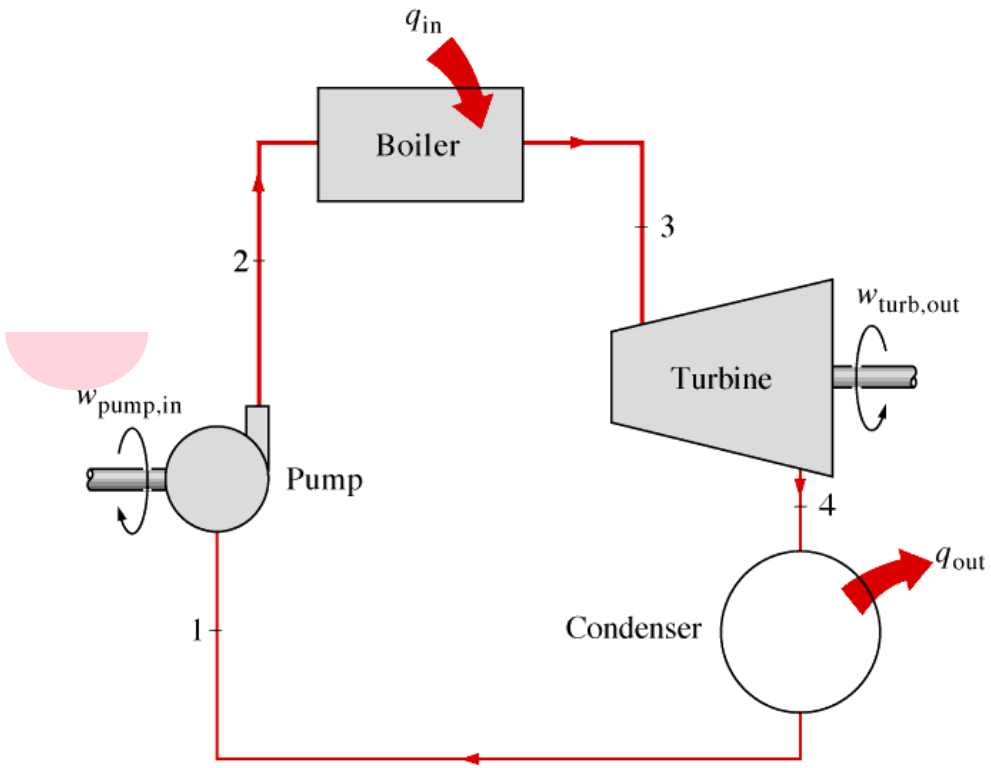
The ideal Rankine Cycle

- Steam power plants are very common (nuclear, coal, natural gas).
- They take profit of the phase transition of the working fluid (water in most cases)
- The Rankine cycle is the ideal cycle for vapor power plants. It is composed of the following processes:
  - 1-2 Isentropic compression in a pump
  - 2-3 Constant pressure heat addition in a boiler
  - 3-4 Isentropic expansion in a turbine
  - 4-1 Constant pressure heat rejection in a condenser



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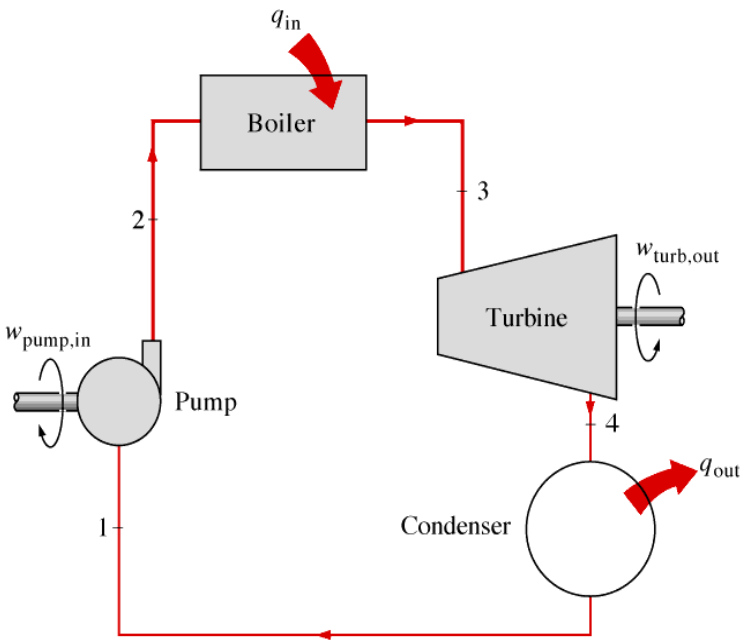
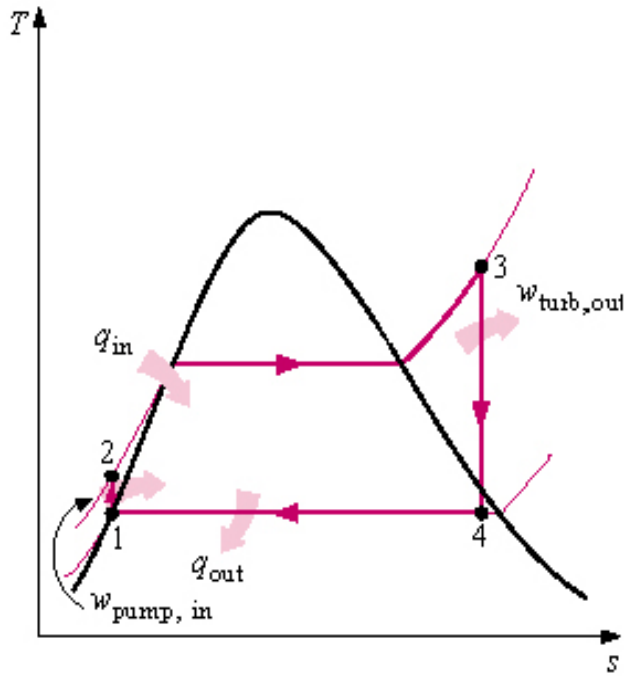
The ideal Rankine Cycle





First law of thermodynamics for open systems applied to each cycle component:

$$w_{\text{pump,in}} = h_2 - h_1$$

$$q_{\text{in}} = h_3 - h_2$$

$$w_{\text{turb,out}} = h_3 - h_4$$

$$q_{\text{out}} = h_4 - h_1$$

First law of thermodynamics:

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = w_{\text{turb,out}} - w_{\text{pump,in}}$$

Cycle efficiency:

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}$$

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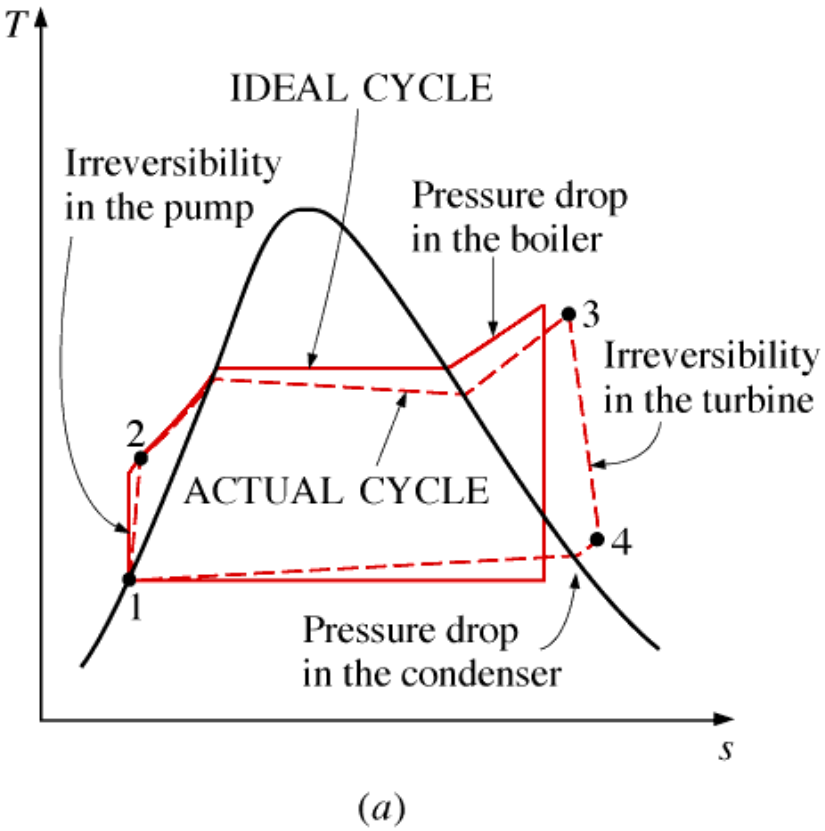
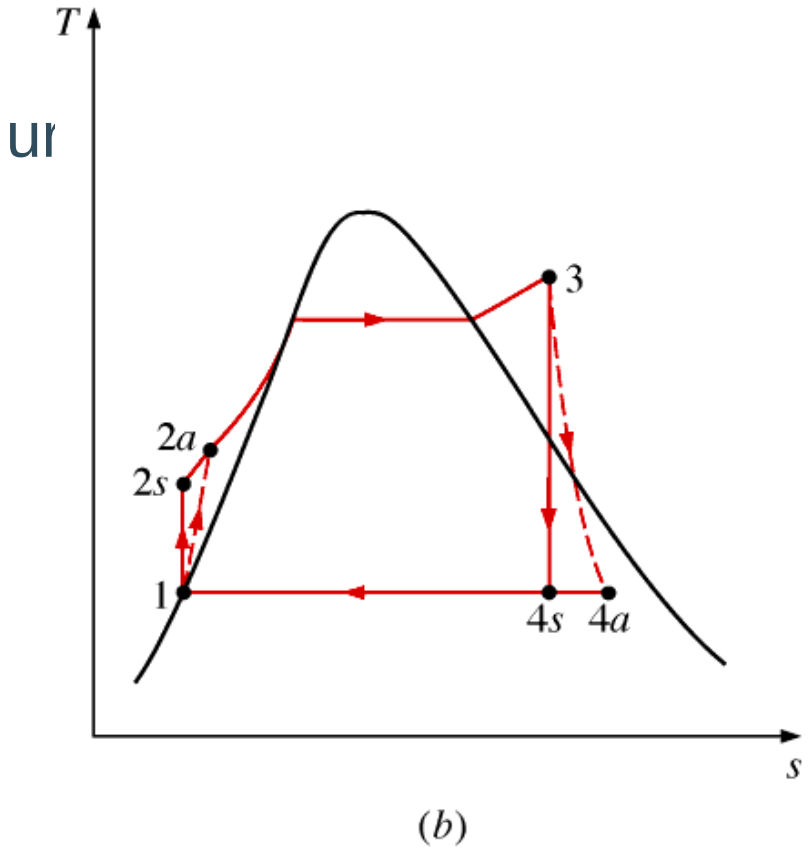
Ideal Rankine cycle vs real vapor cycle





Isentropic efficiency (reminder):

Pump: $$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

Turbine: $$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

(*a*) Deviation of actual vapor power cycle from the ideal Rankine cycle. (*b*) The effect of pump and turbine irreversibilities on the ideal Rankine cycle.

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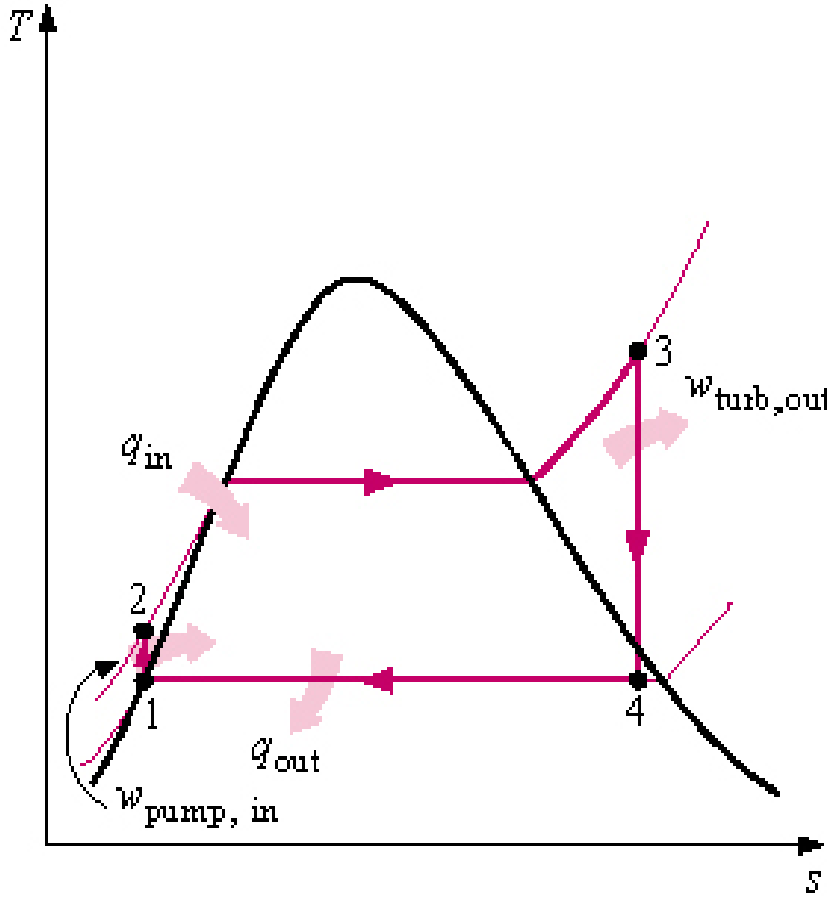
Increasing the efficiency of the Rankine cycle

Basic idea (as for the Carnot cycle):

- Increase the average temperature at which heat is transferred to the working fluid in the boiler (process 2-3)
- decrease the average temperature at which heat is rejected from the working fluid in the condenser (process 4-1).

We will therefore consider the ***average*** temperature in the boiler and in the condenser as good indicators of the cycle efficiency



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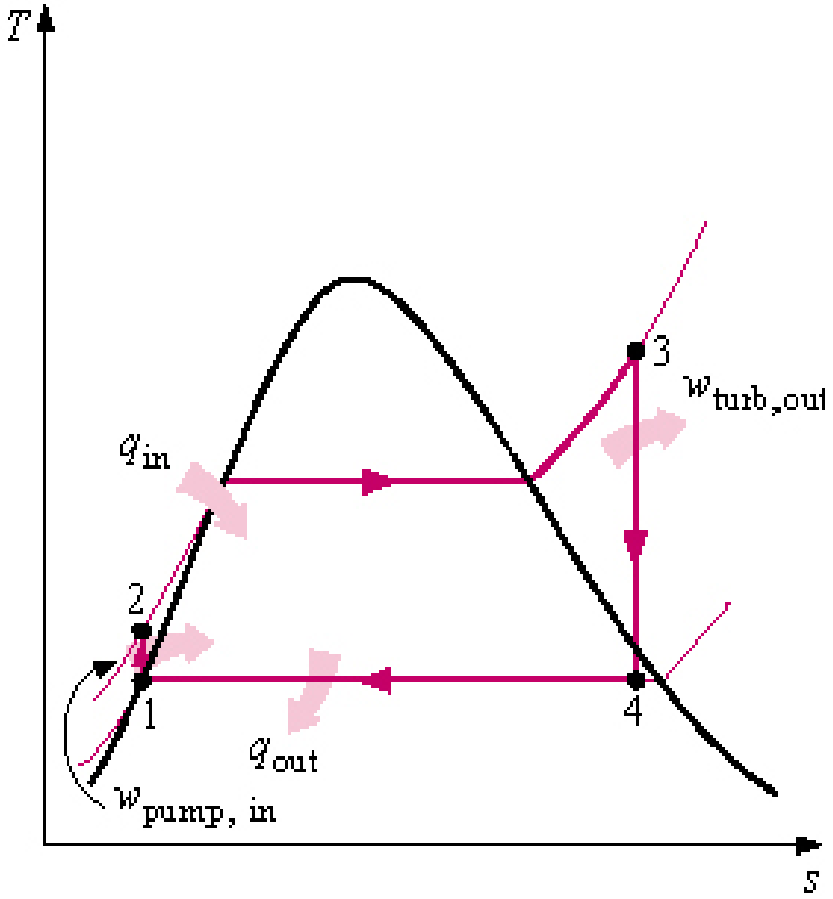
Practical limitations in a Rankine cycle

- The highest temperature in the cycle (T_3) is located at the turbine inlet. It limited (currently to about 620°C) by the materials used in this turbine.
- The vapor quality after the expansion (point 4) should remain above a certain threshold (about 87%). High quantities of moisture decrease the turbine efficiency and erode the turbine blades.



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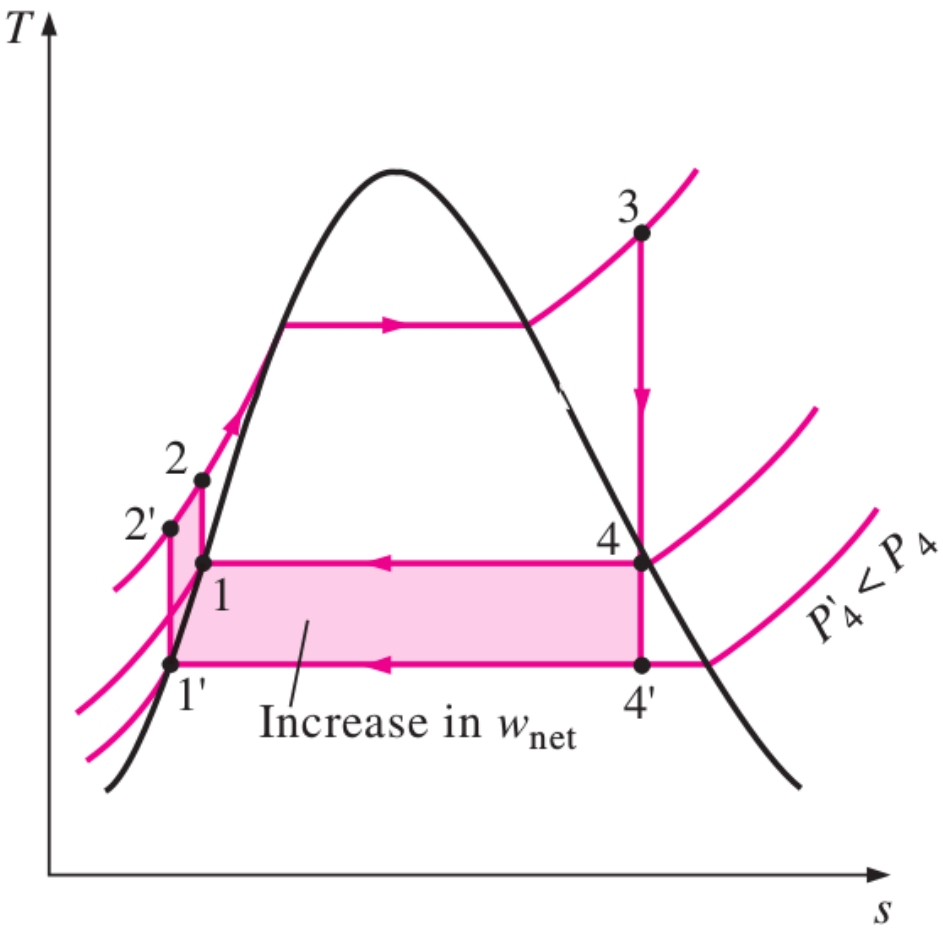
Increasing the efficiency of the Rankine cycle

Reduction of the condensing pressure:

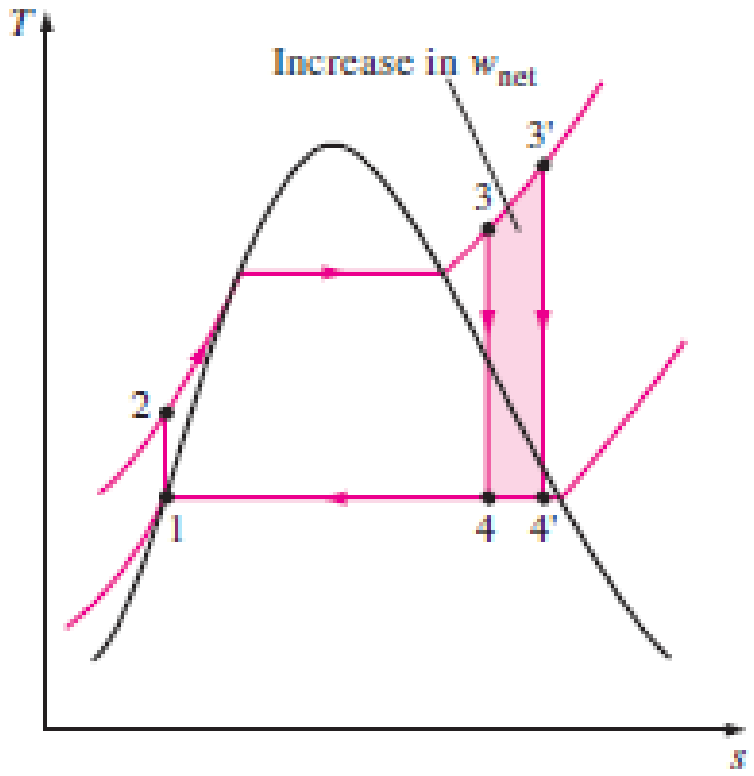
- Increase of the pressure difference between the inlet and the outlet of the turbine
- Increase in the net work output (given by the area of the cycle in the T-s diagram)
- Increase of the thermal efficiency
- Constraint: the condensing temperature cannot be lower than the heat sink temperature



Increasing the efficiency of the Rankine cycle

Superheating to higher temperatures:

- The boiler pressure remains the same
- However, the average temperature at which the heat is transferred is increased
- Therefore the thermal efficiency is increased
- The net work is increased (see T-s diagram)
- Other very useful effect: increase of the vapor quality at point 4. High moisture content



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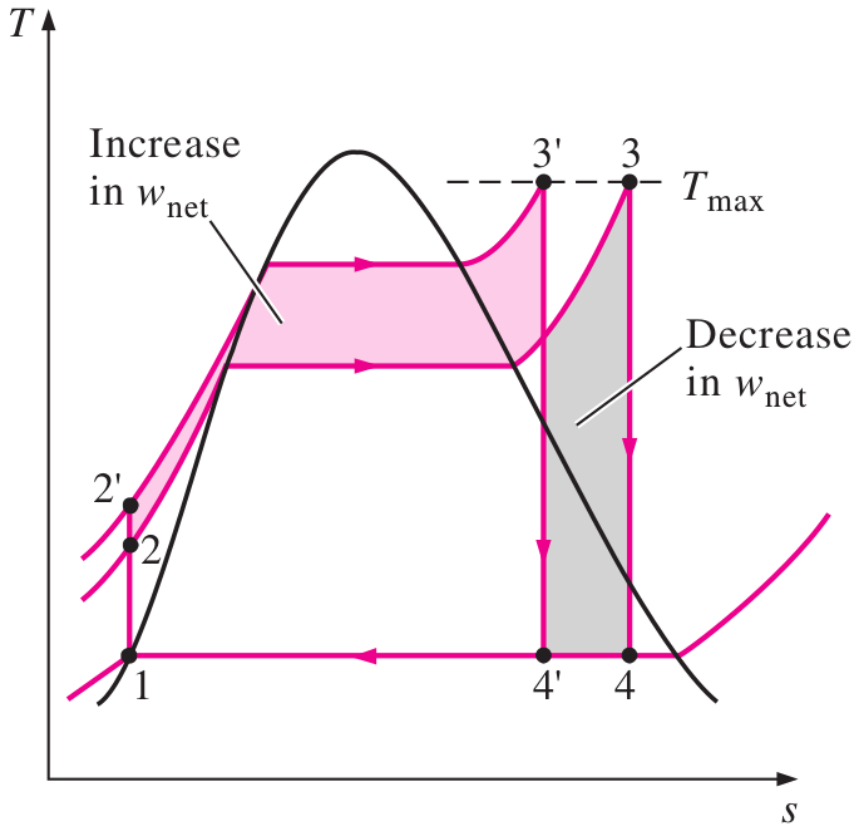
Increasing the efficiency of the Rankine cycle

Increasing the boiler pressure:

- Increase of the average temperature in the boiler
- Increase of the cycle thermal efficiency
- Decrease of the vapor quality after the expansion (4 -> 4’), which should however not go below the threshold
- Ambiguous effect on the net work output



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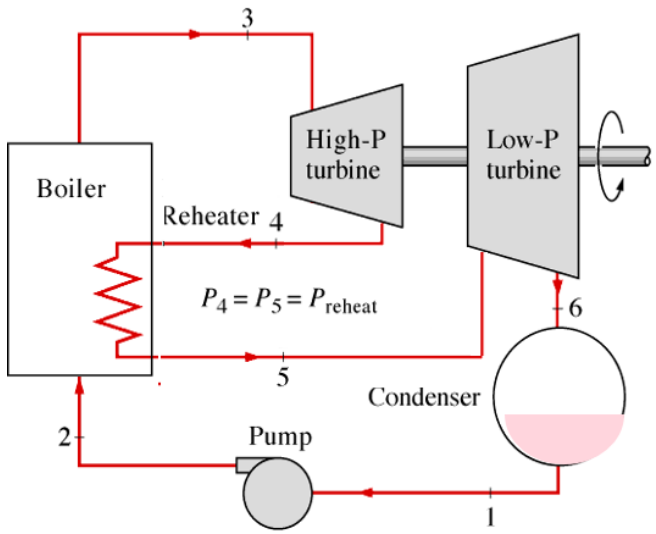
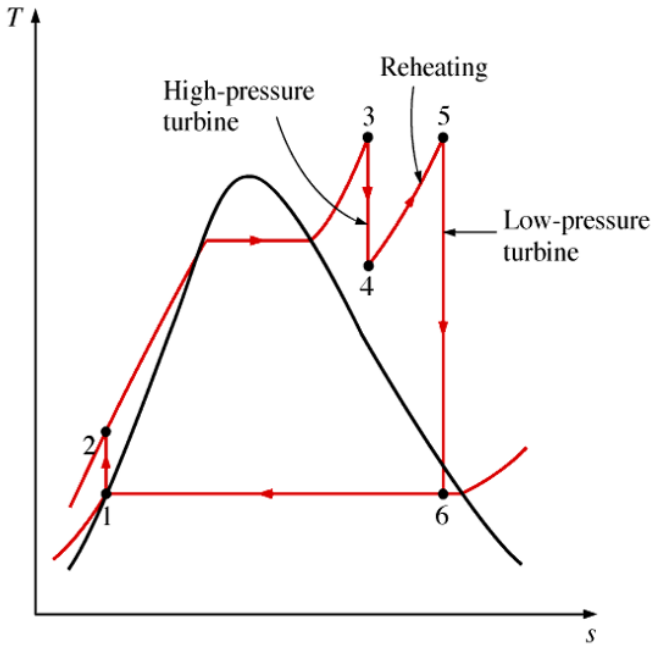
The ideal reheat Rankine cycle

Goal: increase the boiler pressure without facing the problem of excessive moisture at point 4

- The expansion is interrupted and the vapor is re-heated in the boiler
- This displaces the expansion to the right of the T-s diagram
- Average boiler temperature is increased => efficiency is increased
- The vapor quality is increased, which allows increasing the boiler pressure





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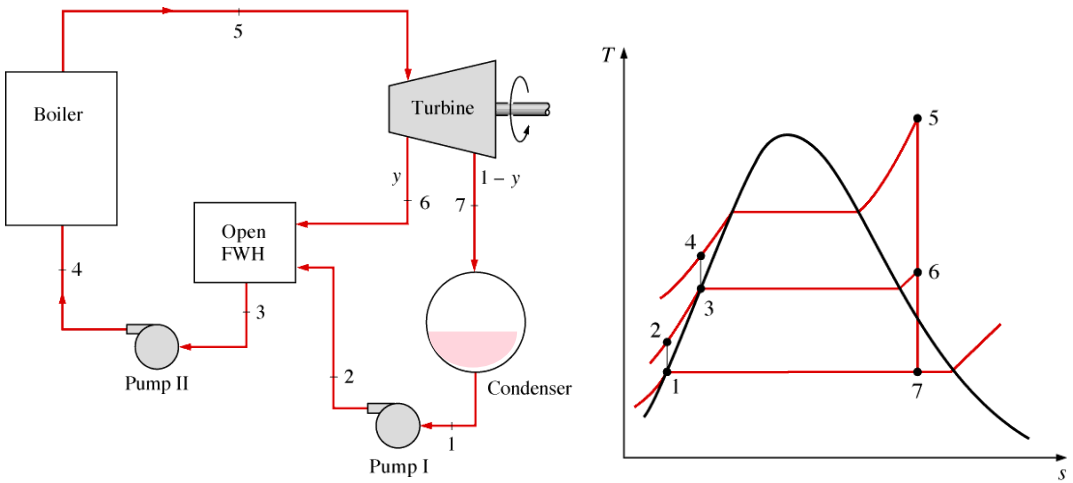
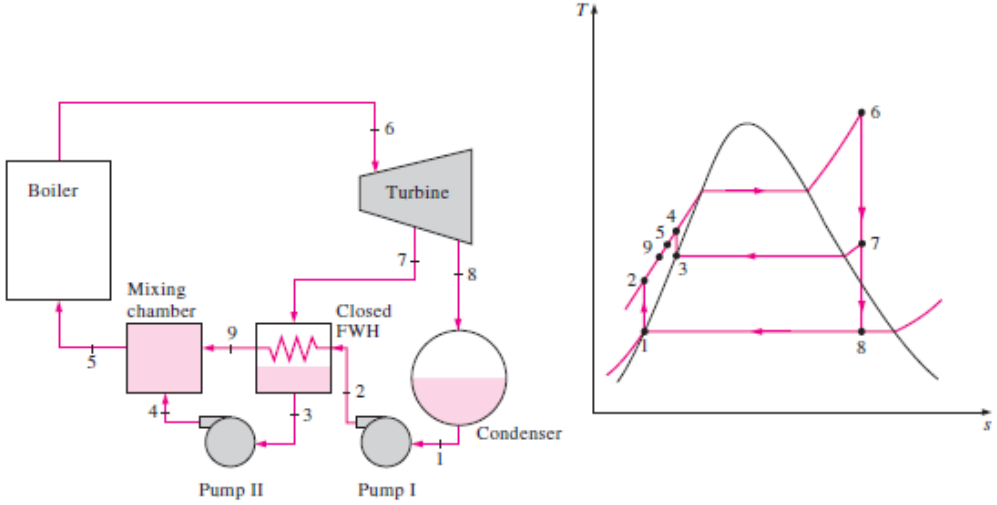
The ideal regenerative Rankine cycle

- A part of the steam is bled from the turbine during the expansion
- This steam is used to pre-heat the liquid water before the boiler
- Two possibilities:
  - Open feedwater heaters: the vapor and the liquid are mixed
  - Closed feedwater heaters: a heat exchanger is used
- The efficiency is increased since the average temperature in the boiler is increased
- The power generation is slightly reduced since the extracted flow does not produced work





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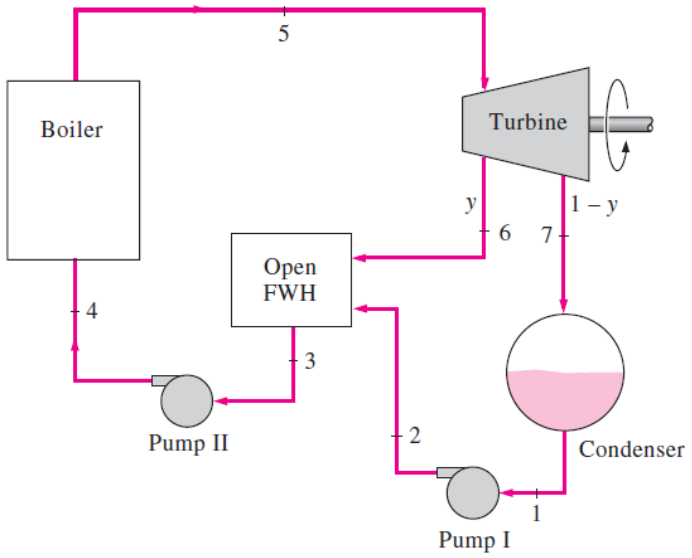
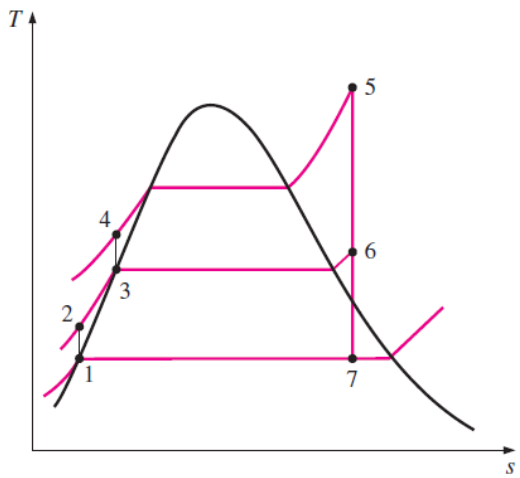
Modeling the regenerative cycle

- The fraction of the flow that is bled from the turbine is y
- For each kg of fluid leaving the boiler, *y* kg only partially expand
- (*1-y*) kg flow to the main condenser
- In the mixing chamber, by application of the first law (W=0, Q=0):
  $h_3 = (1-y) * h_2 + y * h_6$





$$q_{in} = h_5 - h_4$$

$$q_{out} = (1 - y)(h_7 - h_1)$$

$$w_{turb,out} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

$$w_{pump,in} = (1 - y)w_{pump\ I,in} + w_{pump\ II,in}$$

$$y = \dot{m}_6/\dot{m}_5$$

$$w_{pump\ I,in} = v_1(P_2 - P_1)$$

$$w_{pump\ II,in} = v_3(P_4 - P_3)$$

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Common heat sources for Rankine cycles

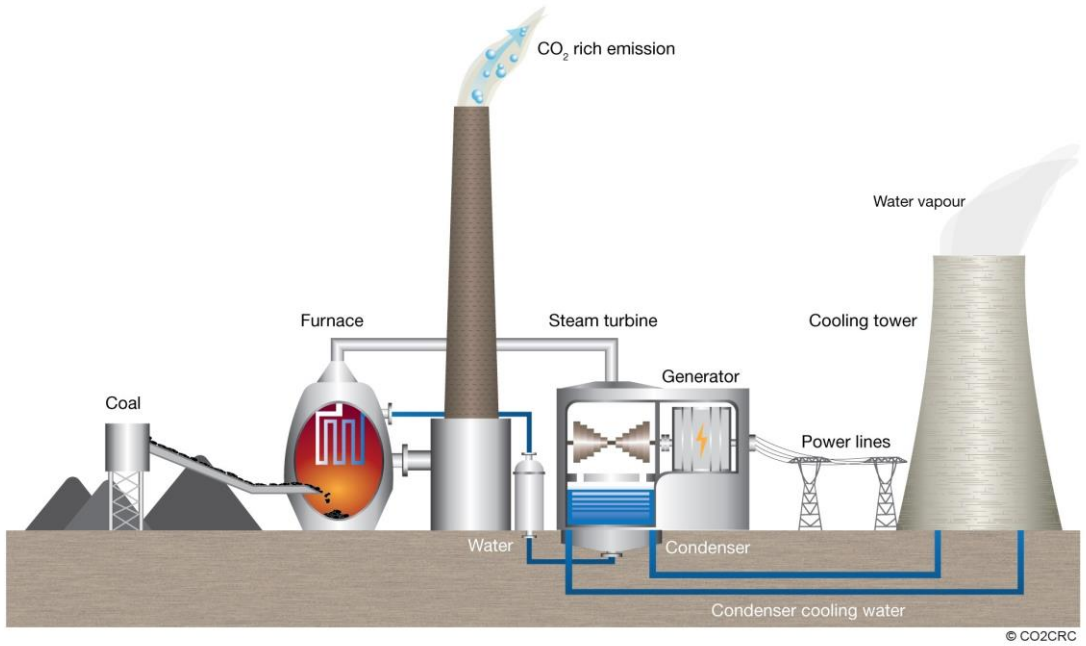
- Boiler using **fossil fuels:**
  - High temperature heat source => P_{max} can be high
  - If P_{max} > 22 MPa => supercritical cycle.
- **Nuclear** reactor (PWR : 15 MPa and Tmax: 300°C).
  - The boiler is replaced by a heat exchanger
  - No superheating!
  - Tmax ≈ 290°C, Pmax ≈ 7MPa
- Exhaust gases of a **gas turbine**
  - This becomes a combined cycle gas turbine (CCGT), as described later in the slides
  - The boiler is replaced by a Heat Recovery Steam Generator (HRSG)

Adapted from: Y.A. Cengel, M. A. Boles, Thermodynamics – An Engineering Approach (5th Edition)

Coal power plants

Ex: Neurath, Germany

- Two main types of fuel:
  - Lignite (brown coal)
  - Black coal
- Typical efficiency (depending on the technolgy): 35-43%
- CO2 emissions: ~900 kg CO2/MWh
- The new power plants use a pressure higher than the critical pressure => supercritical (SC) or ultra-supercritical (USC) power plants



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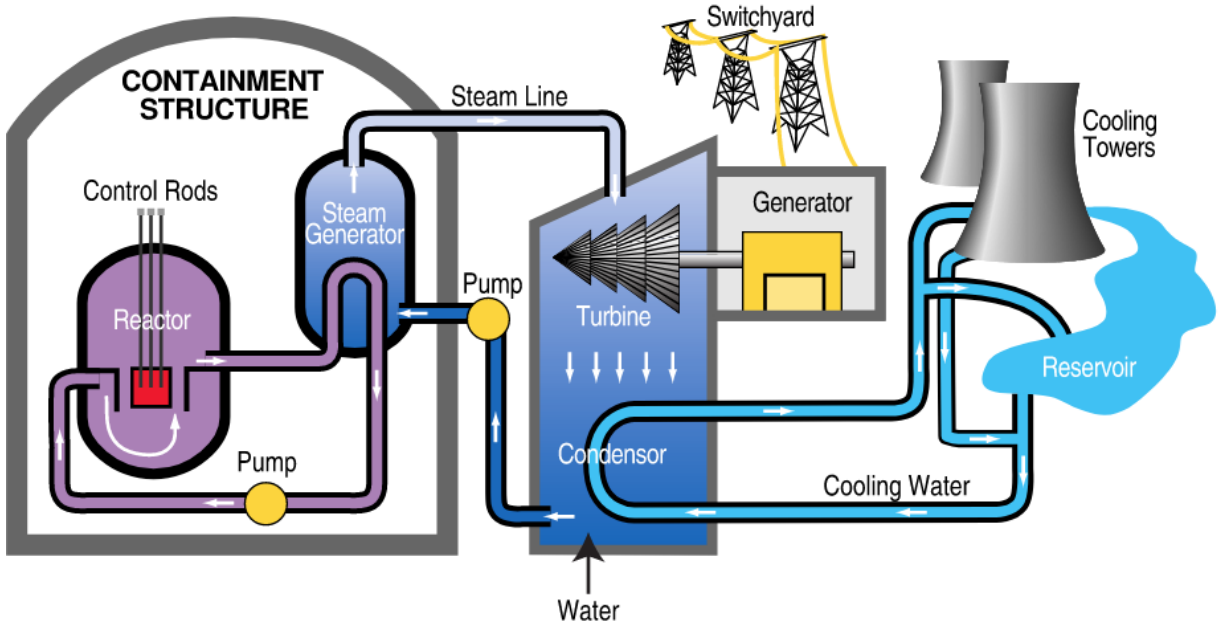
Nuclear power plants

Ex: Tihange, Belgique

- Typical efficiency: 33%
- Various technologies:
  - Pressurized water reactor
  - Boiling water reactor
  - …
- CO2 emissions are negligible during operation
- Issues and current debate with the nuclear fuel:
  - Nuclear waste
  - Nuclear proliferation
  - Nuclear safety



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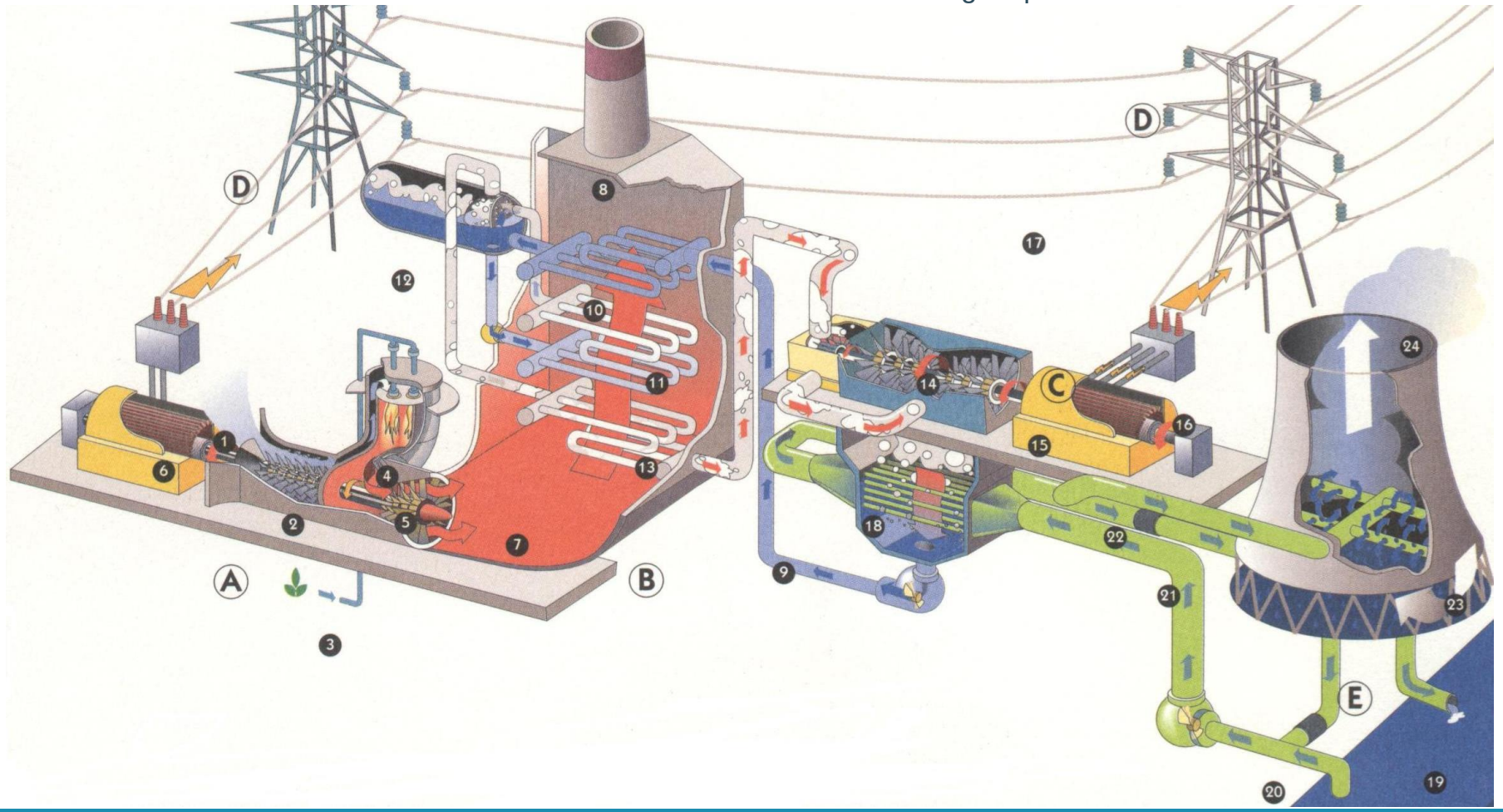
CCGT Power plant

A. Gas turbine
B. HRSG
C. Steam turbine
D. Grid
E. Cooling loop

1. Air intake
2. Compressor
3. Natural gas line
4. Combustion chamber
5. Expander (=turbine)
6. Alternator
7. Combustion gases
8. Stack
9. Liquid feedwater
10. Economizer
11. Vaporizer
12. Steam drum
13. Superheater
14. Steam turbine
15. Alternator
16. Transformer
17. High voltage line
18. Condenser
19. River
20. Makeup water
21. Cold cooling water
22. Warm cooling water
23. Updraft air stream
24. Water vapor



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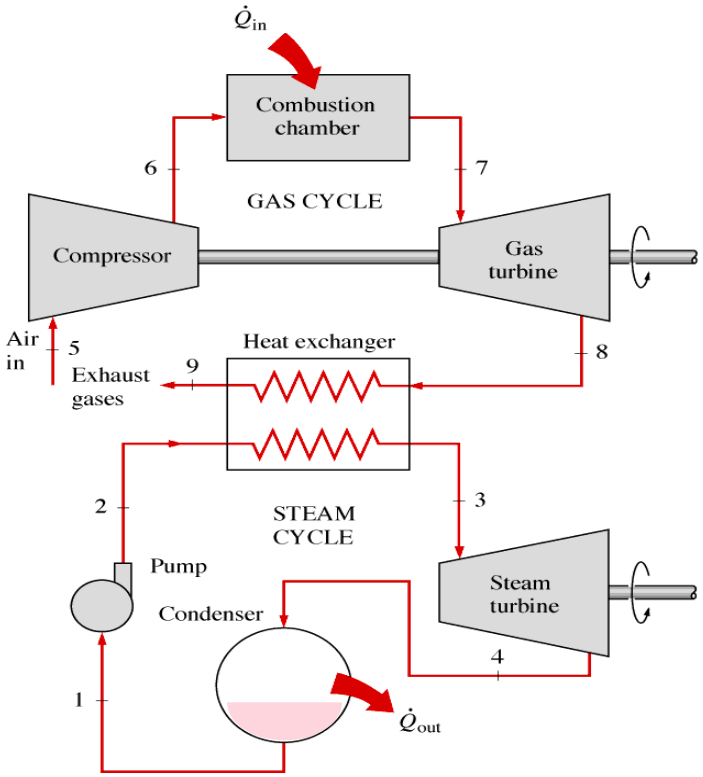
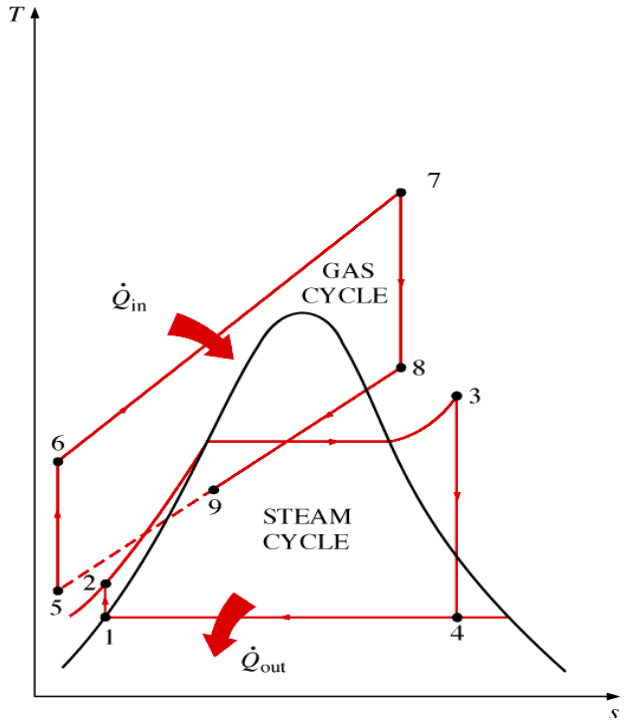
Combined cycle (CCGT power plant)

- Heat source: combustion of natural gas
- High temperature exhaust gases from the gas turbine are used as heat source for the bottoming steam cycle
- The heat transfer occurs in a heat exchanger (HRSG)
- Currently, they are the power plants with the higher thermal efficiency
- The combined cycle efficiency can be expressed as a function of the gas turbine efficiency and of the steam cycle efficiency:

$$\eta_{cc} = \eta_g + \eta_s - \eta_g \eta_s$$





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Combined cycles

Ex: CCGT power plant in Seraing

- Typical efficiency for CCGT power plants: 52 – 62 %
- CO2 emissions: ~450 kg de CO2 / MWh
- Relatively flexible power plants, which allows using them as a good complement to renewables sources

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Cegeneration of heat and electricity with vapor cycles

Cogeneration plant of Avedøre, Denmark

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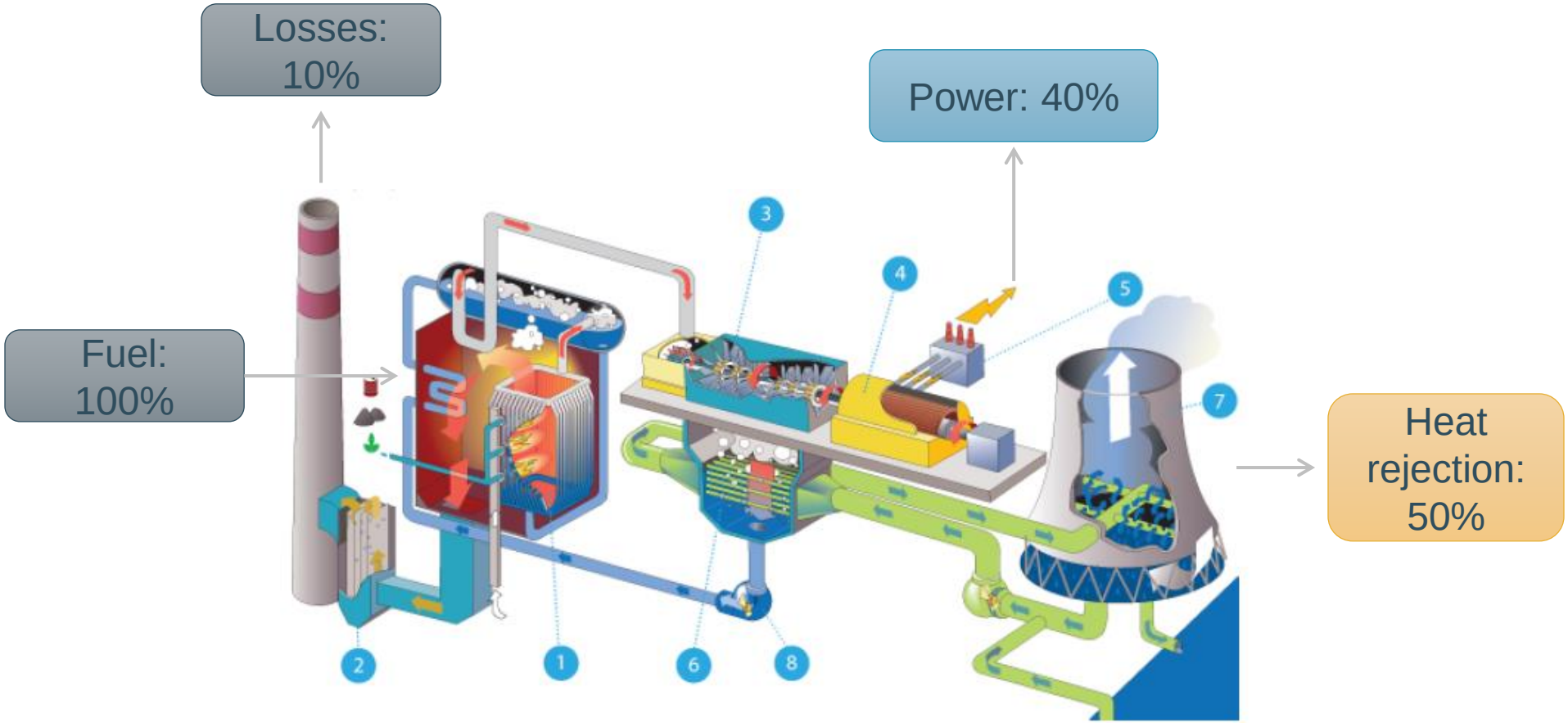
Cogeneration with vapor cycles: example



Overall efficiency: 40%

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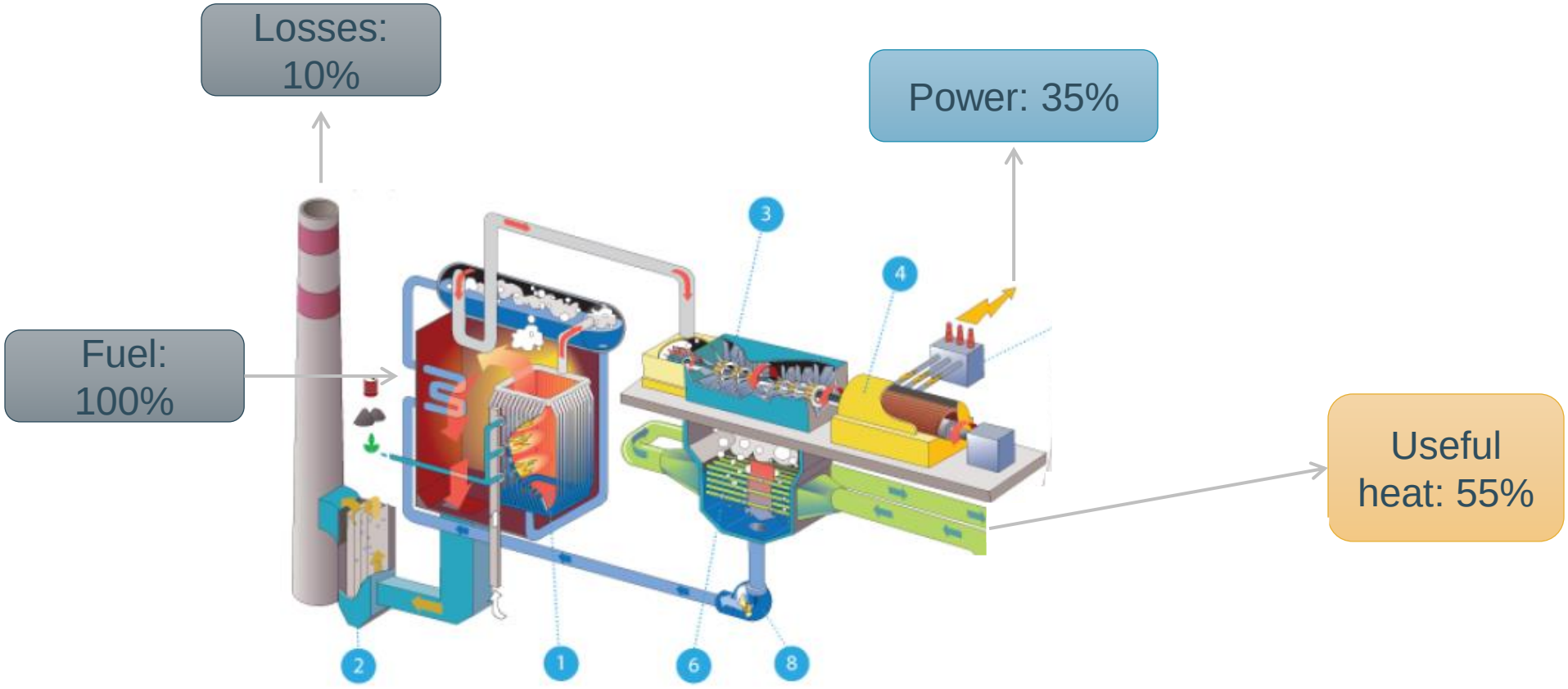
Cogeneration with vapor cycles: example



Overall efficiency : 90%

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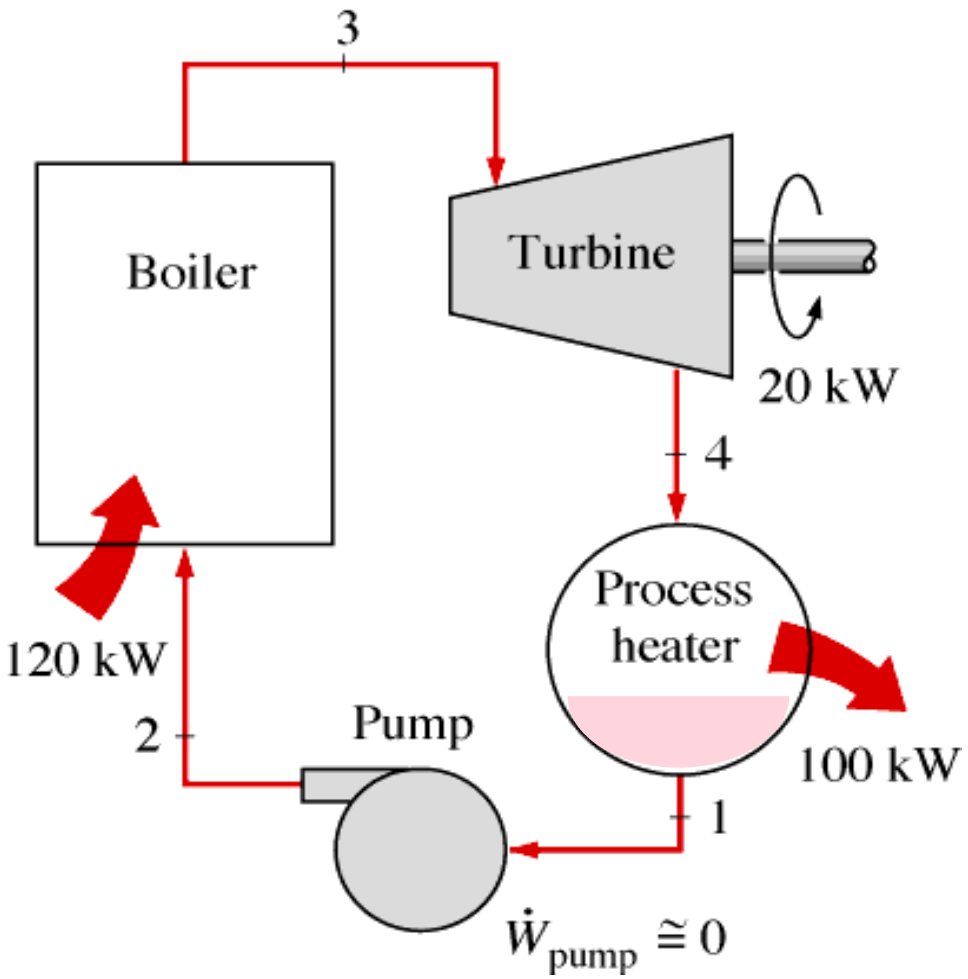
Cogeneration with vapor cycles

- Combined heat and power (CHP) is the simultaneous generation of heat and electricity
- The condenser is replaced by a heat exchanger providing useful heat to a process or for space heating
- The system presented here is called a back-pressure turbine: the condensing pressure is increased to increase the temperature level of heat rejection
- Back-pressure turbines CHPs are not very flexible: the power-to-heat ratio remains relatively constant



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Exercises in EES

10–34 Consider a steam power plant that operates on a reheat Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10 MPa and 500°C and the low-pressure turbine at 1 MPa and 500°C. Steam leaves the condenser as a saturated liquid at a pressure of 10 kPa. The isentropic efficiency of the turbine is 80 percent, and that of the pump is 95 percent. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the quality (or temperature, if superheated) of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, and (*c*) the mass flow rate of the steam. *Answers:* (*a*) 88.1°C, (*b*) 34.1 percent, (*c*) 62.7 kg/s