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Lecture 16

Topic 4

Power & Refrigeration Cycles

Topic

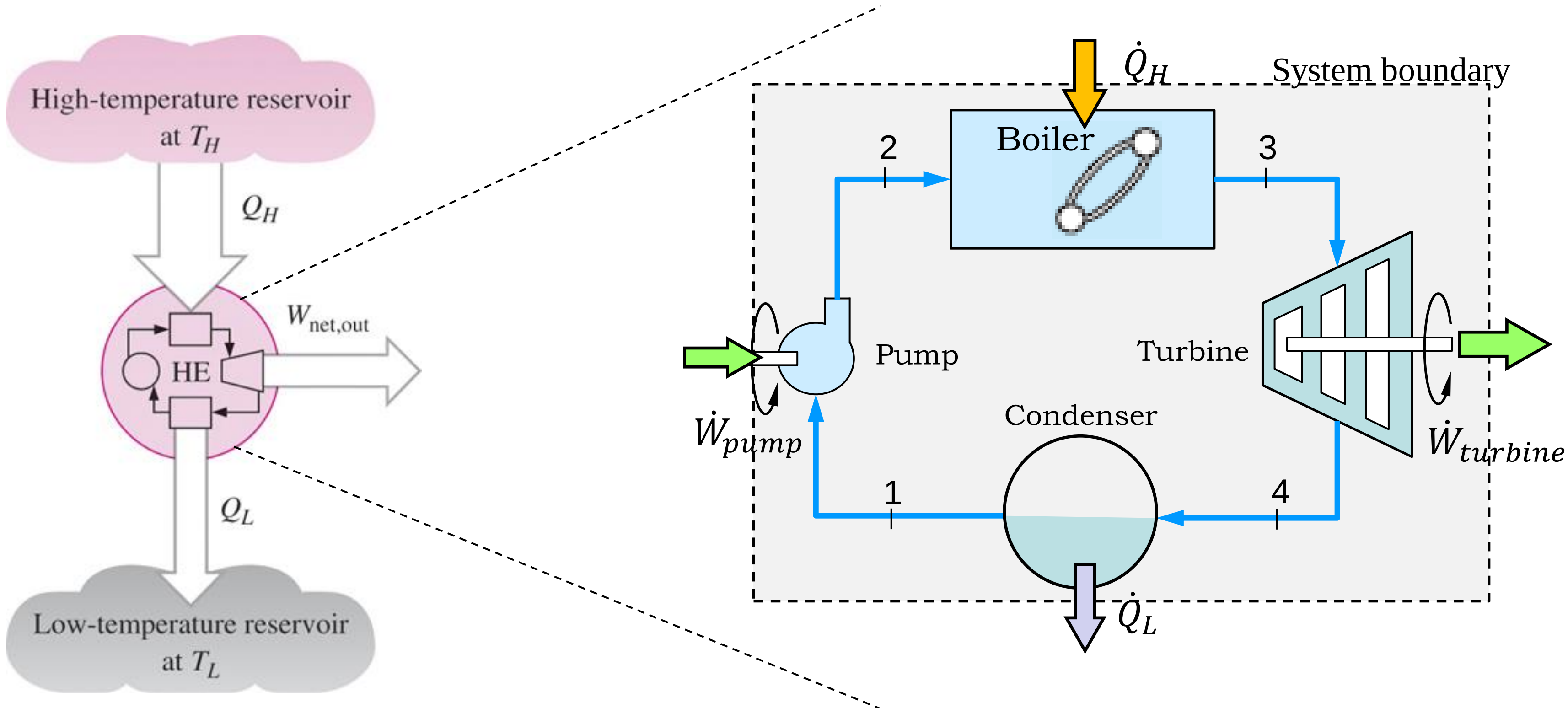
– 4.2 Rankine Cycles (Steam Power Plant)

Reading:
Ch 9: 9.1-9.7 Borgnakke & Sonntag Ed. 8
Ch 10: 10-1 – 10-7 Cengel and Boles Ed. 7

4.2 Rankine Cycle

Rankine Cycle – convert heat into useful work (e.g. to produce electricity).

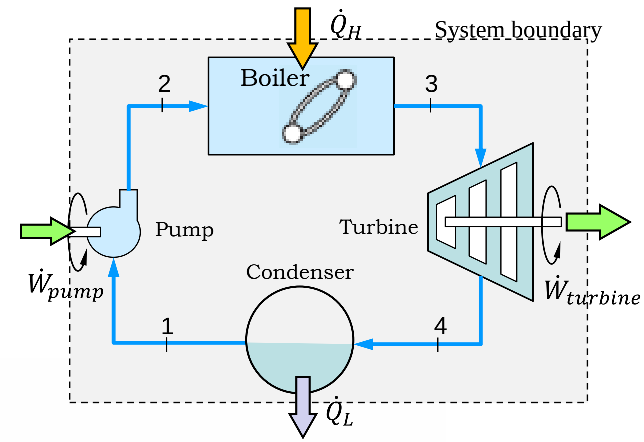
- Heat is rejected to a low temperature reservoir to accomplish this cycle.
- Rankine Cycle → Steam Power Plant (heat engine)

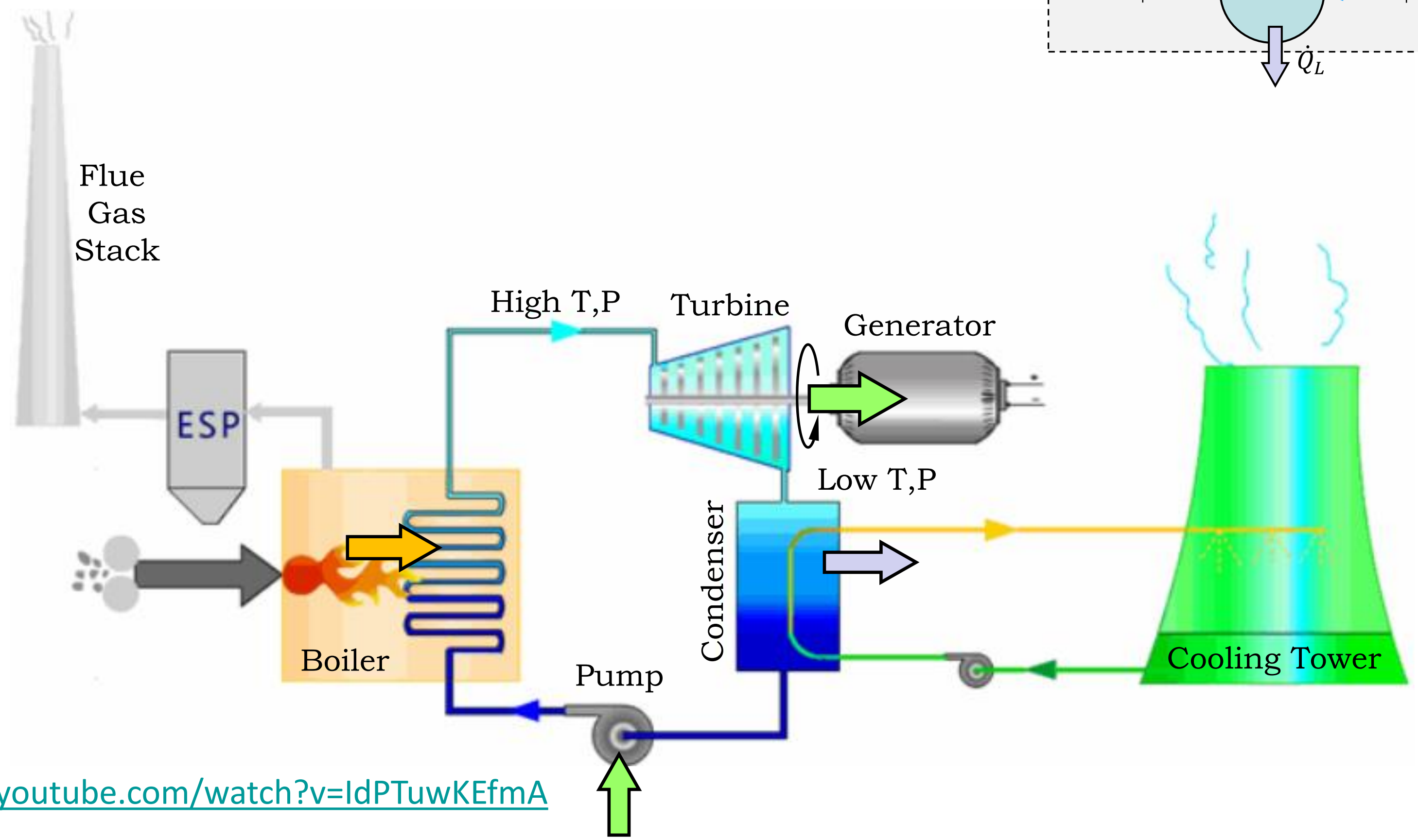


4.2 Rankine Cycle

Components of Steam Power Plant

- Pump
- Boiler: flue gas stack to exhaust products
- Turbine: connected to generator to produce electricity
- Condenser: connected to cooling tower to remove heat





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

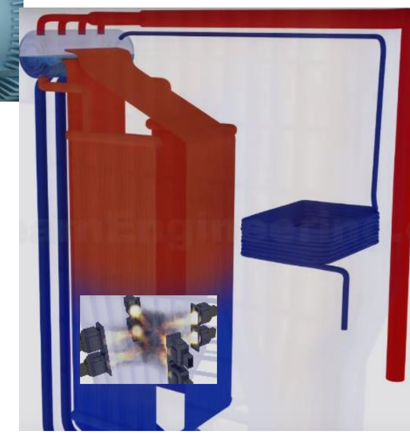
4.2 Rankine Cycle

Components of Steam Power Plant

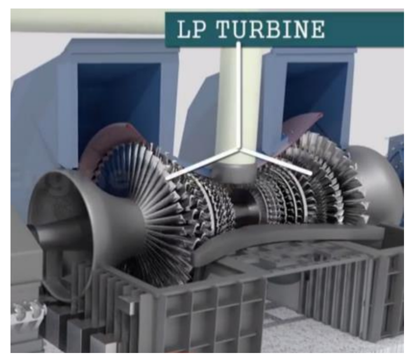
- Pump
  - Increase pressure: $P_2 >> P_1$
- Boiler
  - Increase temperature to T_{max} (evaporation)
- Turbine
  - Vapour expands to P_{low}
  - Temperature decreases.
- Condenser
  - Mixture condenses (heat removed) to LIQUID.
  - Liquid returns to pump & process repeats.

Pump

Boiler



Turbine



Condenser

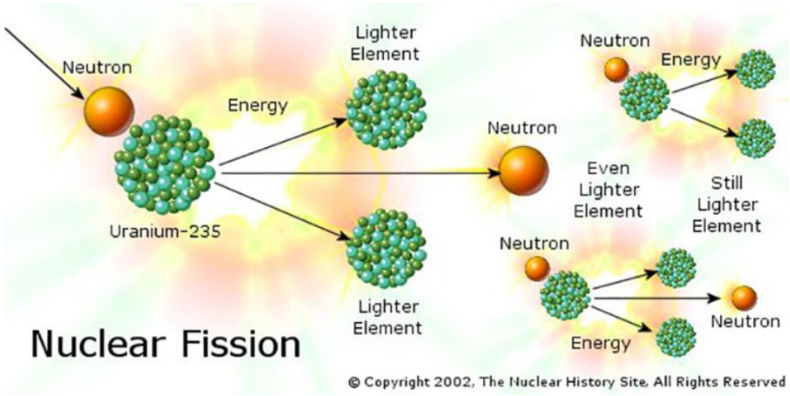
4.2 Rankine Cycle

Different heat sources

Coal

Natural gas & waste carbon fuels

Nuclear



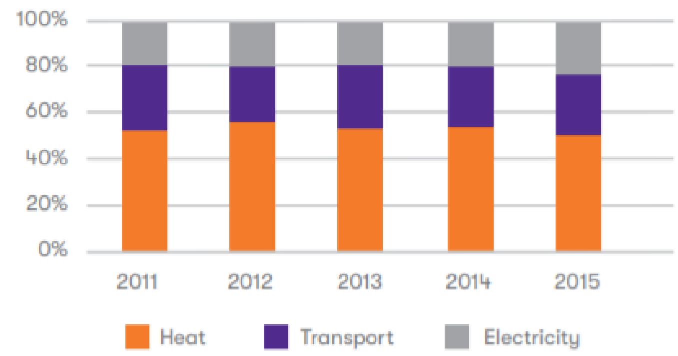
Solar

4.2 Why power plants?

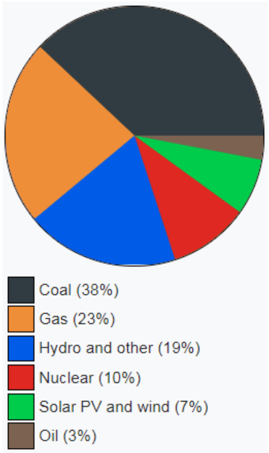
Energy Demand: Scotland, UK & the world

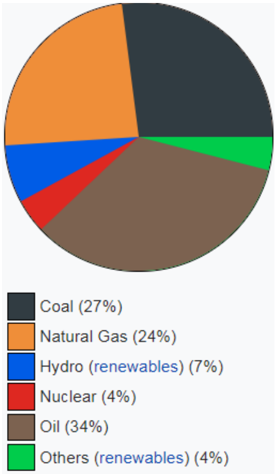
- Scotland (population 5.4 M)
  - 76.2% electricity consumption from renewables (2019)[1]
  - Electricity: ~23% of total energy consumed[2]
- UK (population 66.4 M)
  - 35.8% electricity consumption from renewables (2019)[3]
  - Electricity: ~15% total energy consumed[3]
- World (population 7,700 M)
  - 26% electricity consumption from renewables (2018)[4]
  - Overall energy consumption: 11% renewables (2018)[5]
- Peak demand challenging for wind/solar (storage)

Scotland total energy demand[2]



World electricity consumption / energy consumption[4,5]

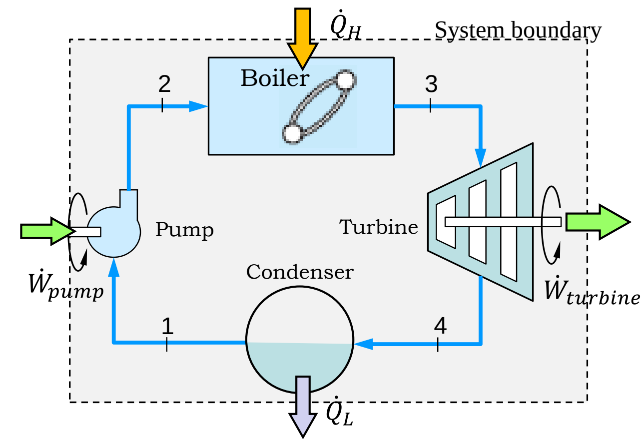




References
[1] https://www2.gov.scot/Resource/0054/00549213.pdf
[2] http://www.rse.org.uk/wp-content/uploads/2019/06/Energy-Report-for-Web-2.pdf
[3] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/812626/Press_Notice_June_19.pdf
[4] https://webstore.iea.org/key-world-energy-statistics-2019
[5] https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

4.2 Ideal Rankine Cycle

All devices operate steady state



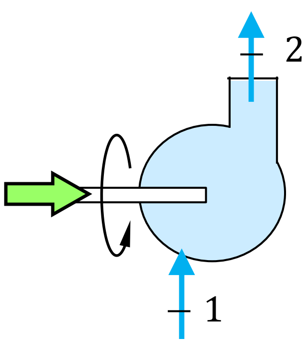
- Pump
  - Pressure increase of liquid water $P_2 >> P_1$
- Ideal: adiabatic, reversible, begins as a saturated liquid

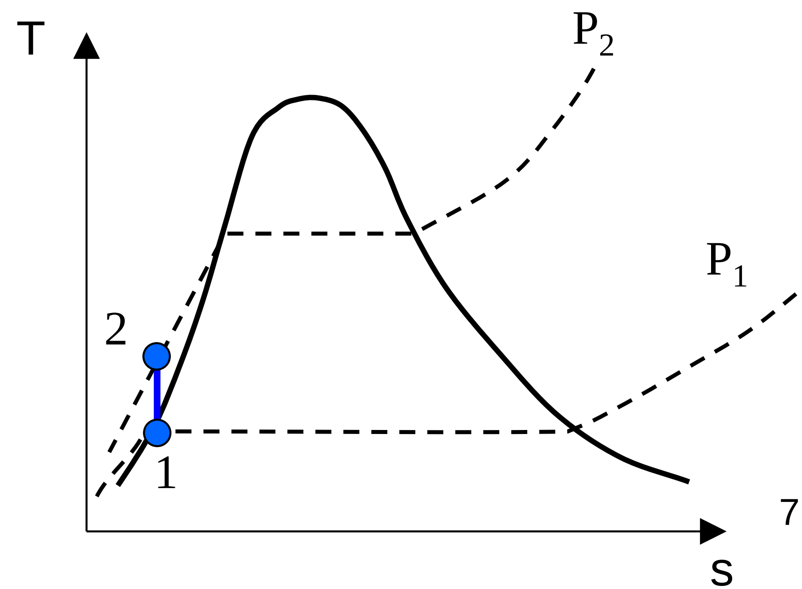
1st Law:

- $\dot{W}_{21,IN} = \dot{m}(h_2 - h_1)$
- $\dot{W}_{21,IN} = v(P_2 - P_1)$;
  - Incompressible substances: $w_{rev,out} = -\int_1^2 vdP - dke - dpe$

2nd Law:

- Ideal: $s_2 - s_1 = 0$
- Reality: $s_2 - s_1 = -\int \delta q_{Loss}/T + s_{gen}$
  - not reversible & possible heat loss





4.2 Ideal Rankine Cycle

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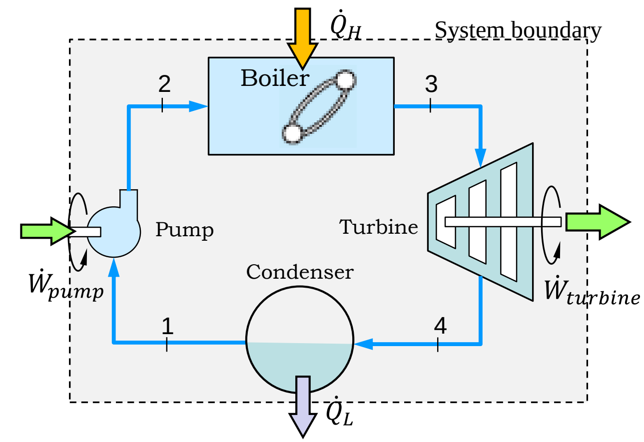
All devices operate steady state

- Boiler
  - Heat IN; temperature increase & evaporation to vapour
- Ideal: constant pressure process $P_2 = P_3$

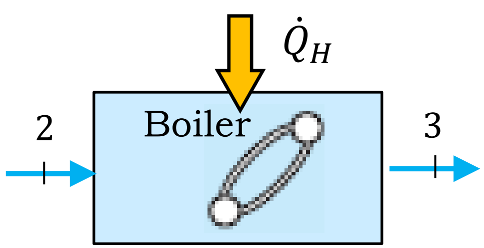


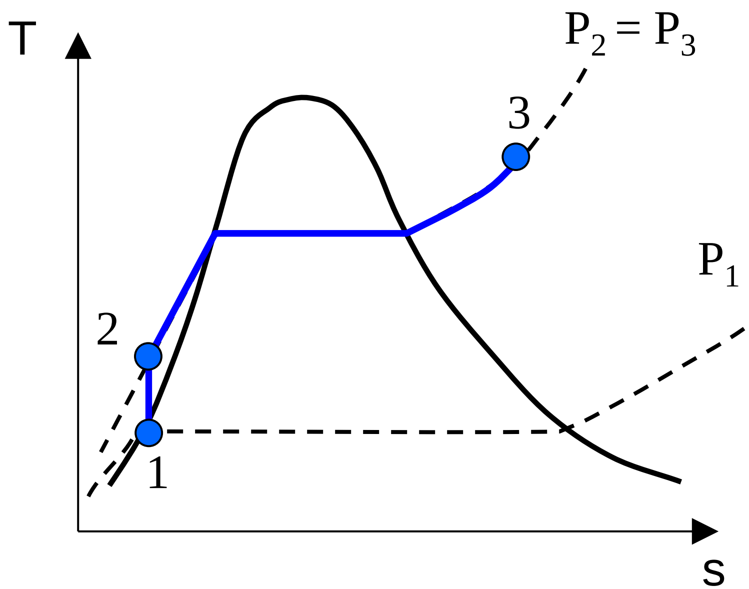
1st Law:

- $\dot{Q}_{32} = \dot{m}(h_3 - h_2)$

2nd Law:

- $s_3 - s_2 = \int \delta q_H / T + s_{gen}$
- Heat supplied from constant T source
  - $s_3 - s_2 = q_H / T_{source} + s_{gen}$





4.2 Ideal Rankine Cycle

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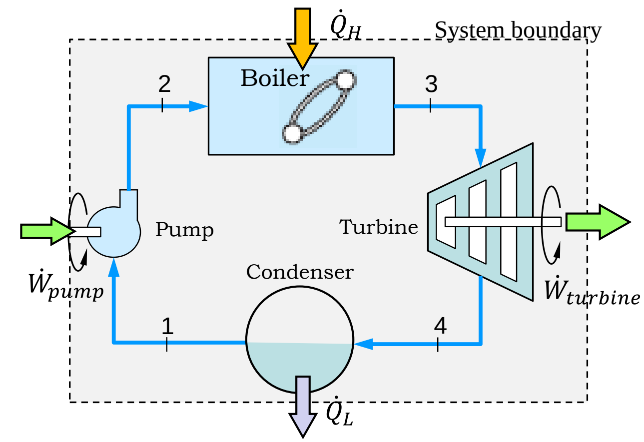
All devices operate steady state

- Turbine
  - Expand to lower pressure / temperature; W_{OUT}
- Ideal: adiabatic, reversible

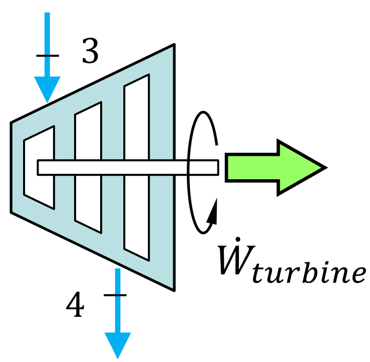


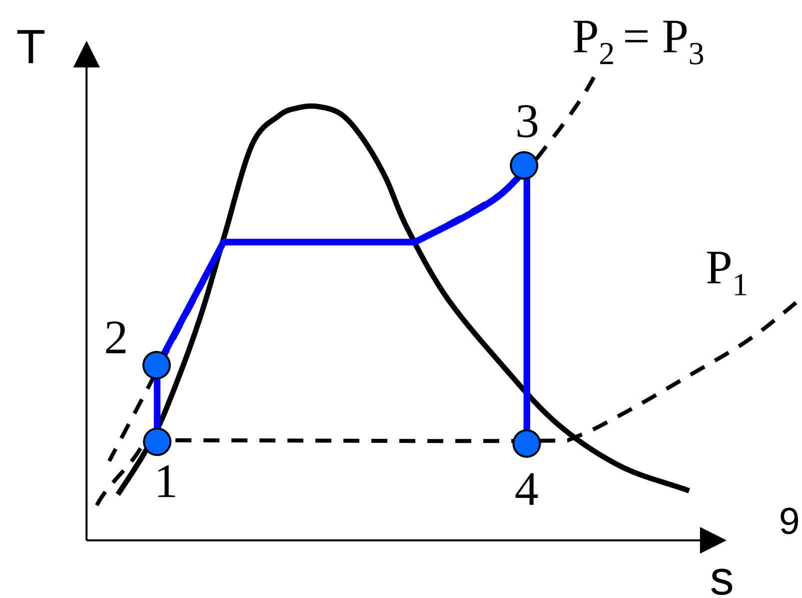
1st Law:

- $\dot{W}_{43,OUT} = \dot{m}(h_3 - h_4)$

2nd Law:

- Ideal: $s_4 - s_3 = 0$
- Real device: $s_4 - s_3 = -\int \delta q_{Loss}/T + s_{gen}$
  - not reversible & possible heat loss





4.2 Ideal Rankine Cycle

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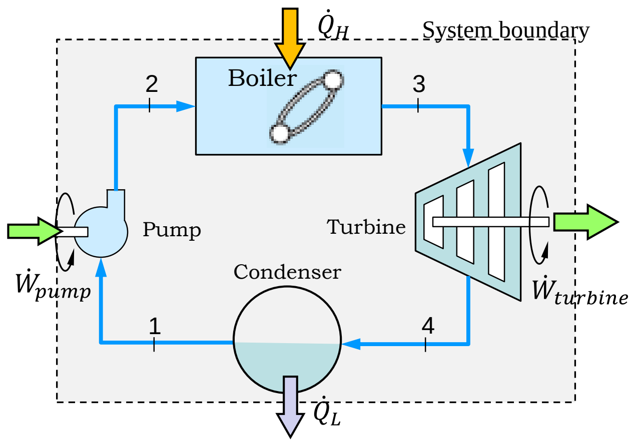


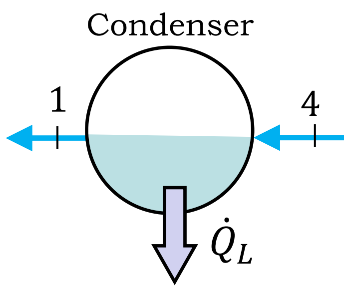
- Condenser
  - Heat rejection; water returns to saturated liquid
- Ideal: constant pressure process $P_4 = P_1$
  - Phase change: constant temperature

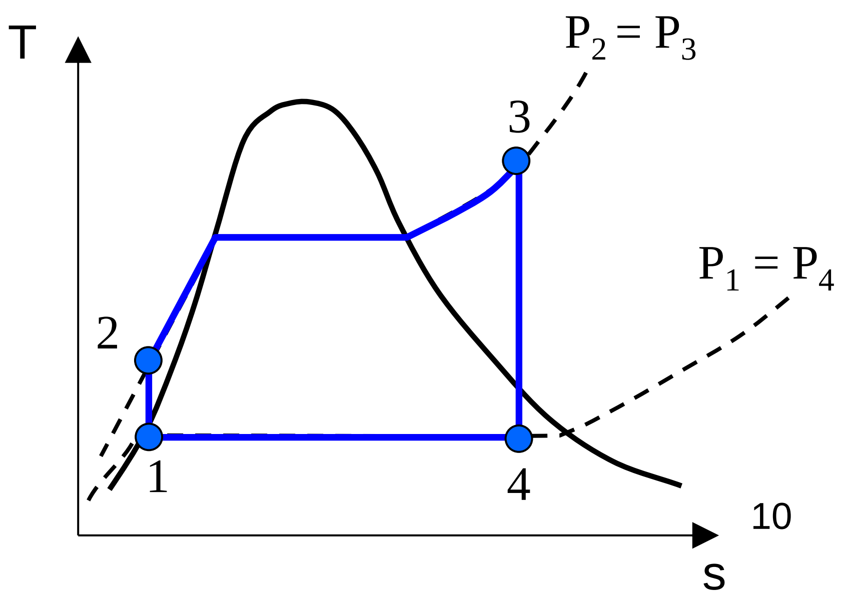
1st Law:

- $\dot{Q}_L = \dot{m}(h_4 - h_1)$

2nd Law:

- Ideal: $s_1 - s_4 = -\int \delta q_L/T + s_{gen}$
- Heat rejected to constant temp. reservoir
  - $s_1 - s_4 = -q_L/T_{sink} + s_{gen}$





4.2 Ideal Rankine Cycle

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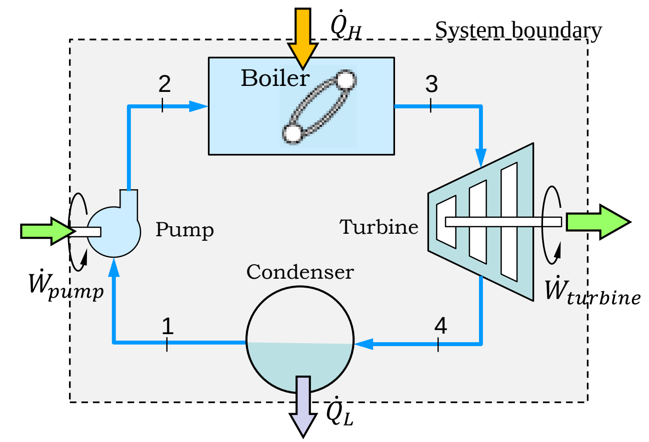
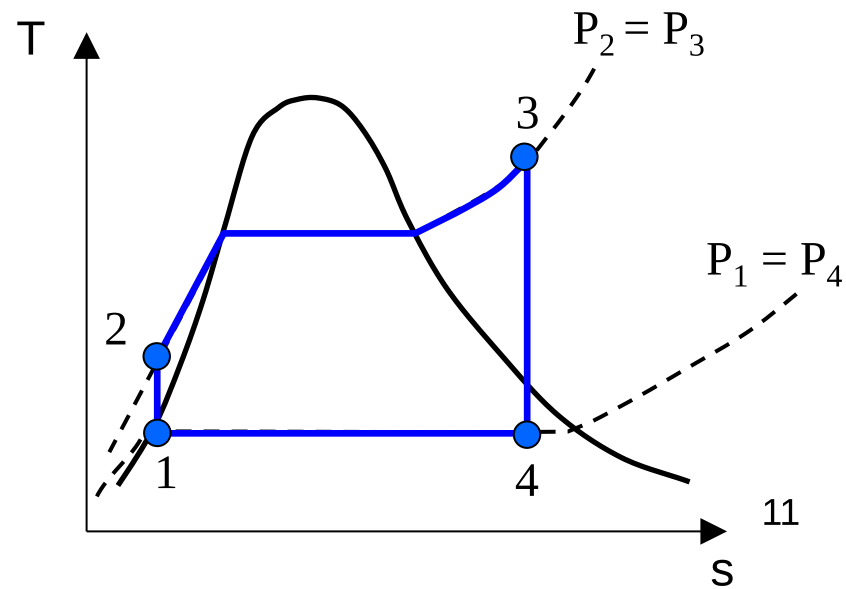
Process	Description
1-2	Isentropic compression in pump
2-3	Constant pressure heat addition in boiler
3-4	Isentropic expansion in turbine
4-1	Constant pressure heat rejection in condenser



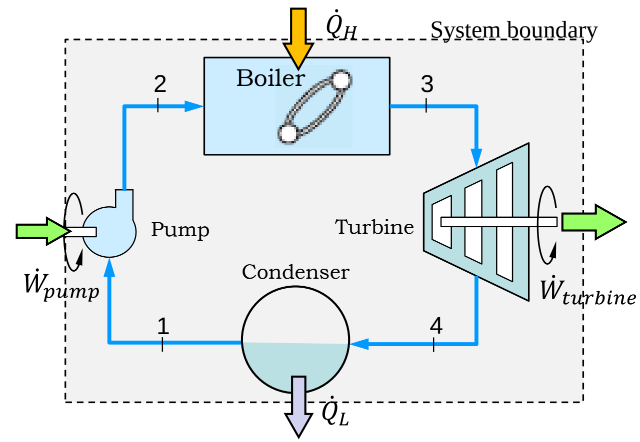
Working pressures: lower (P_1, P_4) & higher (P_2, P_3)

Thermal Efficiency

- $\eta_{th} = \dfrac{desired\ output}{required\ input} = \dfrac{\dot{W}_{NET,out}}{\dot{Q}_H} = 1 - \dfrac{\dot{Q}_L}{\dot{Q}_H}$
- $\dot{W}_{NET,out} = \dot{W}_{turbine} - \dot{W}_{pump}$



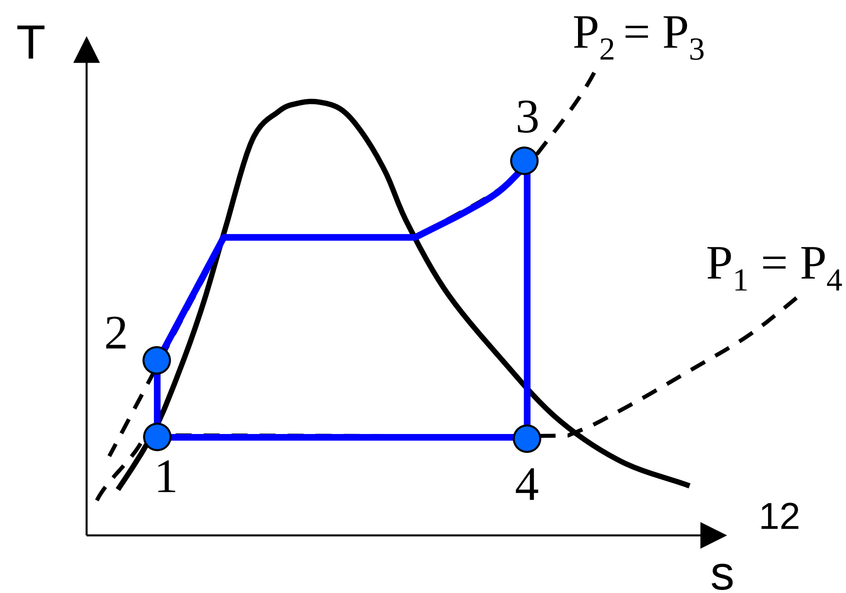
4.2 Rankine Cycle



Component Functionality

- Pump
  - Liquids only
- Turbine
  - Best if working fluid is a vapour
  - Water exiting the turbine should have high quality
  - Liquid water can damage turbine blades (corrosion)
  - Temperature limited to ~ 650ºC
- Boiler
  - Natural gas
  - Coal
  - Nuclear
  - Solar

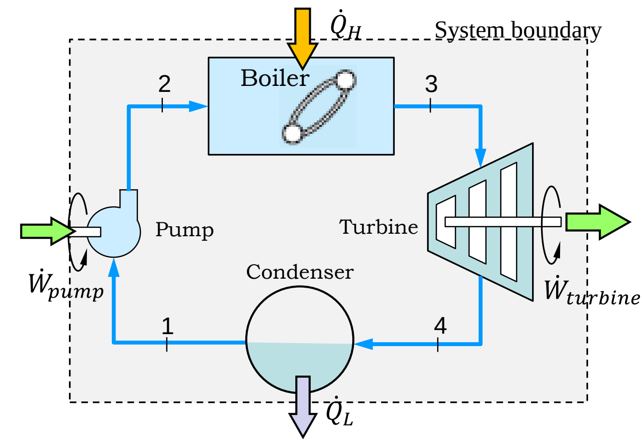
  Natural gas, Coal, Nuclear: Require proper disposal of products
- Condenser
  - Temperature sink
    - Air, lake, ocean, river, water system



4.2 Rankine Cycle

Deviations from the ideal Rankine Cycle

- Pump & turbine are not reversible
- Heat loss from turbine
  - $s_e = s_i - \int_1^2 \delta q_{loss}/T + s_{gen}$

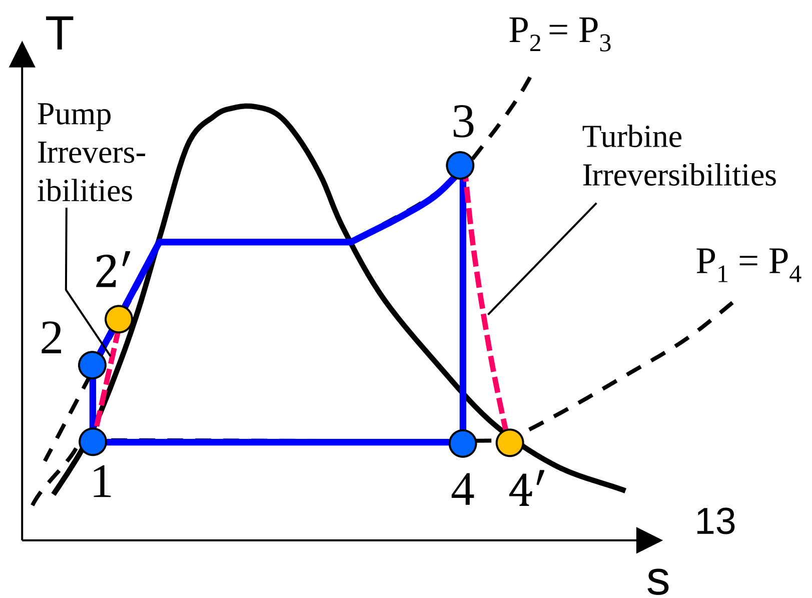


Pump: Isentropic efficiency

$$\eta_{pump} = \frac{w_{reversible,IN}}{w_{irreversible,IN}} = \frac{reversible\ work}{actual\ work} = \frac{h_1 - h_{2s}}{h_1 - h_{2a}}$$

Turbine: Isentropic efficiency

$$\eta_{turbine} = \frac{w_{irreversible,OUT}}{w_{reversible,OUT}} = \frac{reversible\ work}{actual\ work} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$



4.2.1 Example of Rankine Cycle

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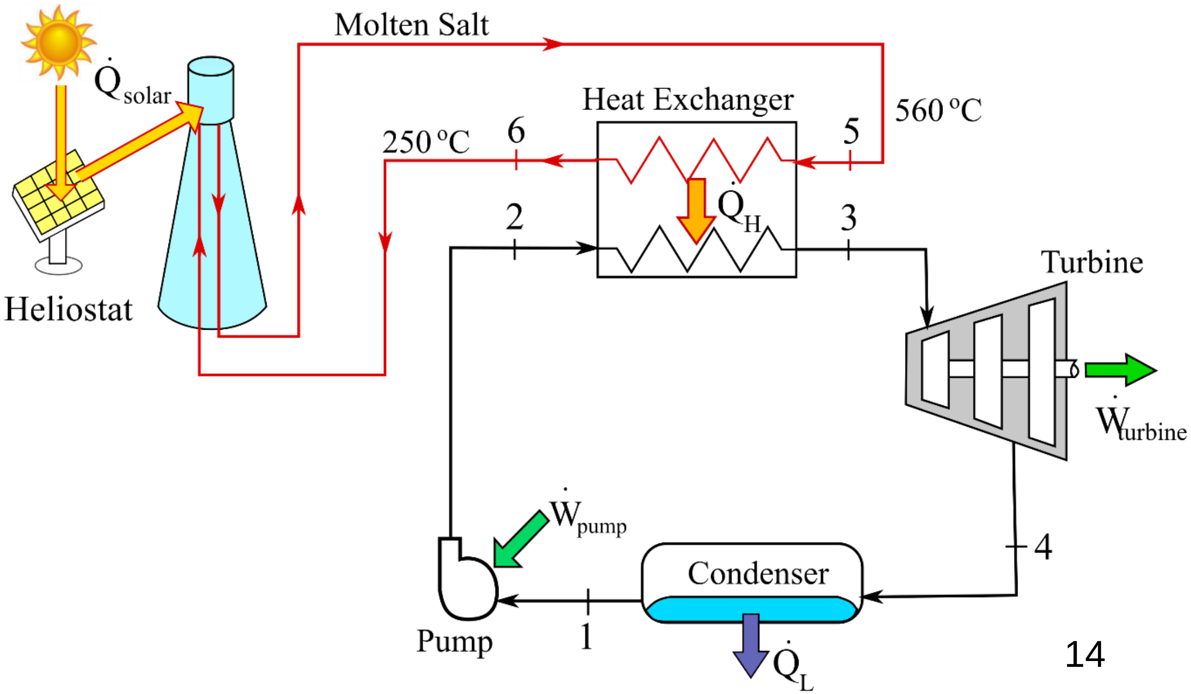
Example 4-3: Consider an <u>ideal</u> Rankine cycle where a solar heat is used to heat molten salt to 560°C in a collector. Molten salt delivers heat to the water in a heat exchanger. The salt leaves the heat exchanger at 250°C and has a mass flow rate of $\dot{m}_{salt}$ = 20 kg/s. The water has a mass flow rate of 5 kg/s. The lower working pressure of the Rankine cycle is 75 kPa, and the higher working pressure is 5 MPa. Molten salt can be treated with constant specific heats $C_{p,salt}$ = 1.5 kJ/kgK.

a) What is the heat source delivered to the water (i.e. $\dot{Q}_H$, in kW)?

b) If a nearby city consumes 5 MW of electricity, can the solar power plant provide enough power to meet this demand?

c) What is the thermal efficiency?



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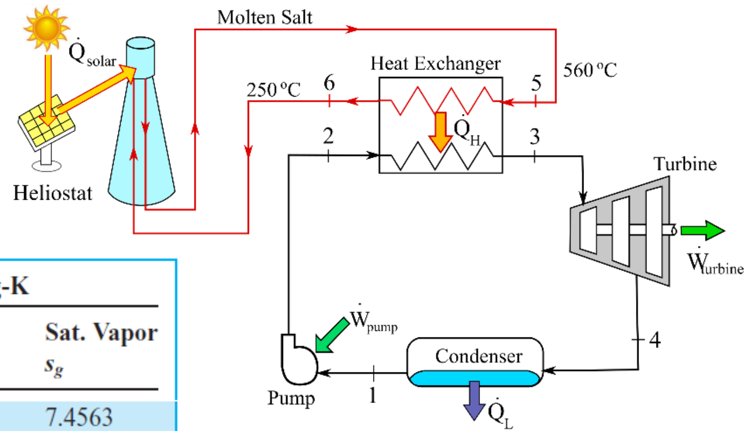


TABLE B.1.2 *(continued)*
Saturated Water Pressure Entry

Press. (kPa)	Temp. (°C)	Enthalpy, kJ/kg Sat. Liquid h_f	Enthalpy, kJ/kg Evap. h_{fg}	Enthalpy, kJ/kg Sat. Vapor h_g	Entropy, kJ/kg-K Sat. Liquid s_f	Entropy, kJ/kg-K Evap. s_{fg}	Entropy, kJ/kg-K Sat. Vapor s_g
75	91.77	384.36	2278.59	2662.96	1.2129	6.2434	7.4563
5000	263.99	1154.21	1640.12	2794.33	2.9201	3.0532	5.9733

TABLE B.1.4
Compressed Liquid Water

Temp. (°C)	v (m³/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)
	5000 kPa (263.99°C)			
80	0.001027	333.69	338.83	1.0719
100	0.001041	417.50	422.71	1.3030

4.2.1 Example of Rankine Cycle

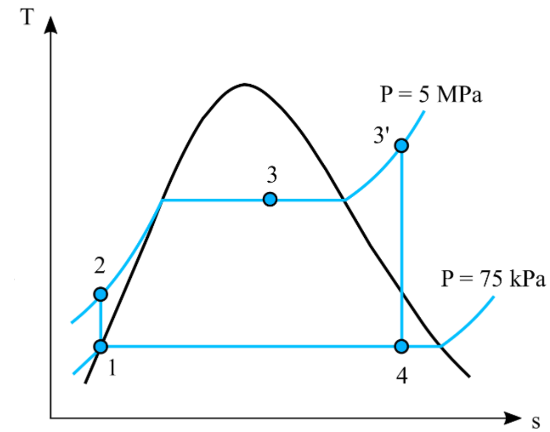
Example 4-4: Consider example 4-3, but now a boiler is used in combination with the solar heating system. The boiler supplies enough heat such that the quality of the mixture leaving the turbine is $x_4 = 0.95$.

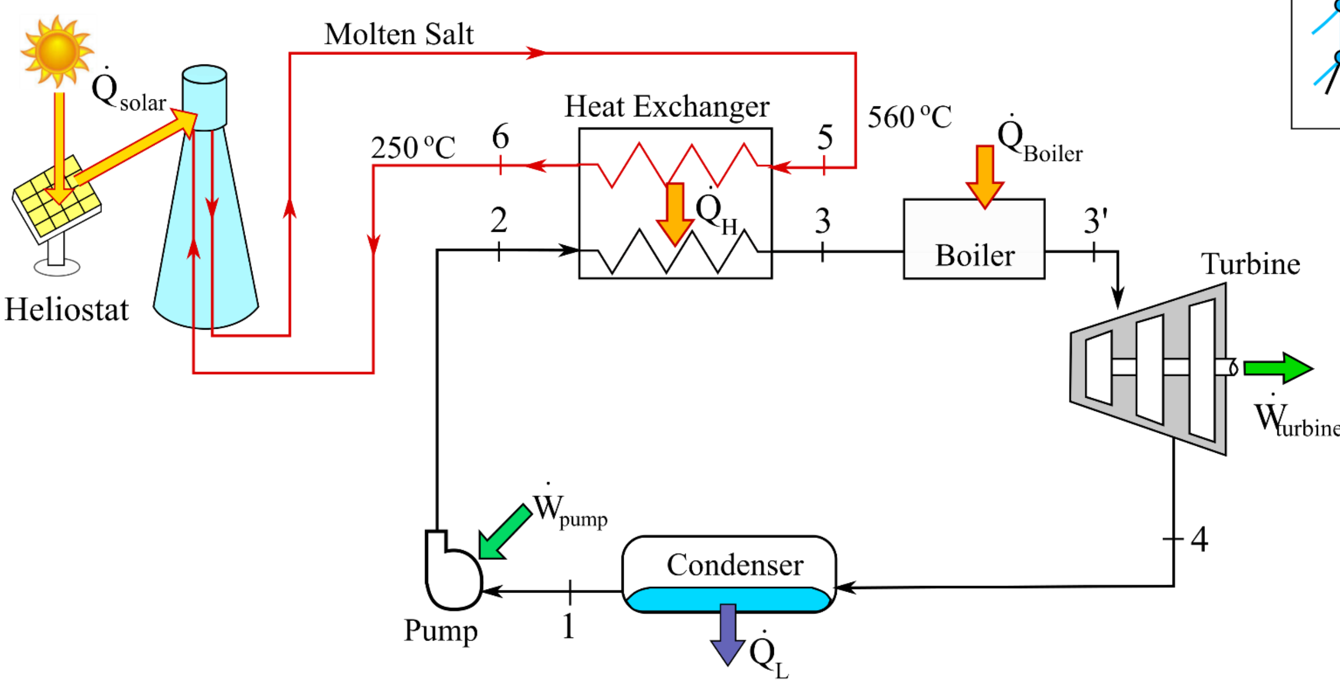
Assuming the turbine to operate reversibly & adiabatically, determine

a) The maximum temperature in the cycle.

b) The power output of the turbine (in kW).

c) The new thermal efficiency.





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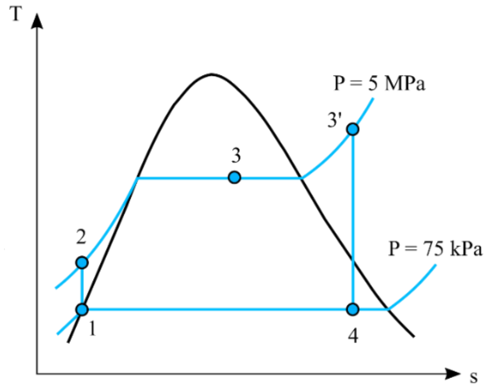


TABLE B.1.2 (*continued*)
Saturated Water Pressure Entry

Press. (kPa)	Temp. (°C)	Enthalpy, kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy, kJ/kg-K Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapor s_g
75	91.77	384.36	2278.59	2662.96	1.2129	6.2434	7.4563
5000	263.99	1154.21	1640.12	2794.33	2.9201	3.0532	5.9733

TABLE B.1.3 (*continued*)
Superheated Vapor Water

Temp. (°C)	v (m^3/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)
	5000 kPa (263.99°C)			
550	0.07368	3181.82	3550.23	7.1217
600	0.07869	3273.01	3666.47	7.2588
700	0.08849	3457.67	3900.13	7.5122

4.2.2 Exercise

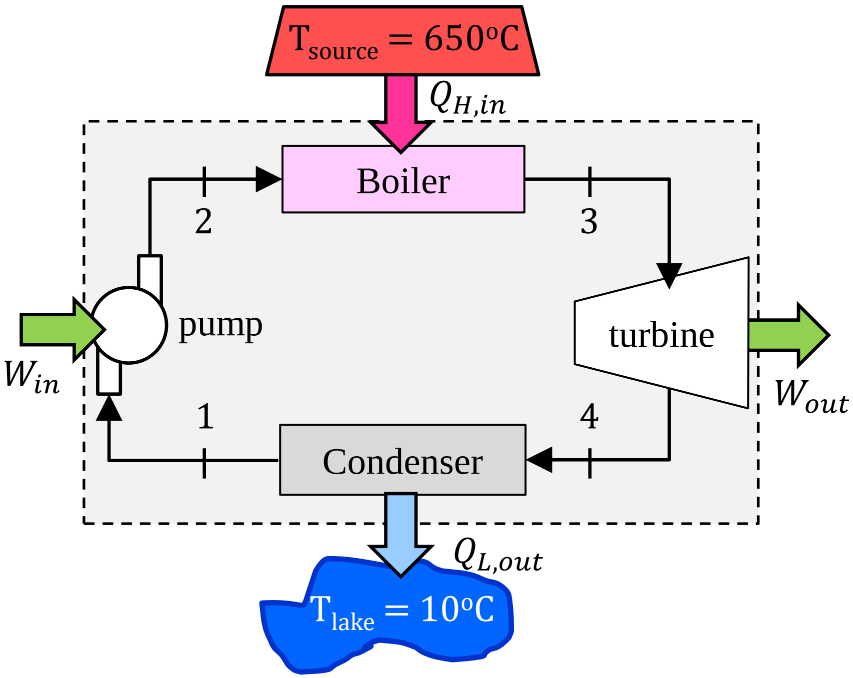
Exercise 4-2

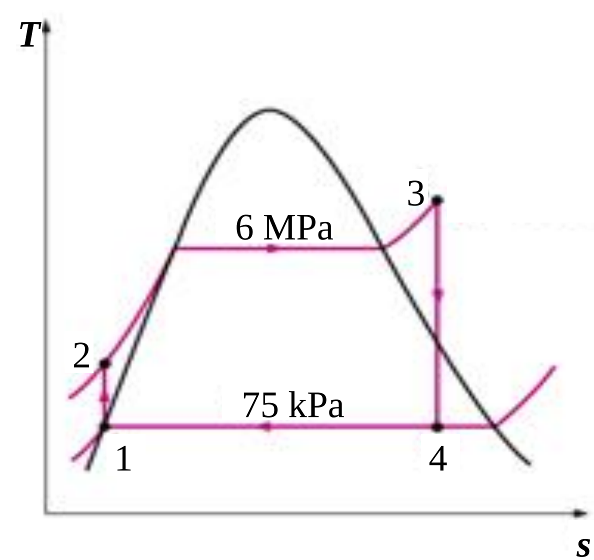
Consider an ideal Rankine cycle where steam leaves the boiler as superheated vapour at 6 MPa, 500^{o}C, and is condensed at 75 kPa.

a) What is the quality of the steam exiting the turbine?

b) What is the thermal efficiency of the cycle?

c) Assume that Q_H is delivered from a high temperature reservoir at constant temperature of 650^{o}C and a lake at constant temperature of 10^{o}C receives the heat rejected from the condenser. What is the entropy generation of the surroundings in kJ/kgK?

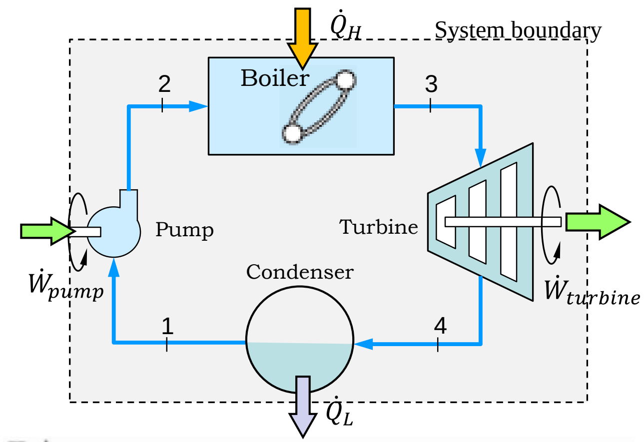




4.2.3 EXTRA – Rankine vs. CARNOT

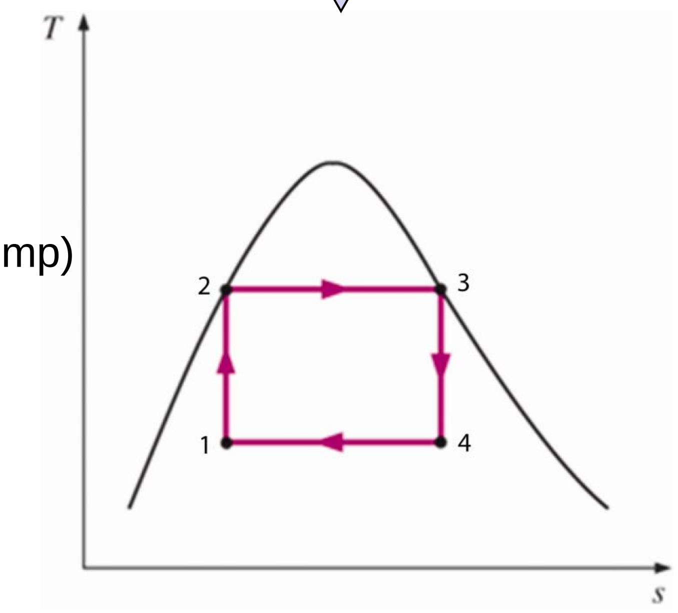
Revisiting the Carnot Cycle:

- The following discussion that follows will consider a steady-flow Carnot cycle executed as a Rankine cycle.
- This will consist of a pure substance underneath the saturated liquid-vapor dome



The ideal cycle consists of four processes:

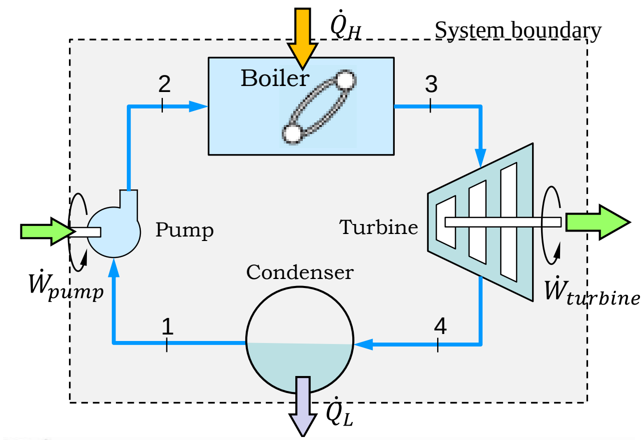
Process	**Description**
1-2	Isentropic compression (compressor/pump)
2-3	Isothermal heating (boiler)
3-4	Isentropic expansion (turbine)
4-1	Isothermal cooling (condenser)

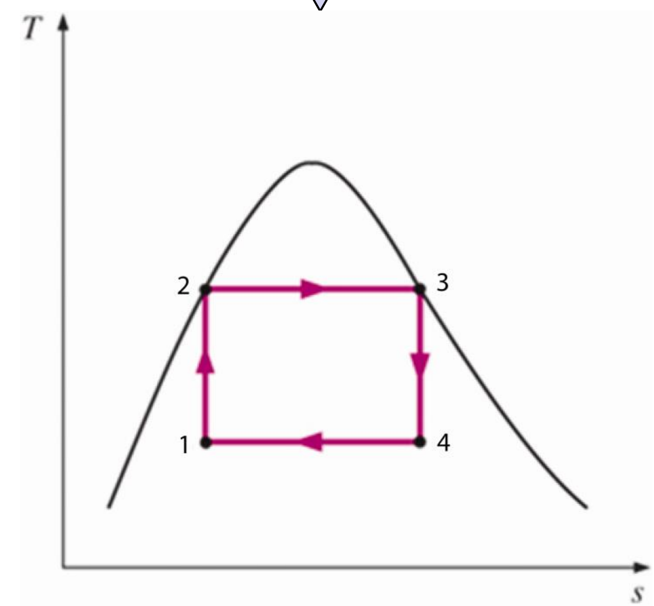


4.2.3 EXTRA – Rankine vs. CARNOT

Problems with a real Carnot vapour cycle

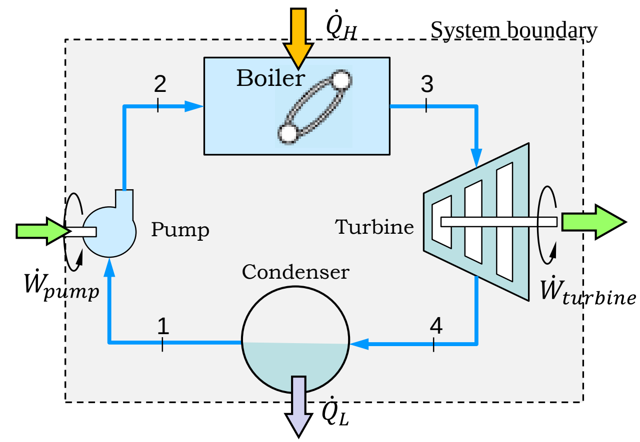
- Process 1-2: The pump will be compressing a liquid and vapor. Two-phase flows in compressors and pumps should be avoided. Pumps are suitable to raise the pressure of liquids, while compressors are best-suited to raise the pressure of vapor.
- Process 2-3: Limiting the heat transfer to 2-phase systems severely limits the maximum temperature that can be used in the cycle as it has to remain under the critical-point value (374ºC for water).
- Process 3-4: the quality of the steam decreases during this process. The turbine does not operate well with increased amounts of liquid water. Liquid water can cause erosion of the turbine blades. The quality of the steam in the operation of power plants should be 90% or higher.





4.2.3 EXTRA – Rankine vs. CARNOT

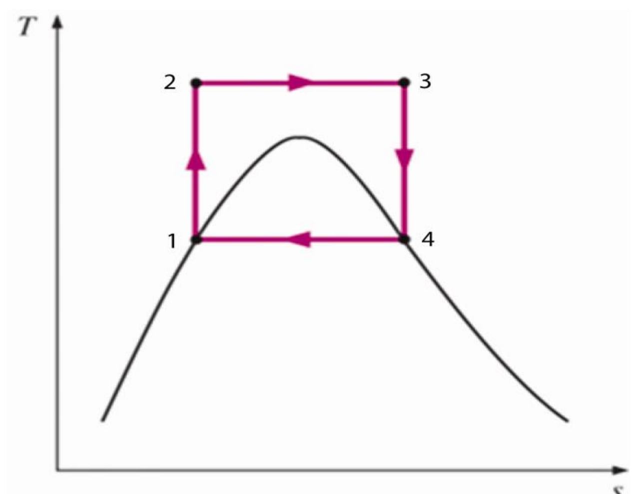
- Some of these difficulties can be eliminated by executing the Carnot cycle so that it is not contained within saturation dome of a pure substance.
- However, this cycle presents other problems such as isentropic compression to extremely high pressures/temperatures and isothermal heat transfer at variable pressures.



Thus we conclude that the Carnot cycle cannot be approximated in real devices and is not a realistic model for vapour power cycles. We can, however, use it as standard against which real vapour power cycles are compared.

In particular, remember that the thermal efficiency of the Carnot cycle is given as

$$\eta_{th,\,Carnot} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{T_L}{T_H}$$



4.2.4 Exercise

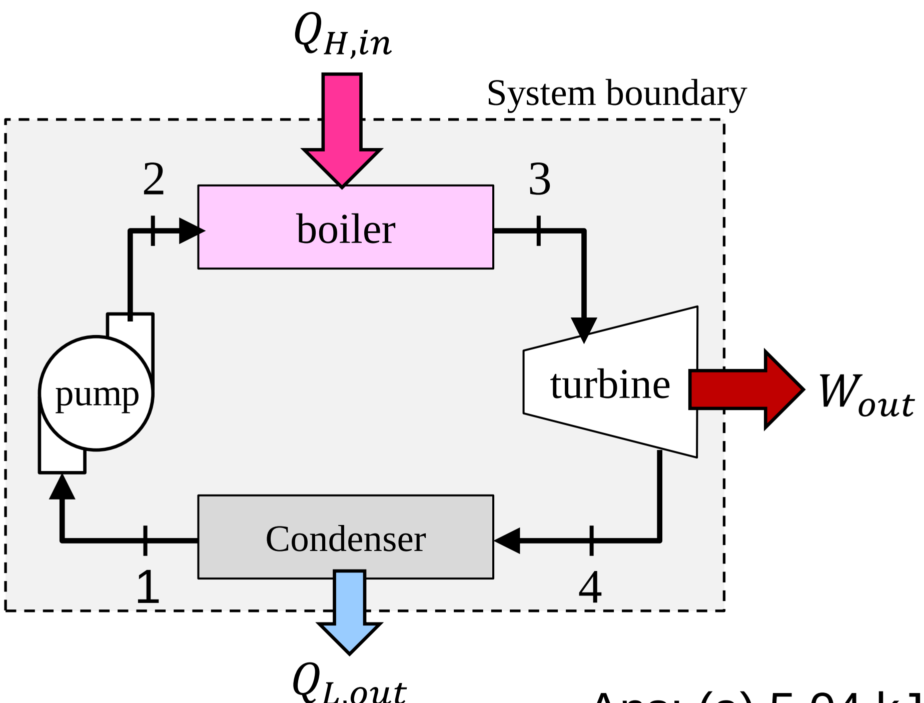
Exercise 4.1

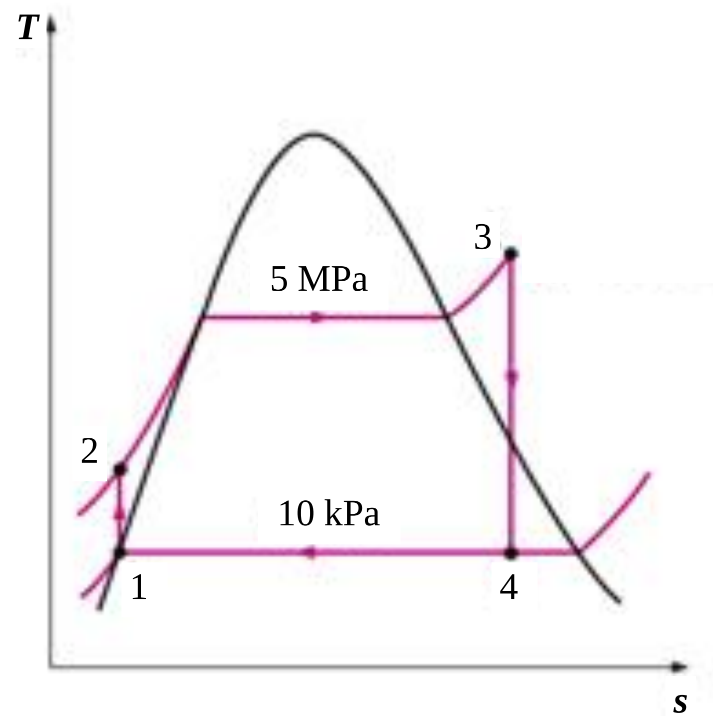
Saturated liquid water at 10 kPa leaves the condenser of a steam power plant and is pumped to the boiler pressure of 5 MPa. Calculate the work for an isentropic pumping process when applying:

a) $\dot{w}_{in} = v(P_2 - P_1)$

b) $s_2 = s_1$ and $\dot{w}_{in} = (h_2 - h_1)$

c) What is the % difference in $\dot{w}_{in}$ and h_2 using the 2 different methods?





Ans: (a) 5.04 kJ/kg