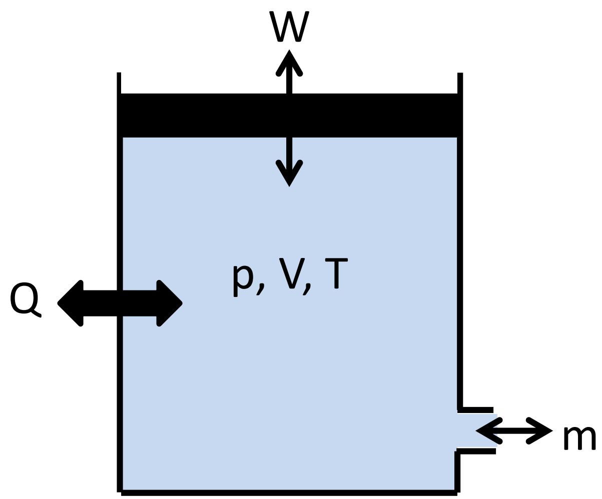
Thermodynamics

Thermodynamics

- Thermodynamics describes processes which include change of temperature, energy transformations and mutual relations between thermal and mechanical energy
- You should know from previous studies:
  - Thermodynamic system
  - Thermodynamic laws
  - Heat, work, enthalpy, entropy, thermodynamic processes, ….

Thermodynamic system

- Part of a matter volume around which we can draw boundary



Isolated – no matter and energy is exchanged with the surroundings

Closed – no matter is exchanged with the suroundings, energy can be exchanged

Open – energy and matter is exchanged with the surroundings

Thermodynamic balance – the state of thermodynamic system in which all parts are in mechanical, thermal and chemical balance

Thermodynamic process

- **State values** – description of a thermodynamic system in the state of equilibrium (p - pressure, V - volume, U - enthalpy, T - temperature, …)
- The thermodynamic process occurs when the system changes from one state of equilibrium to another
  - Values of state variables are <u>independent</u> on the manner (path) how the change occurs
  - Values of non-state variables (Q, W) depend on the manner (path) how the change occurs
- Thermodynamic process are
  - Reversible/Irreversible processes – reversible process can run in both directions, when during the reverse process the system run through all states as during the direct process
  - Circular – initial and final states are the same

Laws of thermodynamics

- **First** law of thermodynamic
  - The change of internal energy dU of isolated system is the sum of change of heat δQ which is introduced to the system and change of work δW which is done on the system

$$dU = \delta Q - \delta W$$

  - The volume work δW is the volume change at constant pressure

$$\delta W = pdV$$

  - The work has positive sign if the system does work – energy goes out from the system and negative sign if the work is done on the system – energy is added to the system

Laws of thermodynamics

- **Second** law of thermodynamics (derived from empirical observations)
  - Entropy definition

$$ds = \frac{\delta Q}{T}$$

  - For a reversible system ds=0, spontaneous process ds>0
  - Entropy never decreases spontaneously
  - The change of entropy at constant value of temperature is higher at lower temperature
- **Third** law of thermodynamics
  - The entropy of pure solid or liquid matter is equal to the zero at absolute zero temperature

Enthalpy

- Definition of enthalpy H

$$H = U + pV$$
$$dH = dU + pdV + Vdp$$

- Isobaric process dp=0

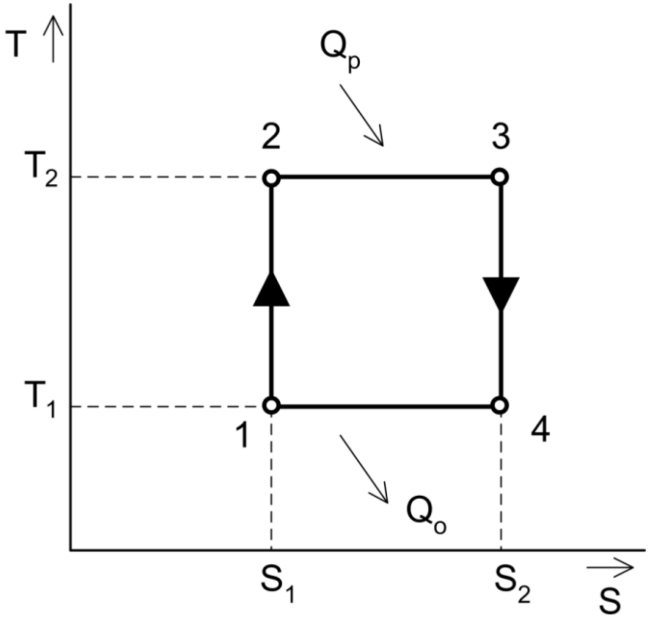
$$dH = \delta Q - pdV + pdV + Vdp$$
$$dH = \delta Q$$

- Adiabatic process $\delta Q = 0$

$$dH = Vdp = -\delta W$$

Carnot cycle

- Theoretical thermal cycle with highest thermal efficiency within the given range of temperature T_1 and T_2 which is independent on medium
- Consists of four processes
  - **1-2** Adiabatic compression between temperatures T_1 and T_2
  - **2-3** Isothermal expansion at temperature T_2
  - **3-4** Adiabatic expansion at temperature drop from T_2 to T_1
  - **4-1** Isothermal compression at temperature T_1



Carnot cycle efficiency

- Efficiency

$$\eta = \frac{total\ mechanical\ work\ of\ cycle}{total\ energy\ consumed\ by\ system} = \frac{W}{Q_p}$$

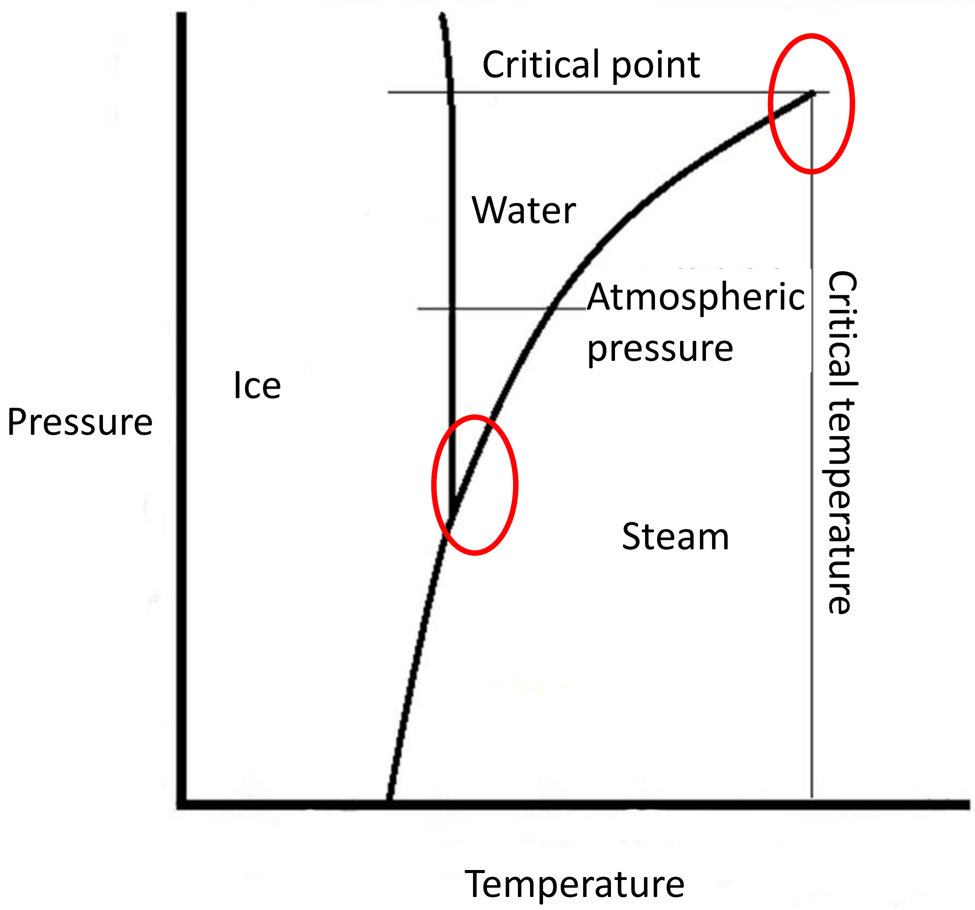
- Mechanical work of cycle

$$W = Q_p - Q_o$$

then the

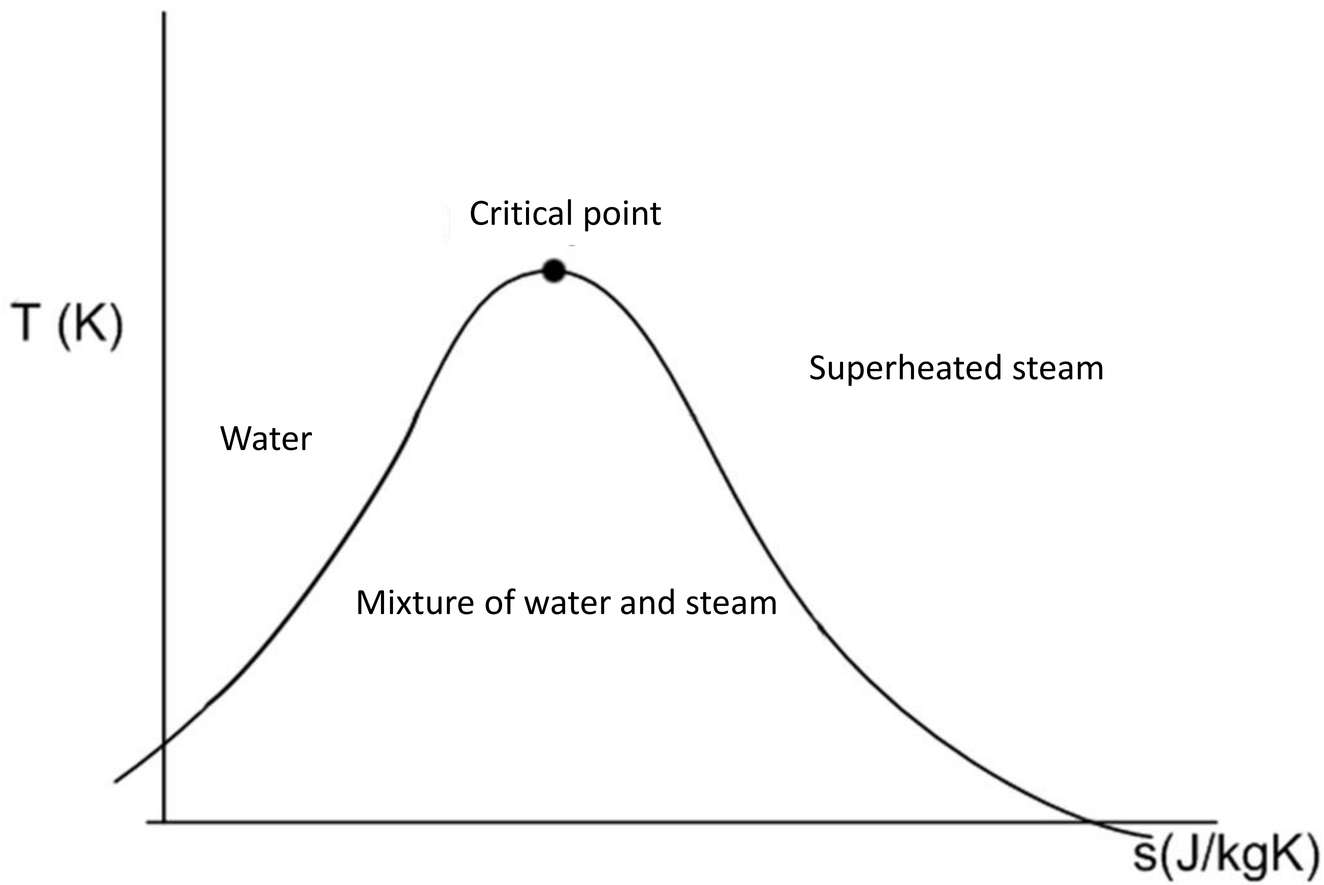
$$\eta = \frac{Q_p - Q_o}{Q_p} = 1 - \frac{Q_0}{Q_P} = 1 - \frac{T_1(s_1 - s_2)}{T_2(s_1 - s_2)} = 1 - \frac{T_1}{T_2}$$

Phase diagram of water

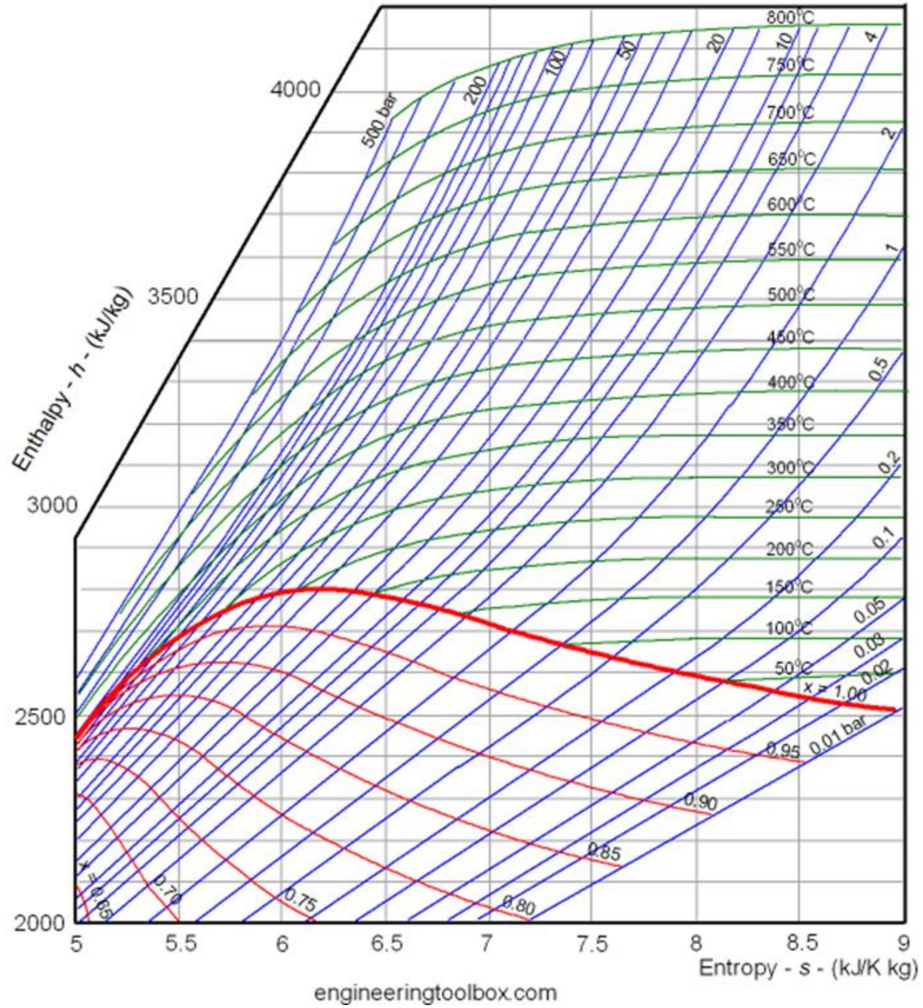


- Triple point of water
  - Temperature 0.01°C and pressure 611 Pa
- Critical point of water
  - Critical temperature t_k= 374 °C and pressure p_k= 22.12 MPa

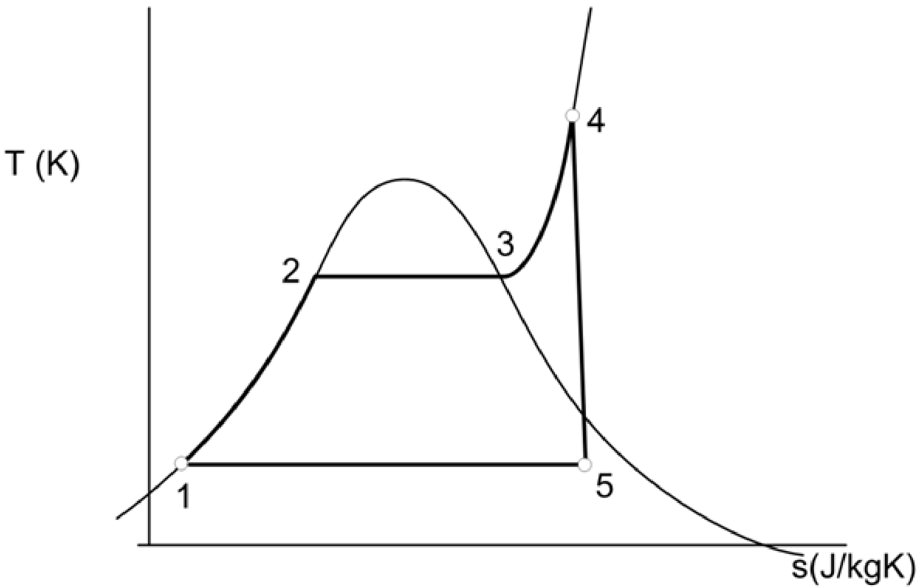
T-s diagram (water-steam)

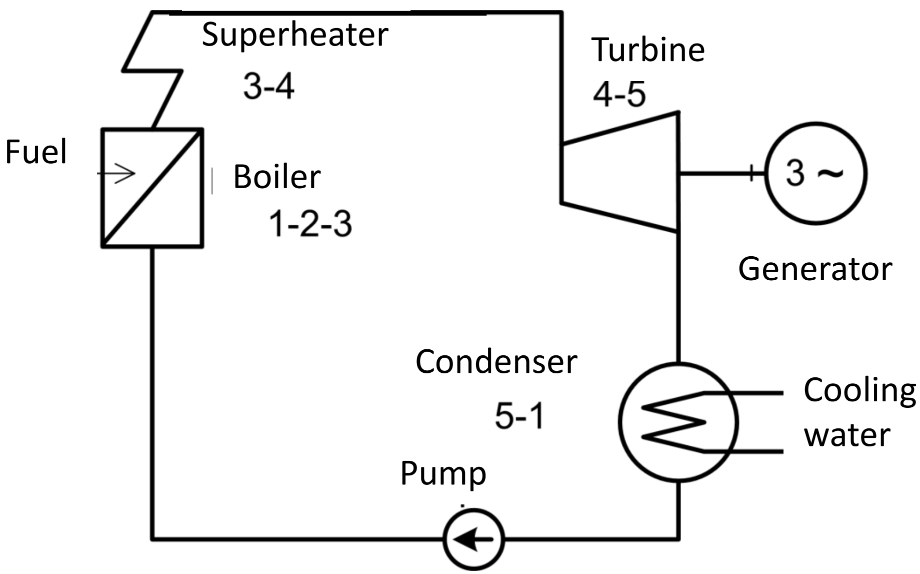


Mollier diagram of water (h-s diagram of water and steam)



Clausius-Rankine cycle





- **1-2-3** Isobaric heating and water vaporization
- **3-4** Isobaric steam superheating
- **4-5** Adiabatic steam expansion in turbine
- **5-1** Isobaric steam condensation in condenser

Clausius-Rankine efficiency

- Determination of heat delivered to the system

$$Q_p = h_4 - h_1$$

- Mechanical work of turbine

$$W = h_4 - h_5$$

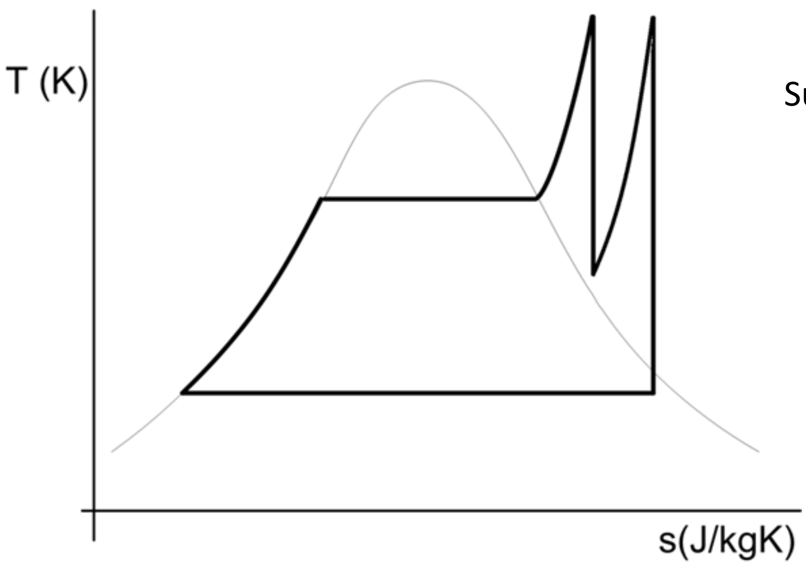
- Thermal efficiency of C-R cycle

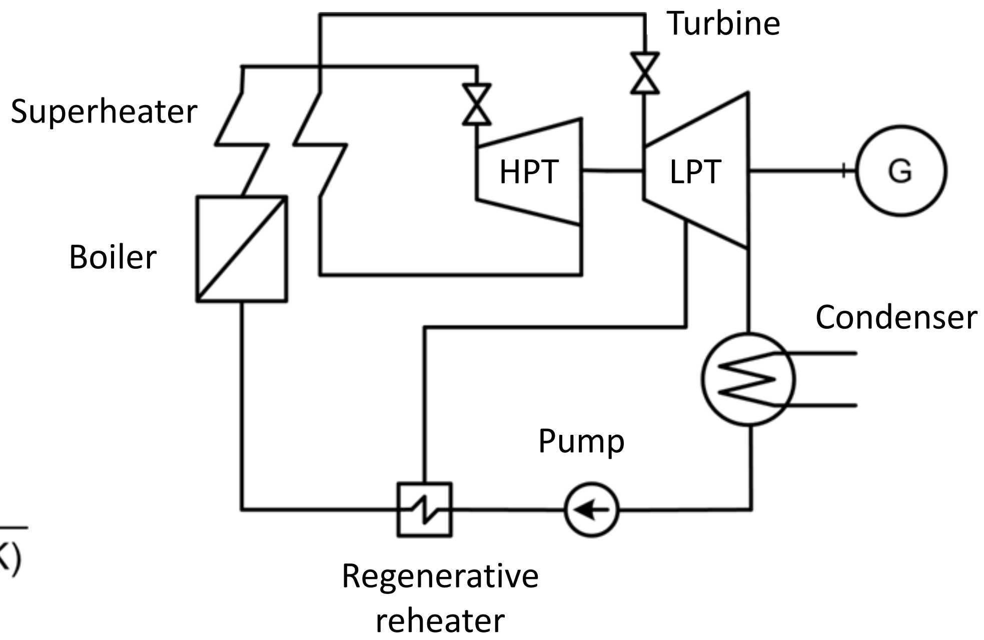
$$\eta = \frac{W}{Q_p} = \frac{h_4 - h_5}{h_4 - h_1}$$

Methods of increasing C-R cycle efficiency

- Increase in temperature and pressure of steam
  - Large demands on material, construction and safety parameters
  - Supercritical power plants
- Decrease in temperature and pressure in condenser
  - Limited by ambient temperature
  - Common condensing temperature and pressure 30 °C, 4 kPa
- Repeating of cycle part with highest efficiency
  - Steam re-superheating (multiple as well)

Increase of C-R efficiency by steam reheating

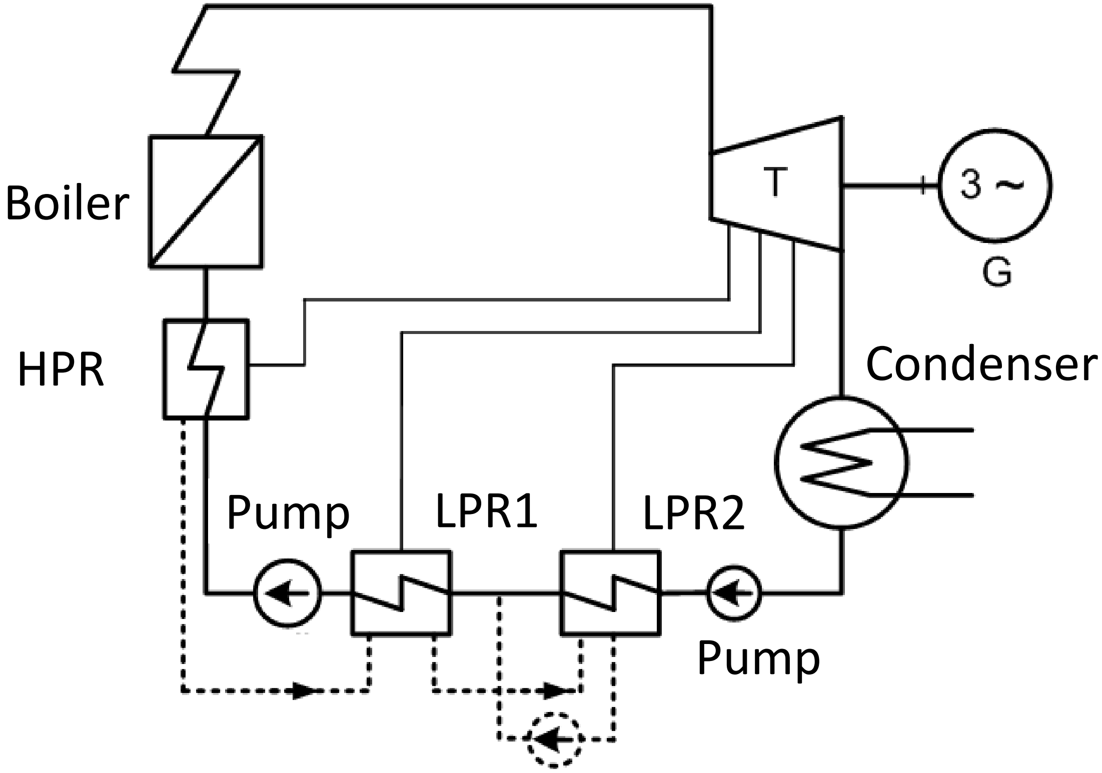




Regenerative reheating of feed water

- Reheating of feed water between condenser and boiler by heat exchanger
- The heating medium is steam taken from turbine
- Decrease in the heat losses in the condenser → increase of efficiency

Regenerative reheating system

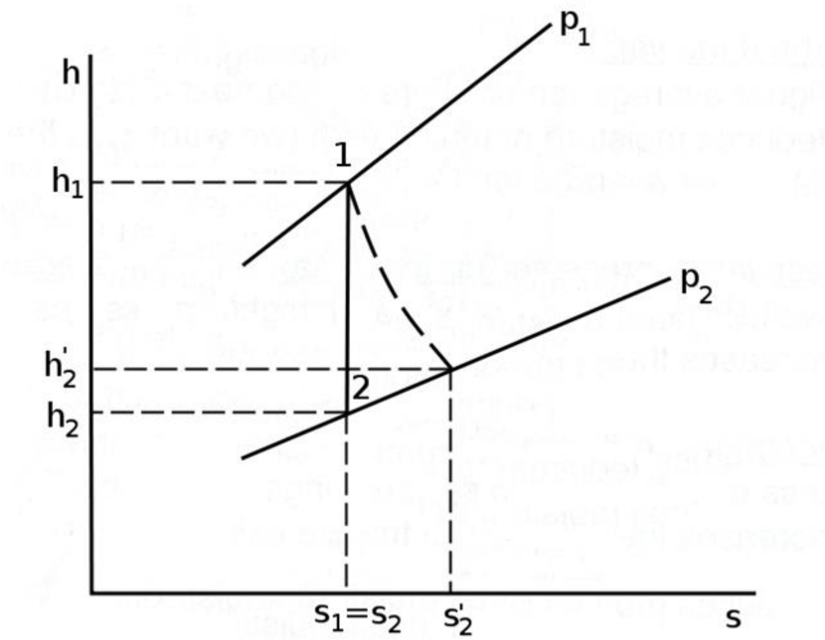


HPR – high pressure reheater

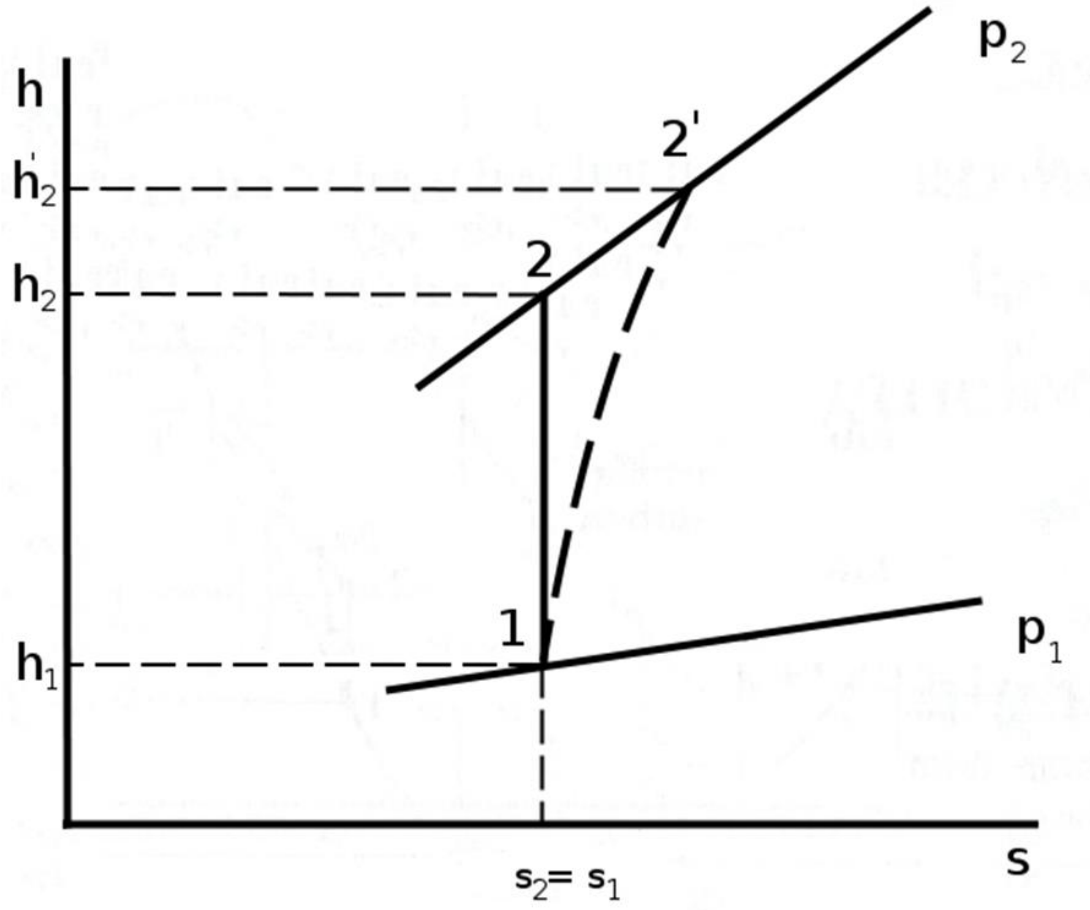
LPR – low pressure reheater

Losses in a turbine

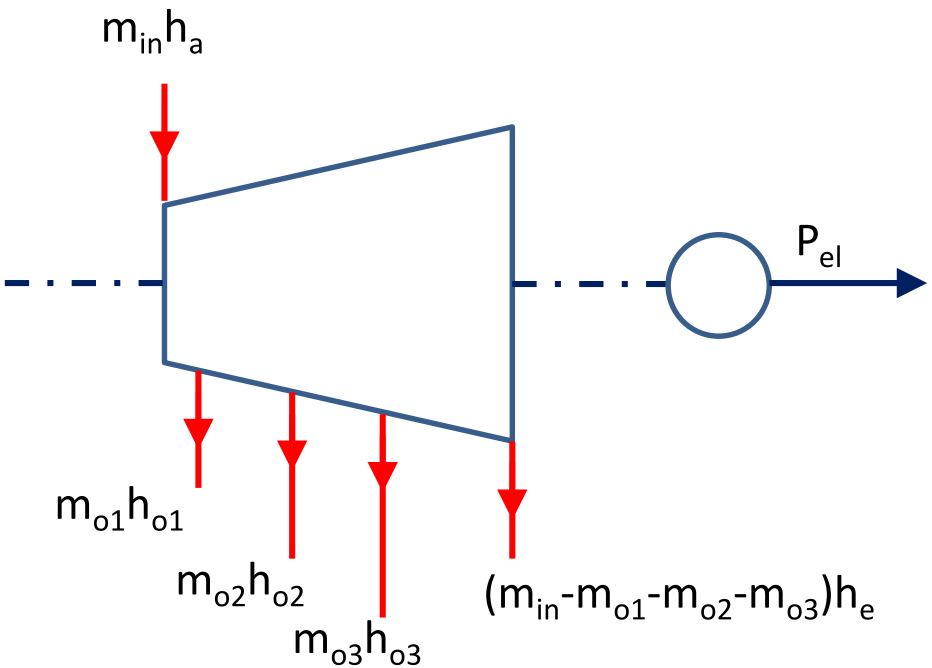
- Friction losses, losses by internal leakages, loss by changing the direction of flow, ...



Losses in feed pump



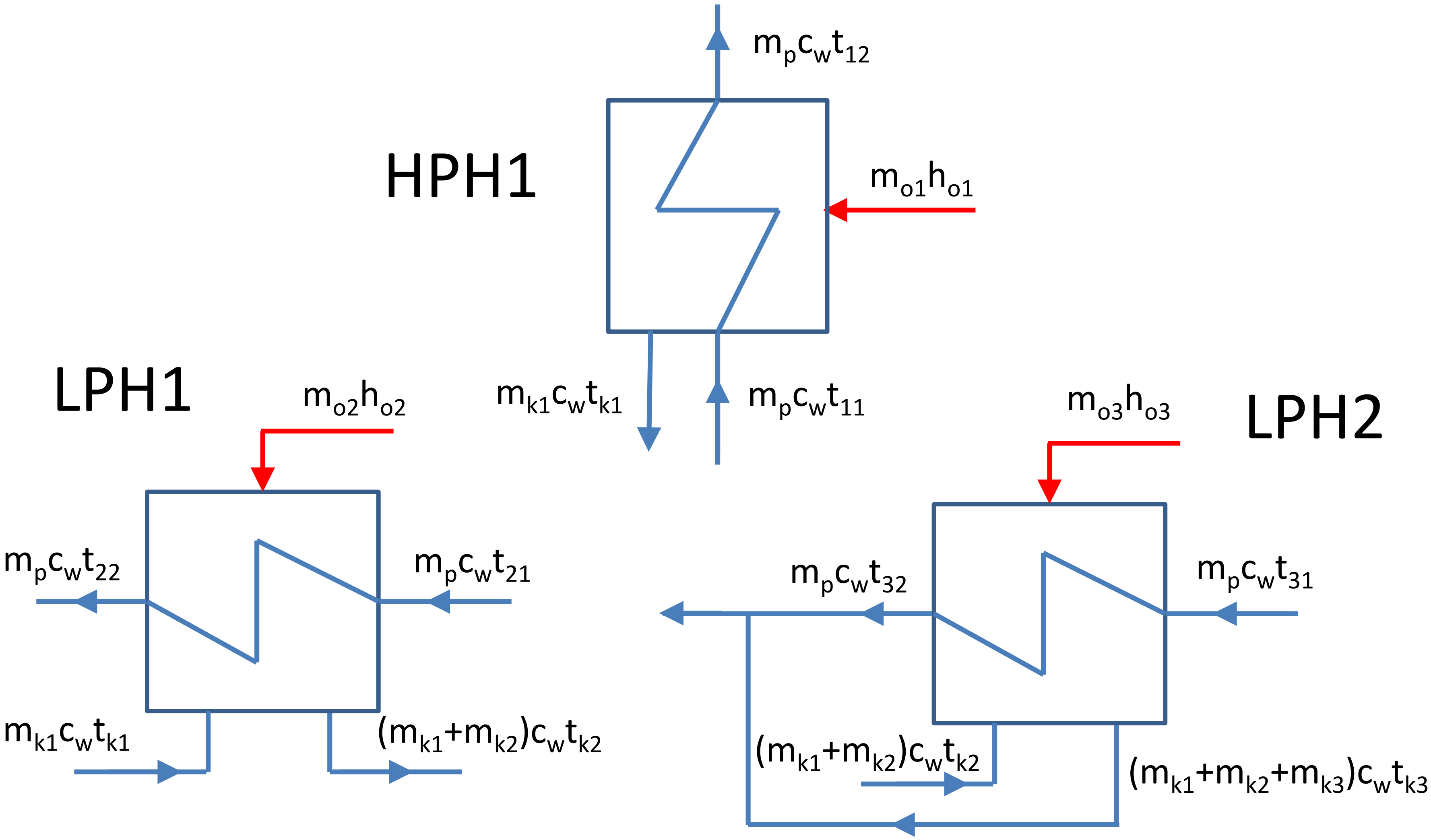
Energy balance of a turbine



$$m_{in}h_a - (m_{o1}h_{o1}+m_{o2}h_{o2}+m_{o3}h_{o3}) - (m_{in} - m_{o1} - m_{o2} - m_{o3})h_e - P_{el} - Q_z = 0$$

Note: m is the mass flow in kg/s, P_{el} is the electric energy, Q_z are energy losses in turbine and generator and h is enthalpy

Energy balance of regenerative reheaters



Energy balance of regenerative reheators

- HPR

$$m_{01}h_{01} + m_p c_w t_{11} - m_p c_w t_{12} - m_{k1} c_w t_{k1} = 0$$

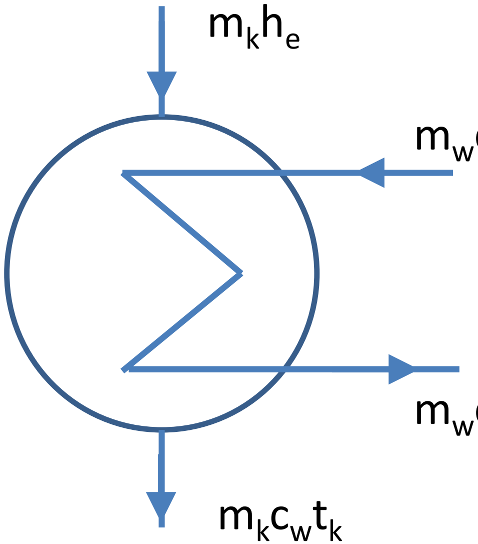
- LPR1

$$m_{o2}h_{02} + m_p c_w t_{21} + m_{k1} c_w t_{k1} - m_p c_w t_{22} - (m_{k1} + m_{k2}) c_w t_{k2} = 0$$

- LPR2

$$m_{o3}h_{03} + m_p c_w t_{31} + (m_{k1} + m_{k2}) c_w t_{k2} - m_p c_w t_{32} - (m_{k1} + m_{k2} + m_{k3}) c_w t_{k3} = 0$$

Energy balance of a condenser



$$m_k h_e + m_w c_w t_{w1} - m_w c_w t_{w2} - m_k c_w t_k = 0$$

Heat power of condenser:

$$Q_k = m_w c_w (t_{w2} - t_{w1}) = m_k (h_e - c_w t_k)$$

Energy balance of a boiler

$$m_p h_{nv} - m_p h_a + m_{pv} q_n - Q_z = 0$$

- Boiler efficiency

$$\eta_b = \frac{m(h_a - h_{nv})}{m_{pv} q_n} = \frac{Q_1}{m_{pv} q_n}$$

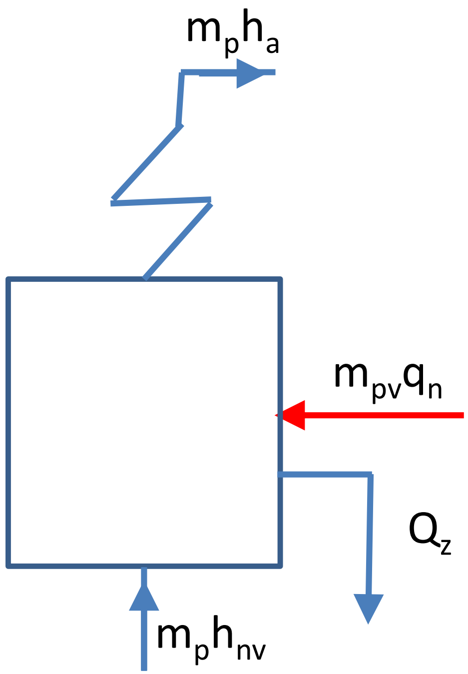
- Specific heat consumption

$$q_s = \frac{3\,600 Q_1}{P} \qquad \text{(kJ/kWh)}$$

- Specific steam consumption

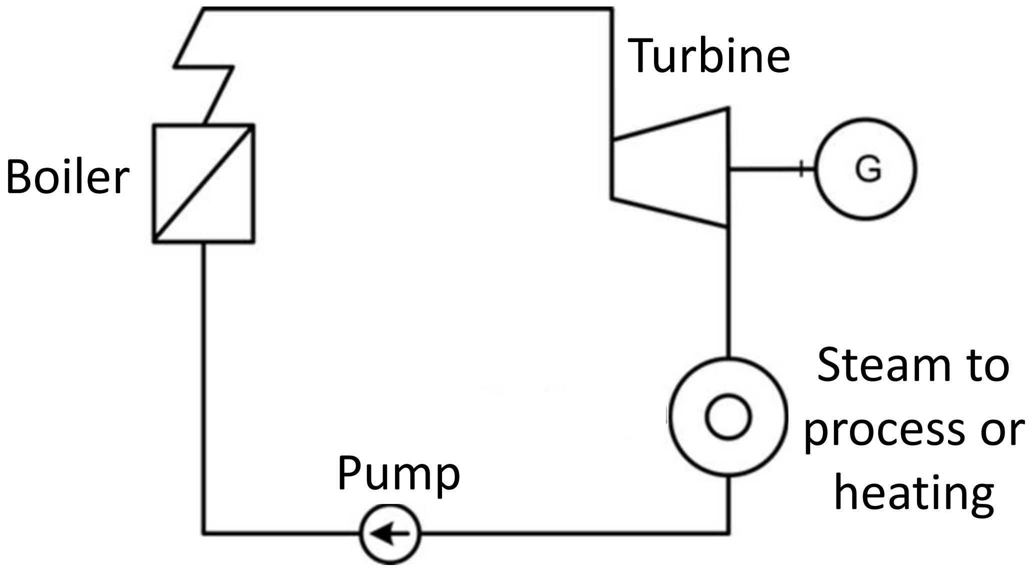
$$m_p = \frac{3\,600 m}{P} \qquad \text{(kg/kWh)}$$

where P is the electric power and m is the steam mass flow



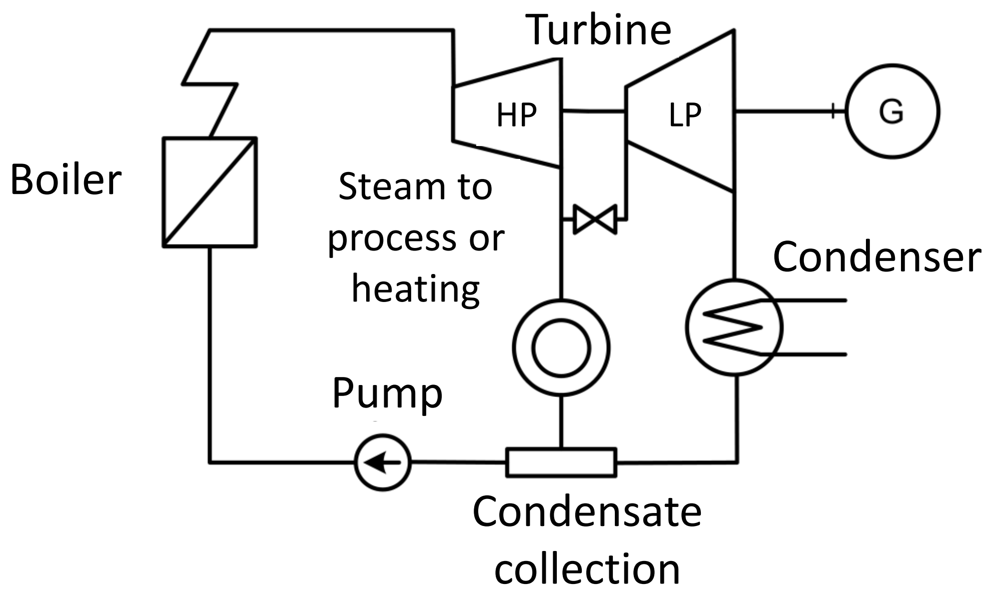
Combined heat and power (CHP) production

- Back-pressure turbine

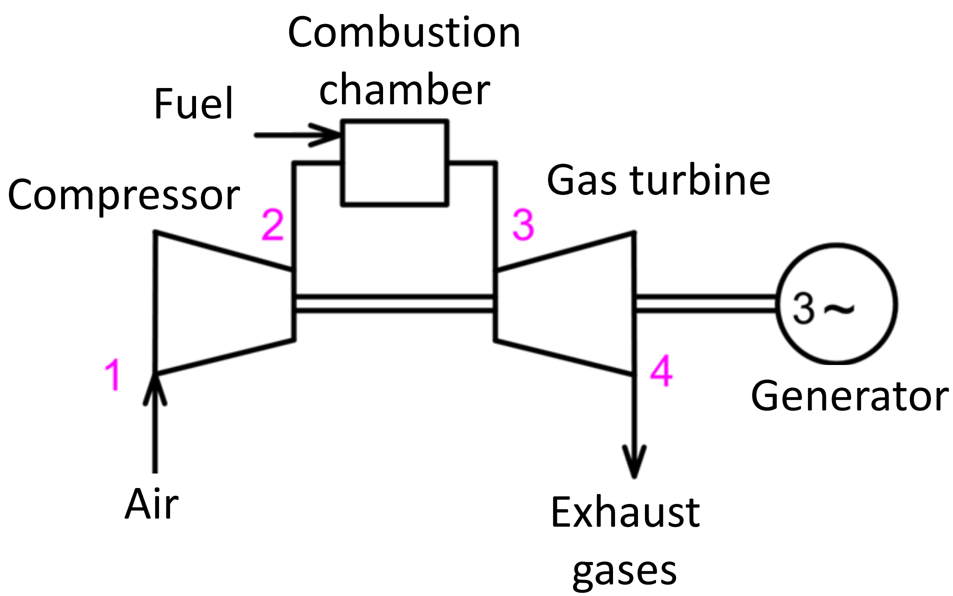


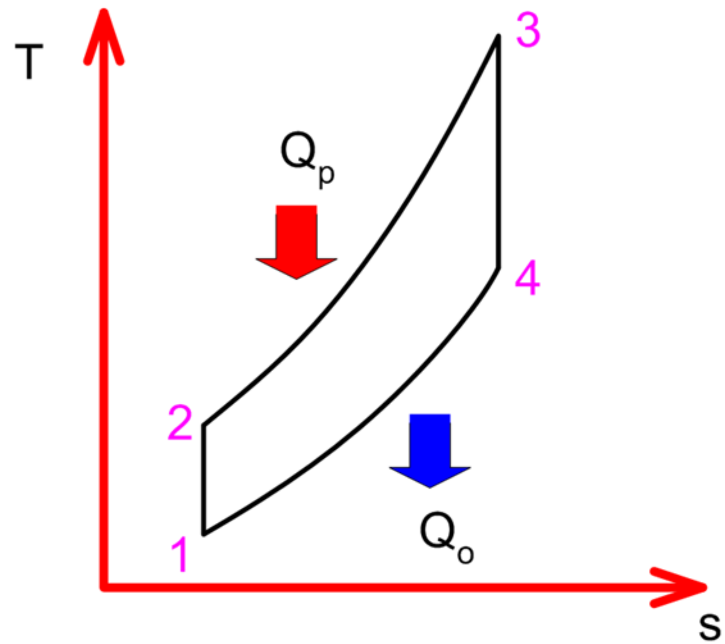
Combined heat and power (CHP) production

- Extraction steam turbine (controlled steam distribution)



Gas power cycle





Combined cycle