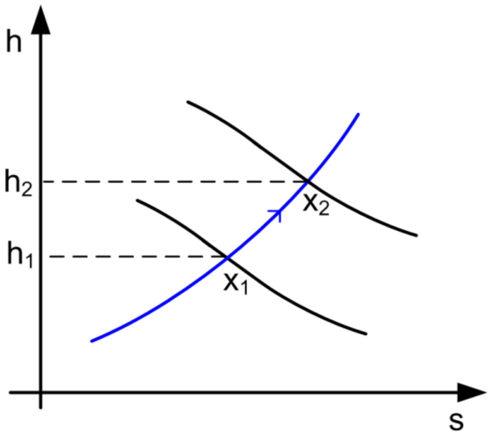
Example 1:

How is the applied heat for 1 kg of water steam at constant pressure p = 1.47 MPa, if the dryness of wet water is increased from x_1 = 0.8 to x_2 = 0.96?

Solution:



Dryness of wet steam – the ratio of steam content and the total mixture of steam and water:

$$x = \frac{m_s}{m_s + m_w}$$

The thermodynamic process is isobaric, thus $\delta Q = dH$ (supplied heat directly corresponds to the change of enthalpy):

$$q_s = h_2 - h_1 = 2\,710 - 2\,400 = 310\ kJ \cdot kg^{-1}$$

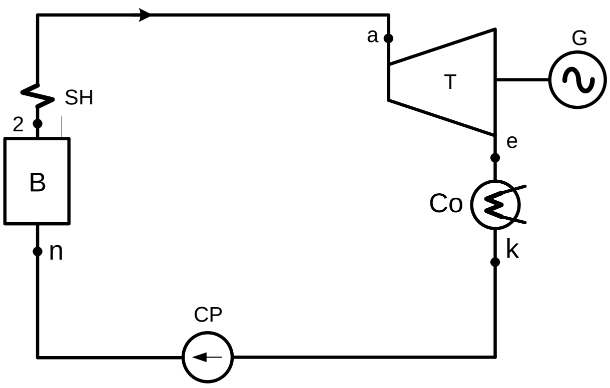
$$Q_s = q \cdot M_p = 310\ kJ$$

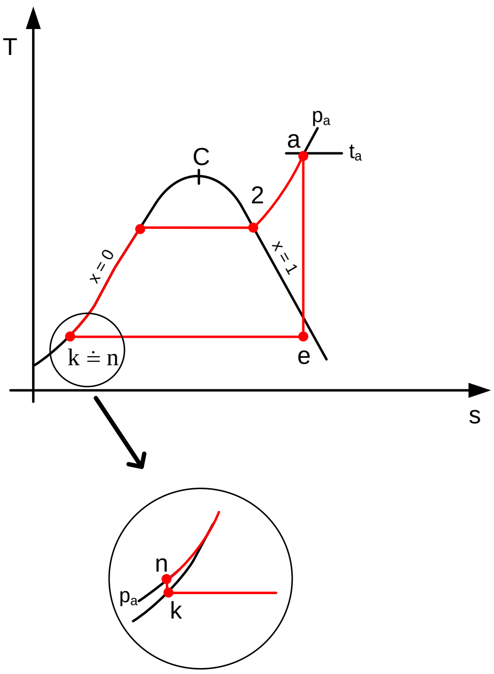
Example 2: Clausius-Rankine cycle

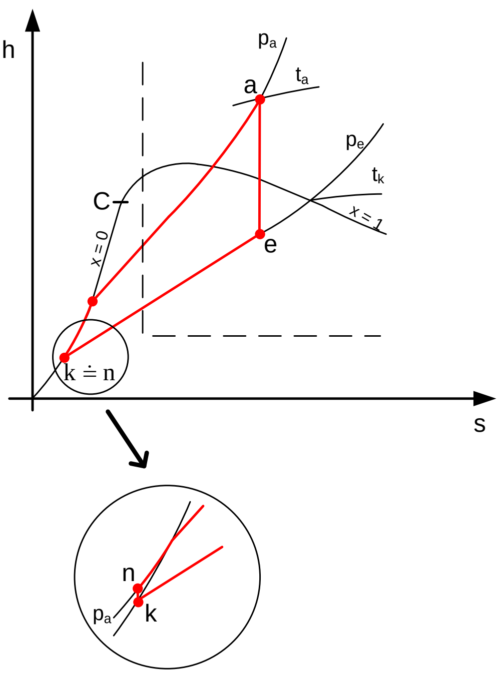
Calculate the heat efficiency of ideal Clausius-Rankine thermal cycle. Parameters of superheat steam (admission steam) are – pressure p_a = 80.10^5 Pa and temperature t_a = 450°C. The emission (output) pressure from turbine is p_e = 5 kPa.

Solution:

Each points (n, 2, a, e, k) are related to points in T-s (temperature-entropy) and h-s (enthalpy-entropy) diagrams:







Process k-n: The working fluid (general water) is pumped from low to high pressure. As the water is liquid at this stage, the pump requires little input energy. Usually this process is neglected for calculation of thermodynamic efficiency.

Process n-a: The high pressurized water enters to the boiler and heated at constant pressure by an external heat source to become a dry saturated steam (n-2). The saturated steam is then overheated by superheater (2-a). The required amount of input heat energy q_s can be easily calculated using the h-s diagram (Mollier diagram of water and steam). The admission enthalpy $\mathbf{h_a}$ is given by pressure and temperature of overheated steam and can be read from h-s diagram or steam table.

Process a-e: The overheated steam expands in a turbine and the power is generated. Temperature and pressure of the steam drop to the low values. The emission steam enthalpy $\mathbf{h_e}$ is given by output pressure and temperature and can be read from h-s diagram or steam table. The ideal adiabatic process (isentropic) is usually assumed.

Process e-k: The wet steam enters to the condenser where the steam condensates to water at constant pressure. The condenser is cooled by cooled water and the heat energy q_w is taken out from the cycle.

Then water is pumped back to the boiler (process k-n).

In general, the efficiency of a simple Clausius-Rankine cycle can be written as:

$$\eta = \frac{q_u}{q_s} = \frac{q_s - q_w}{q_s} = \frac{(h_a - h_k) - (h_e - h_k)}{h_a - h_k} = \frac{h_a - h_e}{h_a - h_k}$$

where q_u is utilized heat, q_s is supplied heat and q_w is waste heat.

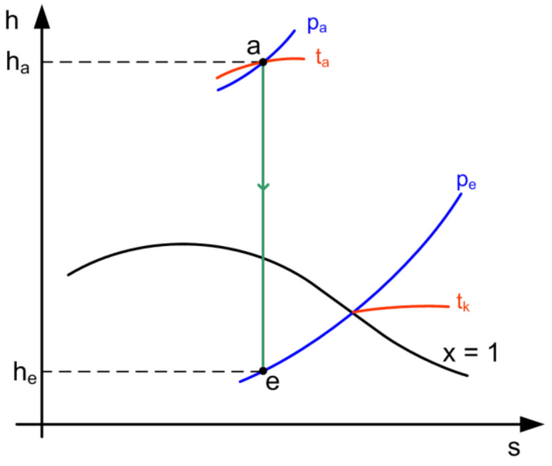
The enthalpies h_a and h_k are determined from h-s diagram. The enthalpy h_a is in the intersection of isobar 8 MPa and isotherm 450 °C. If the ideal adiabatic process is assumed, the entropy is constant, and the enthalpy h_e can be found as enthalpy in the point at isobar 5 kPa which creates the vertical line with intersection of isobar 8 MPa and isotherm 450 °C.

These values are: h_a = 3275 kJ.kg^{-1}, h_e = 2000 kJ.kg^{-1}

The condensate enthalpy (boiling liquid) has to be taken from the steam and water tables for pressure p_e = 5 kPa and temperature t_k = 32.5°C or approximately calculated according to formula:

$$h_k \doteq c_w \cdot t_k = 4.2 \cdot 32.5 = 136.5\ kJ \cdot kg^{-1}$$

The thermal efficiency of the theoretical (ideal) Clausius-Rankine cycle will be:



$$\eta = \frac{h_a - h_e}{h_a - h_k} = \frac{3\,275 - 2\,000}{3\,275 - 136.5} = 0.406$$

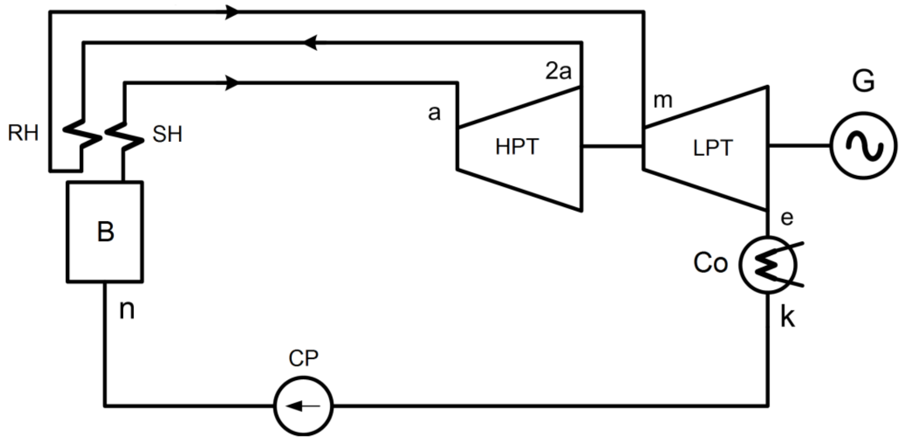
Example 3: The steam reheating

The thermal circuit with steam reheating works with these parameters:

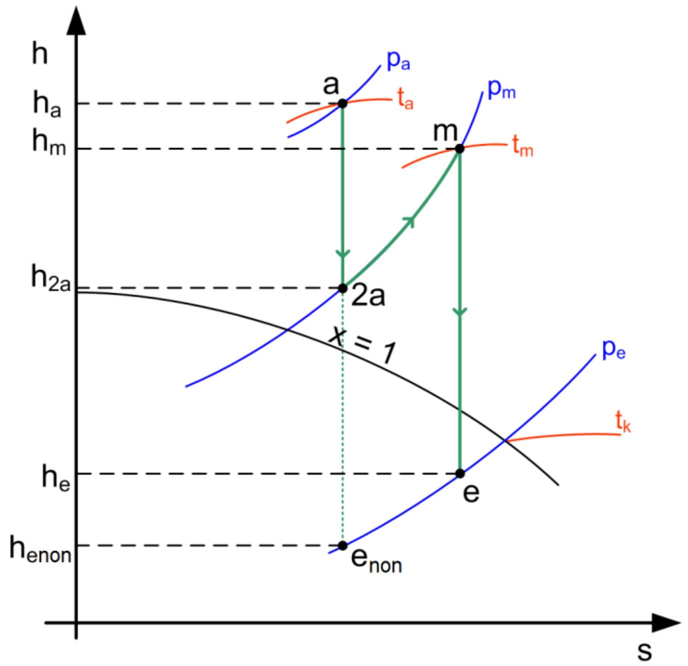
The admission steam pressure p_a = 10 MPa and the temperature t_a = 530°C. The steam pressure after the expansion in the high pressure part of turbine is p_m = 1.5 MPa. Then the steam is isobarically reheated to the temperature t_m = 460°C in the superheater. The output emission pressure from turbine is p_e = 5 kPa. Compare thermal efficiencies of thermal cycle with and without steam reheating.

Solution:

Block diagram of Clausius-Rankine (C-R) cycle with steam reheating:



Enthalpy which is needed for thermal cycle efficiency calculations is given by h-s diagram:



h_a = 3 450 kJ.kg^{-1}; h_{2a} = 2 920 kJ.kg^{-1}; h_m = 3 370 kJ.kg^{-1}; h_e = 2 275 kJ.kg^{-1}; h_{enon} = 2 050 kJ.kg^{-1}

The pressure p_e corresponds approximately to the temperature t_k = 32.9°C.

Enthalpy: $h_k = c_w \cdot t_k = 4.2 \cdot 32.9 = 138.2\ kJ \cdot kg^{-1}$

The heat which is supplied to the cycle is increased by enthalpy difference related to the steam reheating in superheater. The waste heat of the cycle is changed due to the emission enthalpy change.

Thermodynamic efficiency of ideal thermal cycle with steam reheating:

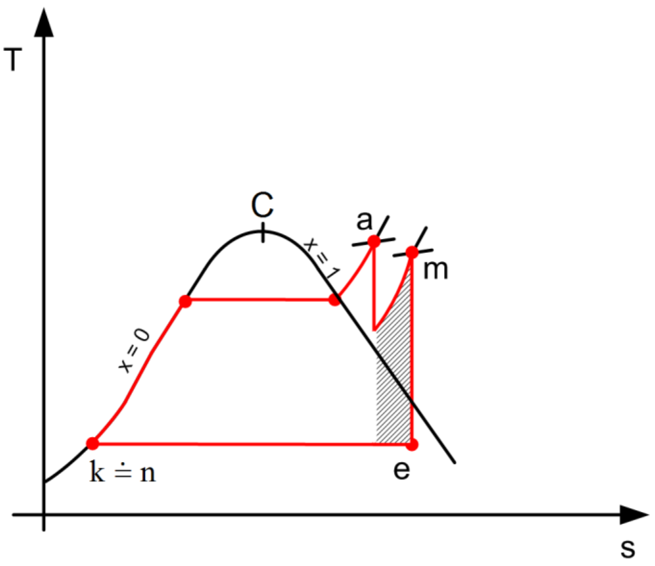
$$\eta = \frac{w}{q_s} = \frac{h_a - h_{2a} + h_m - h_e}{h_a - h_k + h_m - h_{2a}}$$

$$\eta = \frac{3450 - 2920 + 3370 - 2275}{3450 - 138.2 + 3370 - 2920} = 0.432$$

Thermodynamic efficiency of ideal thermal cycle without steam reheating:

$$\eta_{non} = \frac{w}{q_s} = \frac{h_a - h_{enon}}{h_a - h_k} = \frac{3450 - 2050}{3450 - 138.2} = 0.423$$

An influence of the steam reheating to thermal cycle and its thermal cycle efficiency is evident from the following picture. The shaded part of the heat cycle corresponds to the heat supplied by steam reheating.



Example 4: Clausius-Rankine cycle

The steam has admission temperature T_a = 535 °C and pressure p_a = 16.2 MPa. How is the thermal efficiency of cycle when the temperature of condensate water is t_k = 25 °C?

Solution:

The admission enthalpy h_a and emission enthalpy h_e can be read from h-s diagram.

The enthalpy of condensate h_k can be approximately calculated as:

$$h_k \doteq c_p \cdot t_k = 4.2 \cdot 25 = 105\ kJ \cdot kg^{-1}$$

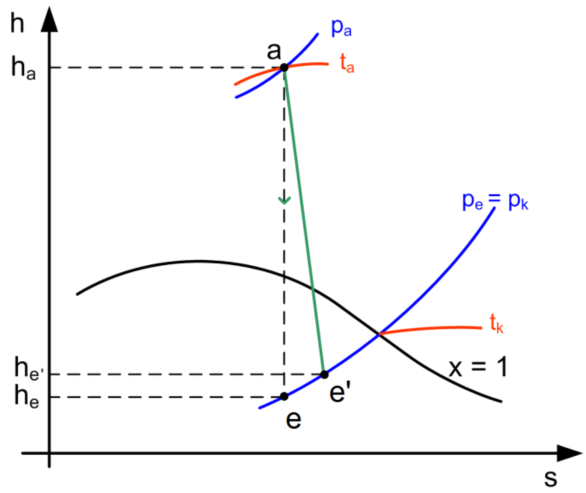
The thermal cycle efficiency of C-R cycle:

$$\eta = \frac{h_a - h_e}{h_a - h_k} = \frac{3405 - 1905}{3405 - 105} = 0.455$$

Example 5: Non-ideal expansion in a turbine

What is the efficiency change of above thermodynamic cycle (T_a = 535 °C, p_a= 16.2 MPa, t_k = 25°C, η = 0.455), if the adiabatic expansion in turbine is non-ideal (losses are taken into account)? Assume the thermodynamic efficiency of turbine η_{td} = 0.8 (instead of 1 in the case of ideal process).

Solution:



The non-ideal emission enthalpy h_e can be calculated from the turbine thermodynamic efficiency formula:

$$\eta_{td} = \frac{h_a - h_{e'}}{h_a - h_e} \rightarrow h_{e'} = h_a - \eta_{td} \cdot (h_a - h_e)$$

$$h_{e'} = 3\,405 - 0.8 \cdot (3\,405 - 1\,905) = 2\,205\ kJ/kg$$

The thermal efficiency of C-R cycle when the non-ideal adiabatic expansion is taken in to account is:

$$\eta' = \frac{h_a - h_{e'}}{h_a - h_k} = \frac{3405 - 2205}{3405 - 4.2 \cdot 25} = 0.364,$$

and the change of efficiency is:

$$\Delta\eta = \eta - \eta' = 0.455\ - 0.364 = 0.091.$$