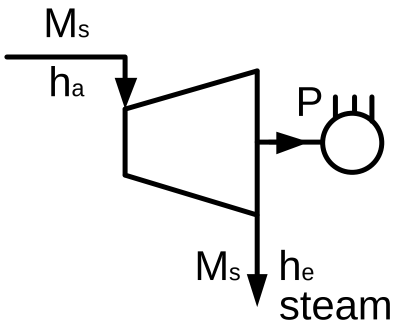
Example 1: The turbine balance

How is the mass flow (kg/h) and specific steam consumption (kg/kWh) per one second of turbine with nominal power 100 MW? Admission superheat steam parameters are: temperature 560 °C and pressure 16 MPa. The emission wet steam temperature is 29 °C.

Solution:



We can use the equation of energy balance for every part of Clausius – Rankine cycle.

The turbine energy balance is (see figure):

$$M_s \cdot h_a - M_s \cdot h_e - P_p \cdot t = 0$$

where:

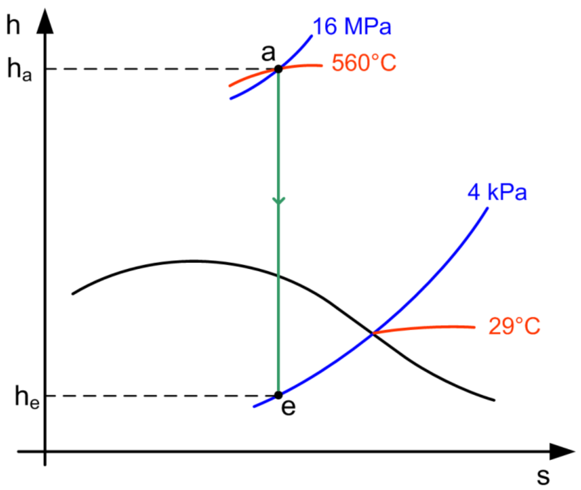
M_s ... mass of steam (kg)

h_a ... enthalpy of admission steam (superheat steam) (kJ/kg), from h-s chart

h_e ... enthalpy of emission steam (wet steam) (kJ/kg), from h-s chart

P_p ... produced power (kW)

t ... time of for mass of steam utilization (t)



Expressing the mass of steam:

$$M_s = \frac{P_p \cdot t}{h_a - h_e} = \frac{100 \cdot 10^3 \cdot 1}{3\,485 - 1\,980} = 66.45\ kg$$

The mass flow:

$$\dot{m}_{sm} = M_s \cdot 3\,600 = 239.2\ \cdot 10^3\ kg \cdot h^{-1}$$

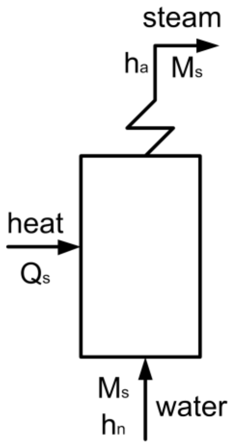
For specific steam consumption:

$$m_s = \frac{\dot{m}_{sm}}{P_p} = \frac{239.2\ \cdot 10^3}{100 \cdot 10^3} = 2.39\ kg \cdot kWh^{-1}$$

Example 2: The boiler balance

How much heat has to be supplied to the water with temperature t_n = 19 °C to create 66.45 kg of superheat steam with temperature 560 °C and pressure 16 MPa?

Solution:



Boiler balance equation is:

$$Q_s + M_s \cdot h_n - M_s \cdot h_a = 0$$

Where Q_s … supplied heat (kJ)

M_s … mass of steam (kg)

h_a … admission enthalpy (steam outlet from boiler) (kJ/kg)

h_n … emission enthalpy (water inlet to boiler) (kJ/kg)

Expression of supplied heat:

$$Q_s = M_s \cdot (h_a - h_n) = M_s \cdot (h_a - c_w \cdot t_n) = 66.45 \cdot (3485 - 4.2 \cdot 19) = 226.3\ MJ$$

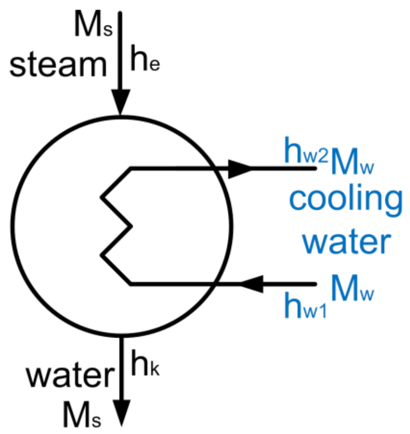
where c_w … specific heat capacity of water (4,2 $kJ \cdot kg^{-1} \cdot K^{-1}$)

t_n … temperature of water (°C)

Example 3: The condenser balance

How is the mass flow of cooling water in a condenser? The input wet steam to the condenser has the mass flow $\dot{m}_s$ = 74.2·10^3 kg.h^{-1},the pressure p_e = 4 kPa and the enthalpy h_e = 2 253 kJ.kg^{-1}. The maximal permitted warming of cooling water is Δt_w = 8 °C.

Solution:



The mass flow of cooling water is given by condenser energy balance in the form:

$$\dot{m}_s \cdot h_e + \dot{m}_w \cdot h_{w1} - \dot{m}_w \cdot h_{w2} - \dot{m}_s \cdot h_k = 0$$

where

$\dot{m}_s$ … mass flow of the steam (kg/h)

$\dot{m}_w$ … mass flow of the cooling water (kg/h)

h_e … enthalpy of the emission steam (inlet to the condenser) (kJ/kg)

h_k … enthalpy of the condensate (outlet from the condenser) (kJ/kg)

h_{w1} … input enthalpy of the cooling water (kJ/kg)

h_{w2} … output enthalpy of the cooling water (kJ/kg)

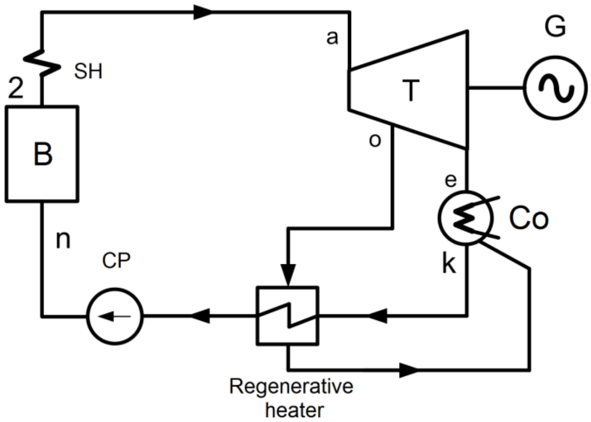
The temperature of condensate at condenser pressure and dryness curve is t_k = 29°C. The mass flow of the cooling water is then:

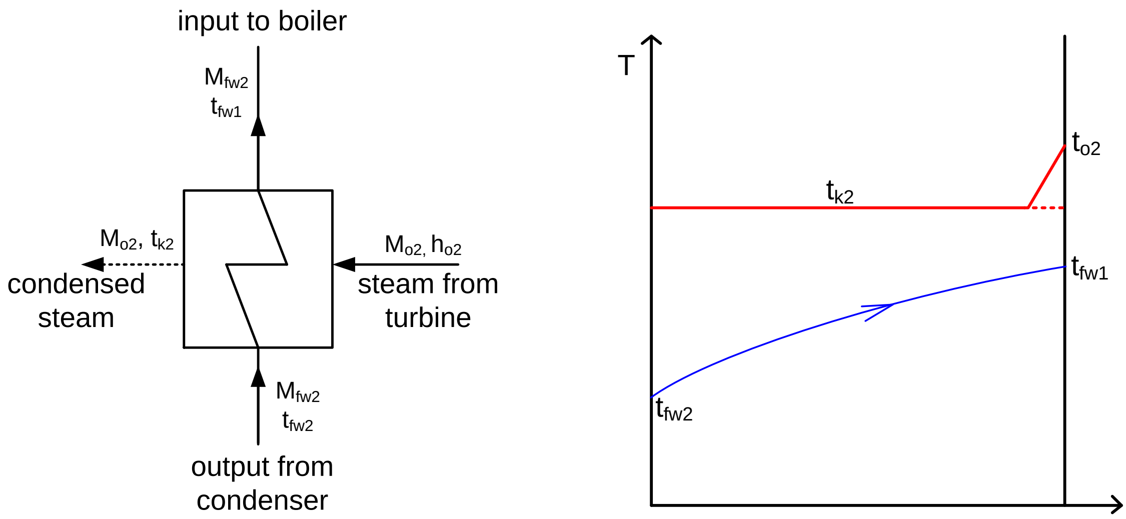
$$\dot{m}_w = \frac{\dot{m}_p \cdot (h_e - h_k)}{h_{w2} - h_{w1}} = \frac{\dot{m}_p \cdot (h_e - c_w \cdot t_k)}{c_w \cdot \Delta t_w} = \frac{74.2 \cdot 10^3 \cdot (2253 - 4.18 \cdot 29)}{4.2 \cdot 8} = 4.73 \cdot 10^6\ kg \cdot h^{-1}$$

Example 4: The regenerative heater balance

How is the needed mass flow of a steam with pressure $p_o = 0.68$ MPa and enthalpy $h_o = 2\ 870$ kJ.kg^{-1} for the heating of feed water to regenerative heater? The temperature increase of feed water should be from $t_{fw2} = 94$ °C to $t_{fw1} = 160$ °C at mass flow $\dot{m}_{fw2} = 97.10^3$ kg.h^{-1}.

Solution:





The temperature of condensed steam (on the dryness curve at steam pressure $p_o = 0.68$ MPa) is $t_{k2} = 163$ °C. The needed mass flow of the steam is calculated according to energy balance of the heater:

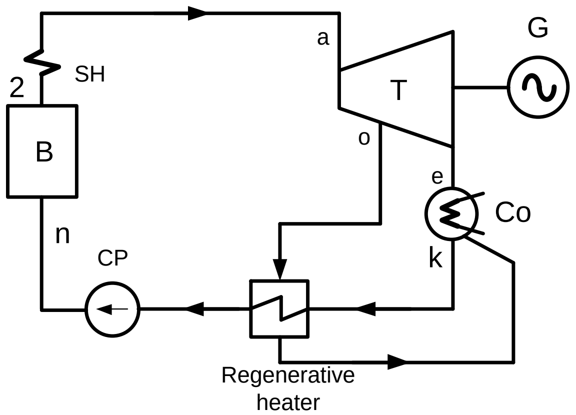
$$\dot{m}_{o2} \cdot (h_{o2} - c_w \cdot t_{k2}) = -\dot{m}_{fw2} \cdot c_w \cdot (t_{fw2} - t_{fw1})$$

$$\dot{m}_{o2} = \frac{\dot{m}_{fw2} \cdot c_w \cdot (t_{fw1} - t_{fw2})}{h_{o2} - c_w \cdot t_{k2}} = \frac{97 \cdot 10^3 \cdot 4.2 \cdot (160 - 94)}{2870 - 4.2 \cdot 163} = 12.3 \cdot 10^3\ kg \cdot h^{-1}$$

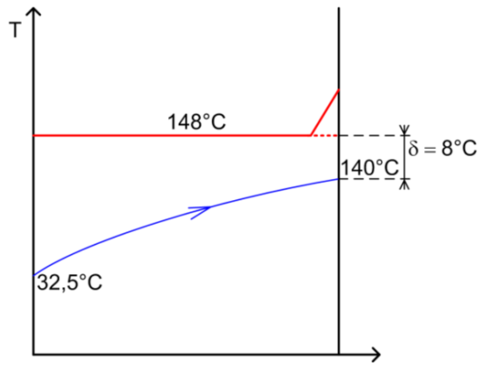
Example 5: The thermal efficiency of the thermal circuit with a regenerative water heating

How is the thermal efficiency of the thermal circuit with a regenerative heating of feed water. The admission steam pressure and temperature are $p_a = 80.10^5$ Pa and $t_a = 450$ °C. The emission steam pressure is $p_e = 5$ kPa. The required temperature of feed water is 140°C. The temperature of the steam from turbine which is needed for regenerative heater is about 8 °C higher than the temperature of output feed water.

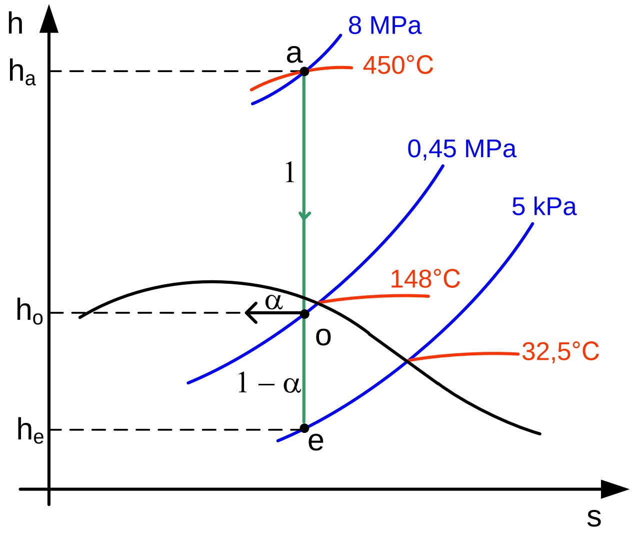
Solution:

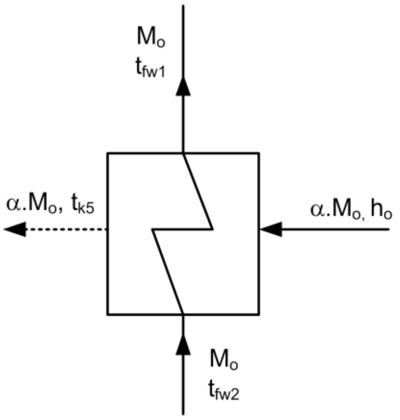


The enthalpy of admission steam for the admission pressure and temperature is given from h-s diagram: $h_a = 3\,275$ kJ.kg^{-1}. The emission enthalpy of the steam turbine is $h_e = 2\,000$ kJ.kg^{-1}.



The temperature of the steam which is needed for regenerative heater is about 8 °C higher than temperature of the output warm feed water => $t_o = 148$ °C. This temperature corresponds to the pressure $p_o = 0.45$ MPa. The enthalpy of the steam for regenerative heater $h_o = 2\,610$ kJ.kg^{-1} can be found as intersection of isobar 0.45 MPa and expansion line (line with constant entropy connecting point a and o in h-s diagram).





The amount of steam for regenerative heater is calculated according to the heat balance of heater. The ratio of the steam needed for regenerative heater to the total amount of the steam M_o flowing through the turbine is marked as α. Then,

$$\alpha \cdot M_o \cdot (h_o - h_5) = -M_o \cdot (h_{w2} - h_{w1})$$

and

$$\alpha = \frac{c_w \cdot (t_{fw1} - t_{fw2})}{h_o - c_w \cdot t_{k5}} = \frac{4.2 \cdot (140 - 39)}{2610 - 4.2 \cdot 148} = 0.213.$$

One kg of input steam to the turbine performs the work:

$$w = \alpha \cdot (h_a - h_o) + (1 - \alpha) \cdot (h_a - h_e) = 0.213 \cdot (3275 - 2610) + (1 - 0.213) \cdot (3275 - 2000) = 1145.1\ kJ \cdot kg^{-1}$$

The amount of heat which is needed for 1 kg of feed water in the boiler is:

$$Q_s = h_a - h_{fw1} = h_a - c_w \cdot t_{fw1} = 3275 - 4.2 \cdot 140 = 2687\ kJ \cdot kg^{-1}$$

and then the efficiency of the thermal cycle is:

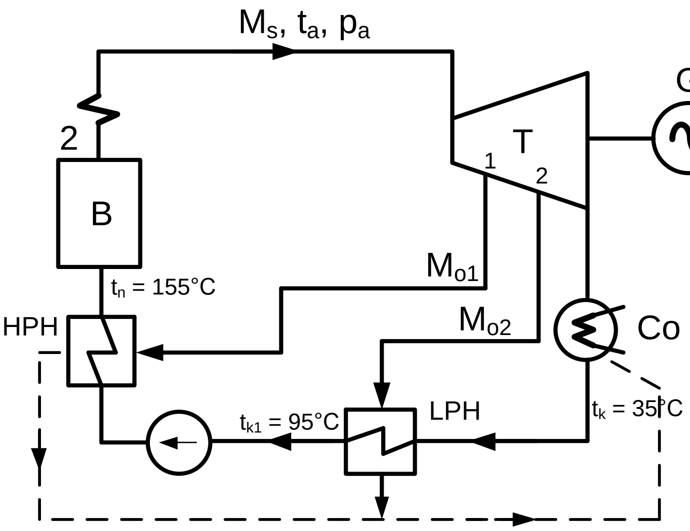
$$\eta = \frac{A}{Q_s} = \frac{1145.1}{2687} = 0.426.$$

(The efficiency of the same thermal circuit without regenerative heating is η = 0.406, see the example 1 in 3th lecture)

Example 6: Influence of regenerative heater outages

Perform an approximate calculation of turbine mechanical power decrease or increase when the a) HPH – high pressure regenerative heater of feed water or b) LPH – low pressure regenerative heater of feed water are switched off.

The steam mass flow to turbine is $\dot{m}_s = 100\ \text{kg.s}^{-1}$, admission pressure and temperature are p_a = 10 MPa and t_a = 500 °C. The output temperature of condensate is t_k = 35 °C. The temperature of input feed water to the boiler is t_n = 155 °C. The steam which is needed for heaters LPH and HPH is always higher about 5°C then the output feed water from the relevant heater. The thermal gradient is divided equally between LPH and HPH. The situation is shown in diagram.



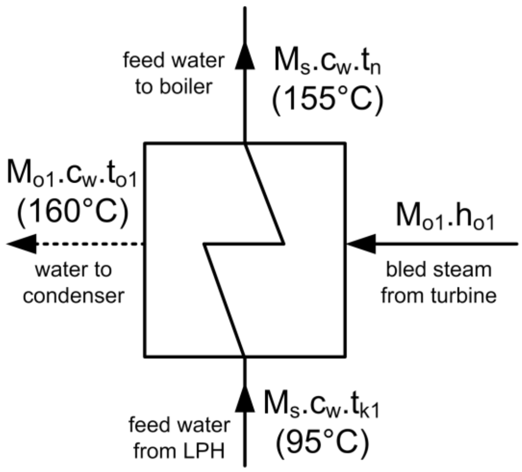
Solution:

The temperature difference of feed water heating is:

$$\Delta t = 155\ °C - 35\ °C = 120\ °C$$

Two heaters are used to heat the feed water – LPH and HPH. The thermal gradient is divided equally, it means that each heater increases the temperature about 120 °C / 2 = 60 °C.

The HPH energy balance is shown in diagram. The needed amount of steam to heat the feed water can be calculated from balance equation of heater:

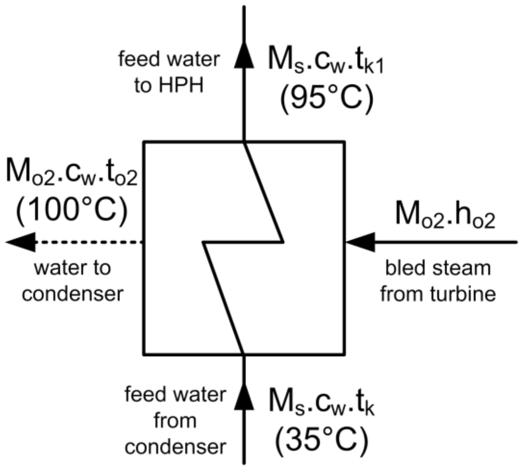


$$\dot{m}_s \cdot c_w \cdot t_{k1} + \dot{m}_{o1} \cdot h_{o1} - \dot{m}_s \cdot c_w \cdot t_n - \dot{m}_{o1} \cdot c_w \cdot t_{o1} = 0$$

The steam condensates at the pressure 0.6 MPa and steam temperature 160 °C – intersection of expanse turbine line and isobar 0.6 MPa gives the enthalpy $h_{o1} = 2\ 650\ \text{kJ.kg}^{-1}$. Then,

$$\dot{m}_{o1} = \frac{\dot{m}_s \cdot c_w \cdot (t_{k1} - t_n)}{h_{o1} - c_w \cdot t_{o1}} = \frac{100 \cdot 4.2 \cdot (155 - 95)}{2650 - 4.2 \cdot 160} = 12.74\ kg \cdot s^{-1}.$$

The needed amount of steam to heat feed water by LPH, , can be calculated from balance equation of heater LPH (see the diagram):



$$\dot{m}_s \cdot c_w \cdot t_k + \dot{m}_{o2} \cdot h_{o2} - \dot{m}_s \cdot c_w \cdot t_{k1} - \dot{m}_{o2} \cdot c_w \cdot t_{o2} = 0$$

Steam condensates at the pressure 0.1 MPa at the steam temperature 100 °C – intersection of expanse turbine line and isobar 0.1 MPa gives the enthalpy h_{o2} = 2 350 kJ.kg^{-1}, then

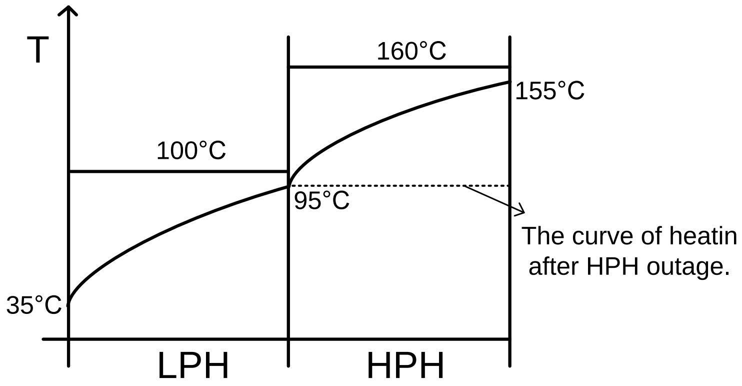
$$\dot{m}_{o2} = \frac{\dot{m}_s \cdot c_w \cdot (t_{k1} - t_1)}{h_{o2} - c_w \cdot t_{o2}} = \frac{100 \cdot 4.2 \cdot (95-35)}{2350 - 4.2 \cdot 100} = 13.06\ kg \cdot s^{-1}.$$

The total mechanical power of turbine P_m can be expressed from the equation:

$$\dot{m}_s \cdot (h_a - h_e) - \dot{m}_{o1} \cdot (h_{o1} - h_e) - \dot{m}_{o2} \cdot (h_{o2} - h_e) = P_m$$

$$P_m = 100 \cdot (3\,375 - 2\,000) - 12.74 \cdot (2\,650 - 2\,000) - 13.06 \cdot (2\,350 - 2\,000) = 124\,648\ kW$$

Part a):



The mass flow of the steam is stopped in the turbine point 1 if the HPH is in outage (i.e. $\dot{m}_{o1}$ = 0). The temperature of feed water to the boiler drops to the value t_{k1}. The heating power of the boiler must be increased for the same steam mass flow $\dot{m}_s$ (more fuel is needed). The steam which is not taken away from turbine produces mechanical work.

Then the mechanical power of turbine P_m is changed to the value:

$$P_m = \dot{m}_s \cdot (h_a - h_e) - \dot{m}_{o2} \cdot (h_{o2} - h_e) = 100 \cdot (3\,375 - 2\,000) - 13.06 \cdot (2\,350 - 2\,000) = 132\,929\ kW$$

The mechanical power is increased about ΔP_m = 8.3 MW compare with both LPH and HPH in the operation.

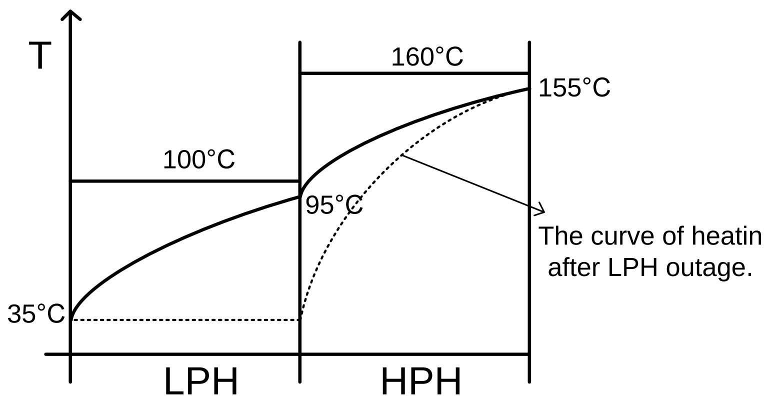
However, the total thermal efficiency of the cycle is decreased (the operation economy is worse – more fuel is needed). It means, that the power of turbine can be increased at the expense of operation economy by switching one or more HPH off.

Part b):

The mass flow of the steam is stopped in the turbine point 2 if the LPH is in outage (i.e. $\dot{m}_{o1} = 0$). The thermal gradient between warmed water and condensate of HPH is doubled. The power of HPH is increased so that the lost power of LPH is almost replaced. The temperature of the feed water to the boiler keeps unchanged just as the fuel consumption for the same steam mass flow $\dot{m}_s$. The only effect is an increase of the steam consumption by HPH.

Then a new value of the mass flow of the steam which is needed in HPH is:

$$\dot{m}'_{o1} = \frac{\dot{m}_{o1} \cdot h_{o1} + \dot{m}_{o2} \cdot h_{o2}}{h_{o1}} = \frac{12.74 \cdot 2650 + 13.06 \cdot 2350}{2650} = 24.32\ kg \cdot s^{-1}$$



Then the mechanical power of turbine P_m is changed to the value:

$$P_m = \dot{m}_s \cdot (h_a - h_e) - \dot{m}'_{o1} \cdot (h_{o1} - h_e) = 100 \cdot (3375 - 2000) - 24.32 \cdot (2650 - 2000) = 121\ 692\ kW$$

The mechanical power is decreased about $\Delta P_m = 3.0$ MW compare to the operation with both LPH and HPH.

The turbine power is decreased by LPH switching off with the same fuel consumption (again the operation economy is worst).