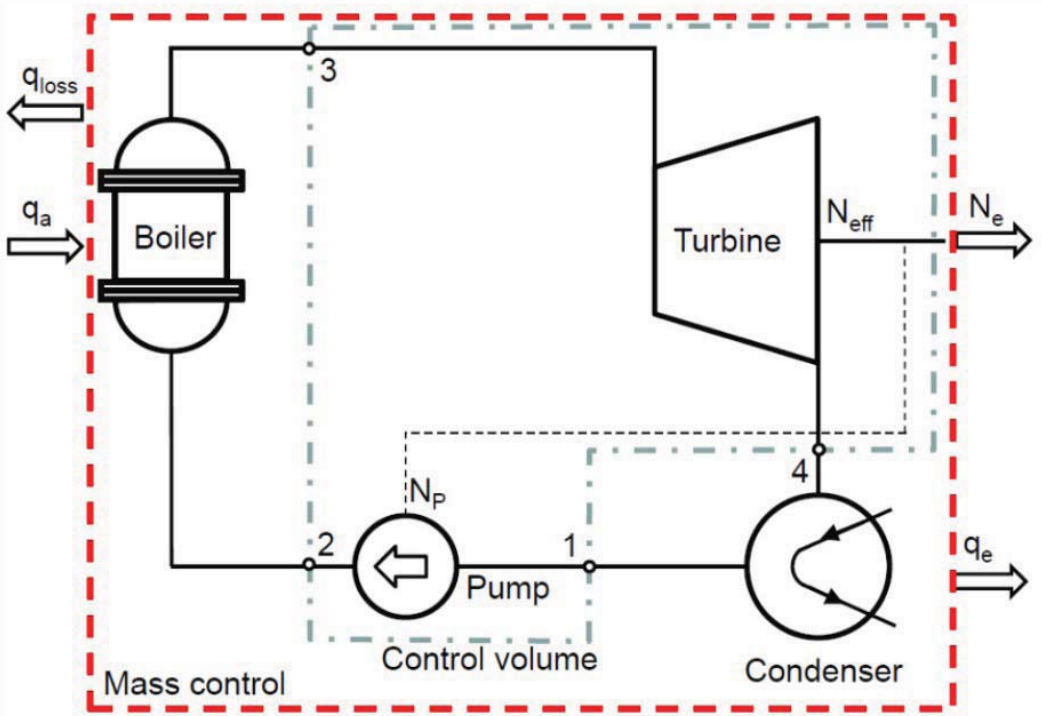
SH2706
Sustainable Energy Transformation Technologies

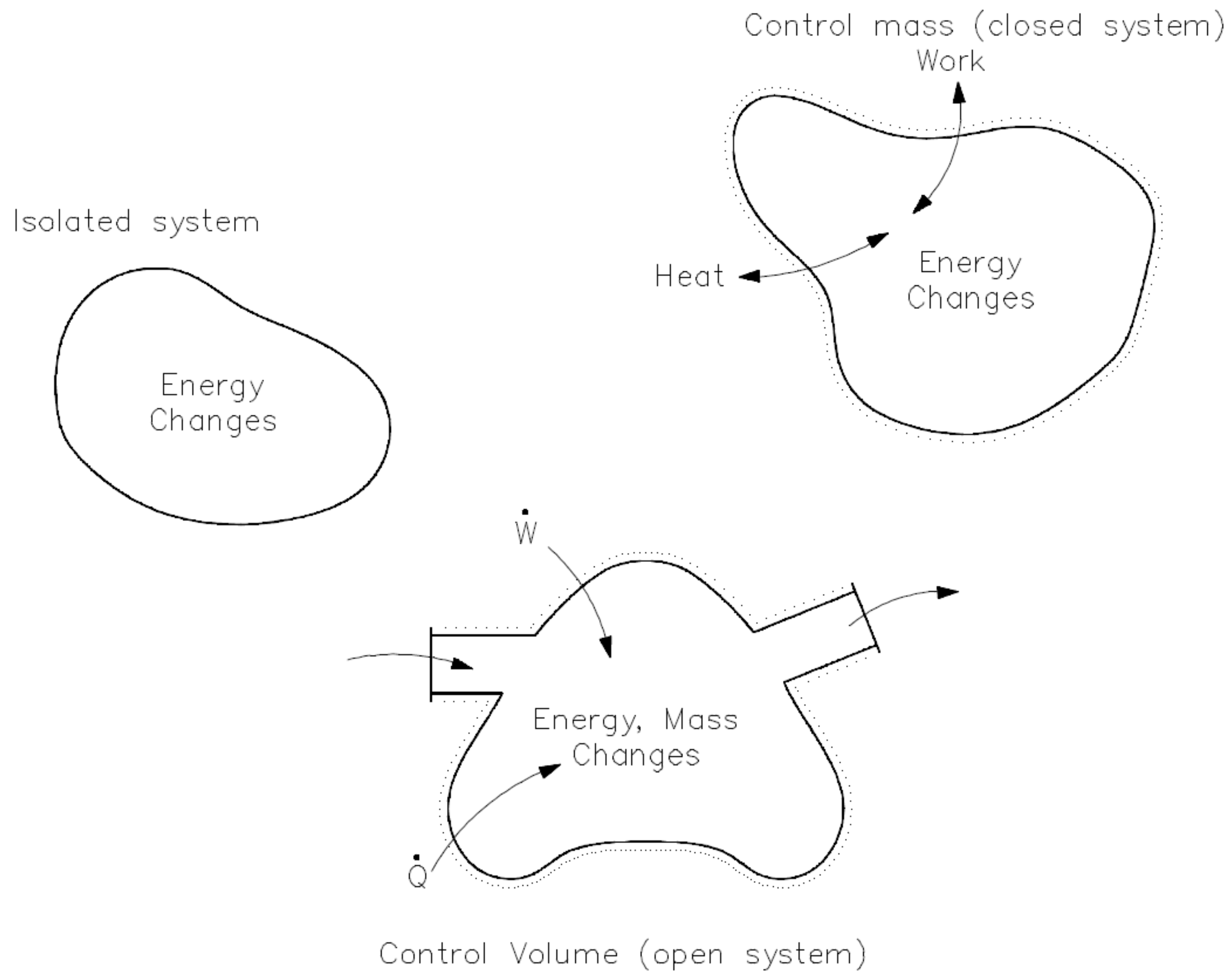
Exercise Session 01

E01_P01

- Applying the control mass system as shown in the figure, calculate the added thermal power q_a.
  - The net shaft power extracted from the system is N_e = 1 MW.
  - The thermal power extracted in the condenser is equal to 65% of q_a.
  - Assume thermal losses q_{loss} = 1.5% of q_a.



Thermodynamic systems



Control Mass Formulation (7)

- Frequently the energy equation is expressed in terms of the specific total energy, that is the total energy per unit mass, $e_T = E_T/m$, where $e_T = e_I + e_K + e_P$:

$$\frac{dE_T}{dt} = \frac{d}{dt}\left[m\left(e_I + e_K + e_P\right)\right] = q - N_{shaft} - N_{normal} - N_{shear}$$

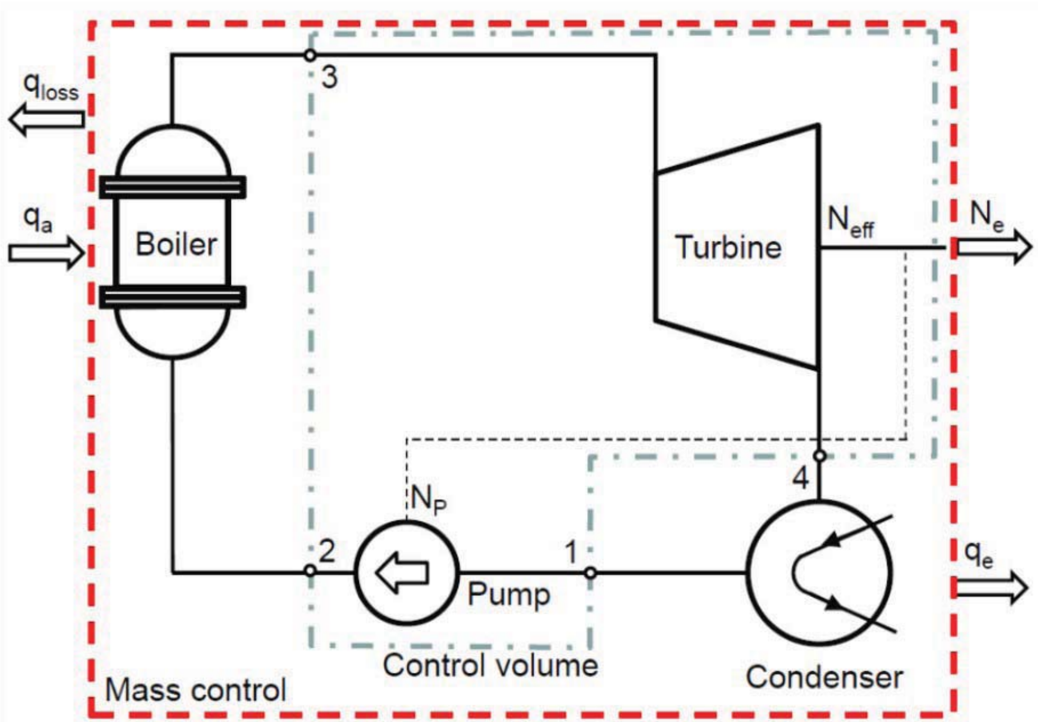
- we should note that e_I is the specific internal energy, $e_K = U^2/2$ – is the specific kinetic energy and $e_P = gh$ – is the specific potential energy

E01_P01

- Applying the control mass system as shown in the figure, calculate the added thermal power q_a.
  - The net shaft power extracted from the system is $N_e = 1$ MW.
  - The thermal power extracted in the condenser is equal to 65% of q_a.
  - Assume thermal losses $q_{loss} = 1.5\%$ of q_a.

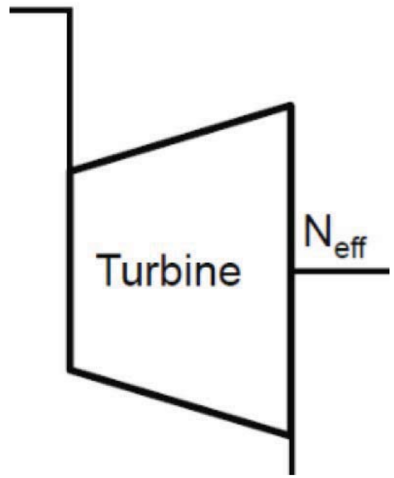
Solution

- First law: $dE = Q - L$
- $0 = (q_a - q_e - q_{loss}) - N_e$ (1)
- $q_e = 0.65 * q_a$ (2)
- $q_{loss} = 0.015 * q_a$ (3)
- $q_a = 2.985$ MW



E01_P02

- A steam turbine operates at steady-state conditions and delivers effective (shaft) power N_{eff} = 423 MW.
- Steam mass flow rate through the turbine is W = 500 kg/s.
- The inlet specific enthalpy and the mean velocity of the steam are i_{in} = 2770 kJ/kg and U_{in} = 90 m/s, respectively.
- The corresponding parameters for steam at the outlet are i_{out} = 1900 kJ/kg and U_{out} = 230 m/s.
- Neglect potential energy of the steam streams.
- Calculate the turbine heat losses to the surroundings.



Control Volume Formulation (4)

- Thus the total energy change of the system is

$$\frac{dE_T}{dt} = e_T W - \left(-pW/\rho\right) = \left(e_T + p/\rho\right)W = W\left(e_I + p/\rho + e_K + e_P\right)$$

- since the specific enthalpy is $i = e_I + p/\rho$ we can write

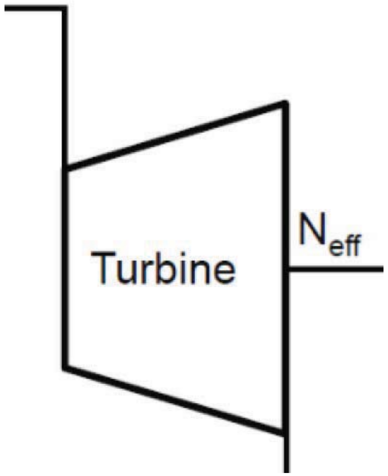
$$\frac{dE_T}{dt} = W\left(i + e_K + e_P\right)$$

- and the energy conservation equation becomes

$$\frac{dE_T}{dt} = q - N_{shaft} - N_{normal} - N_{shear} + \sum_{j \in in}\left(i + e_P + e_K\right)_j W_j - \sum_{k \in out}\left(i + e_P + e_K\right)_k W_k$$

E01_P02

- A steam turbine operates at steady-state conditions and delivers effective (shaft) power N_{eff} = 423 MW.
- Steam mass flow rate through the turbine is W = 500 kg/s.
- The inlet specific enthalpy and the mean velocity of the steam are i_{in} = 2770 kJ/kg and U_{in} = 90 m/s, respectively.
- The corresponding parameters for steam at the outlet are i_{out} = 1900 kJ/kg and U_{out} = 230 m/s.
- Neglect potential energy of the steam streams.
- Calculate the turbine heat losses to the surroundings.

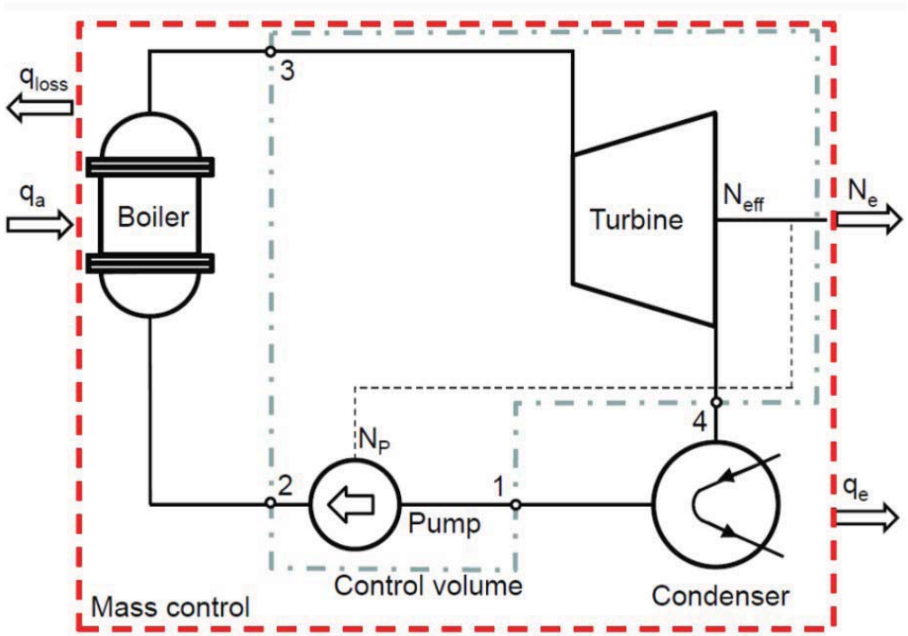


Solution

- $de = q - N + W^*d(i+k_e+p_e)$
- $0 = 0 - q_{loss} - N_{eff} + W^*(i_{in} + U_{in}^2/2 - i_{out} - U_{out}^2/2)$
- q_{loss} = 800 kW

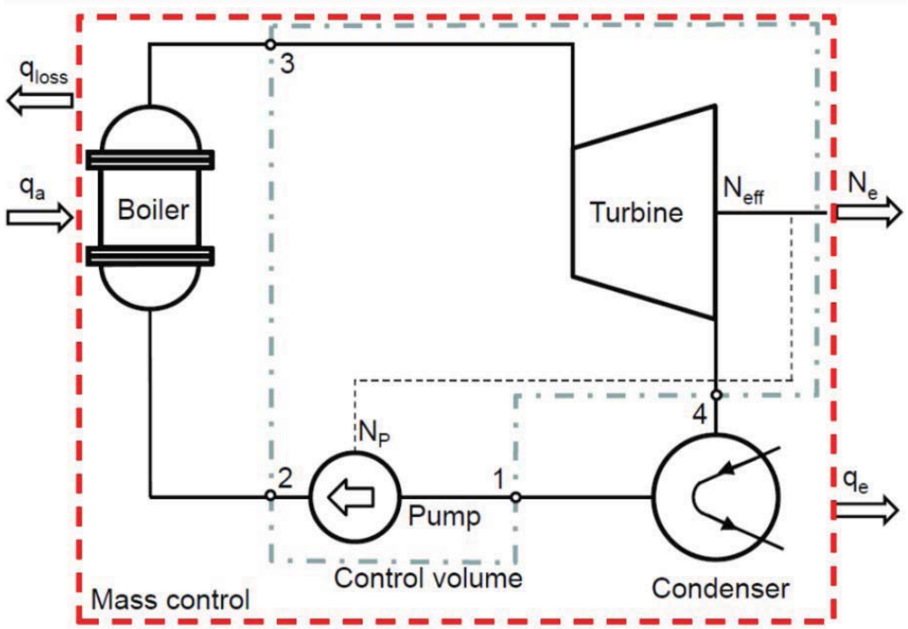
E01_P03

- A thermodynamic system is shown in the figure. Calculate the thermal power that is extracted in a condenser q_e.
  - The specific enthalpy of steam at the inlet to the turbine is i_3=3130 kJ/kg and its mass flow rate is W_3 = 10 kg/s.
  - Specific enthalpy after isentropic expansion in the turbine is i_{4s}=2710 kJ/kg .
  - The turbine internal efficiency is η_i = 0.75 and its mechanical efficiency is η_m = 0.95. The system energy efficiency is η_E = 0.38.
  - Assume q_{loss} = 0.01 q_a and pumping power N_p = q_{loss}.



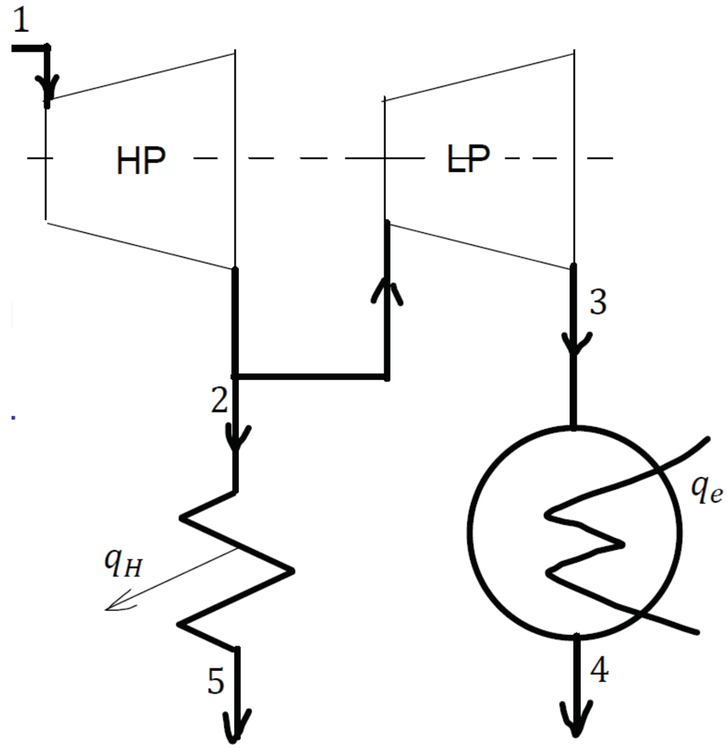
E01_P03

- A thermodynamic system is shown in the figure. Calculate the thermal power that is extracted in a condenser q_e.
  - The specific enthalpy of steam at the inlet to the turbine is i_3=3130 kJ/kg and its mass flow rate is W_3 = 10 kg/s.
  - Specific enthalpy after isentropic expansion in the turbine is i_{4s}=2710 kJ/kg .
  - The turbine internal efficiency is η_i = 0.75 and its mechanical efficiency is η_m = 0.95. The system energy efficiency is η_E = 0.38.
  - Assume $q_{loss} = 0.01\, q_a$ and pumping power $N_p = q_{loss}$.
  -
  - Solution
  - $dE = Q - L$
  - $0 = q_a - q_{loss} - q_e - N_e$ (1)
  - $N_{th} = W_3 * (i_3 - i_{4s})$ (2)
  - $N_{eff} = N_{th} * \eta_i * \eta_m$ (3)
  - $N_e = N_{eff} - N_p$ (4)
  - $q_{loss} = 0.01 * q_a$ (5)
  - $N_p = q_{loss}$ (6)
  - $N_e / q_a = \eta_E$ (7)



q_e = 4.68 MW (7 unknowns: q_a, q_{loss}, q_e, N_e, N_{th}, N_{eff}, N_p)

E01_P04



- Superheated steam with specific enthalpy i_1 flows into high-pressure turbine which has internal efficiency η_{iHP}. The isentropic expansion enthalpy is i_{2s}.
- After leaving the turbine, the steam is partly used for heating with thermal power q_H at temperature T_H, and the rest is feeding the low pressure turbine, which has internal efficiency η_{iLP}. The isentropic expansion enthalpy is i_{3s}.
- The exit specific enthalpy and entropy of bleeding steam are i_5 and s_5.
- Condensate leaving the condenser has a specific enthalpy i_4 and the specific entropy s_4.
- The total internal power of turbines is N_i.
- Heat is extracted in the condenser at temperature T_{amb}.
- Ambient steam specific enthalpy and entropy are i_{amb} and s_{amb}.
- Calculate the total exergy loss in the system.

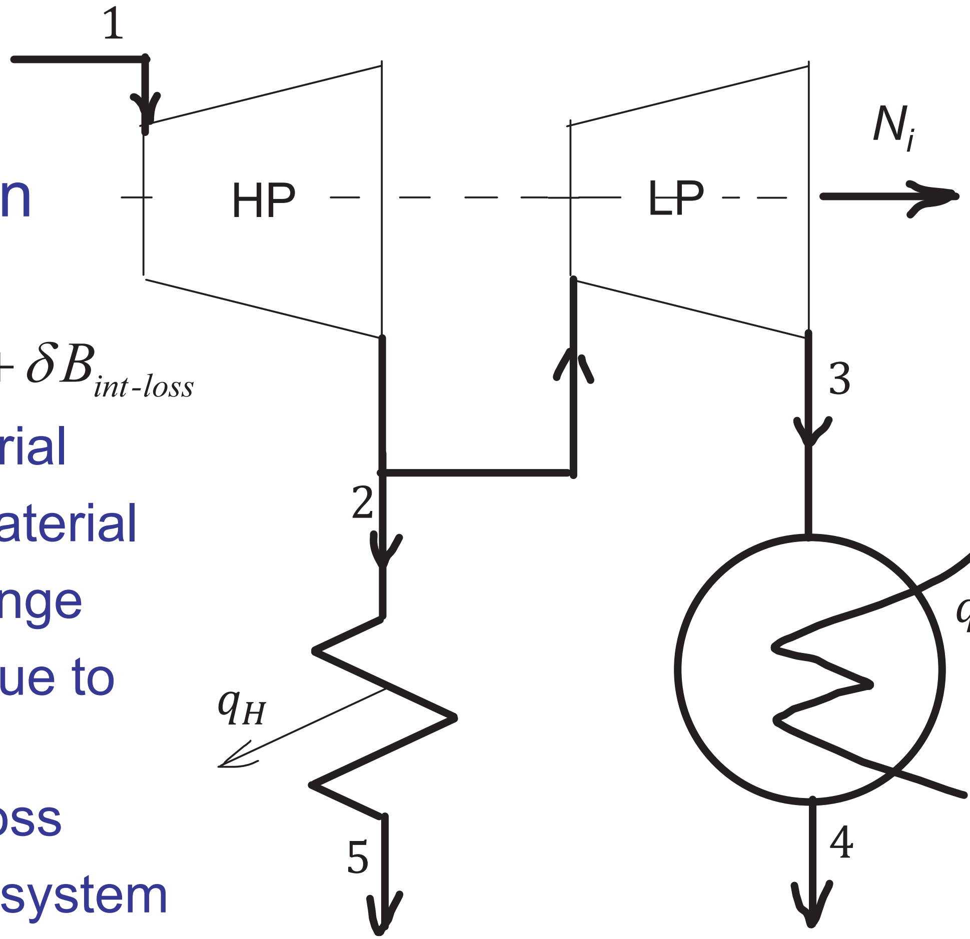
- i_{amb} = 62.3 kJ/kg; s_{amb} = 0.222 kJ/kg/K; T_{amb} = 288K;
- i_1 =3130 kJ/kg; s_1 = 7.125 kJ/kg/K;
- i_4 =116.6 kJ/kg; s_4 = 0.406 kJ/kg/K;
- i_5 =292.4 kJ/kg; s_5 = 0.953 kJ/kg/K;
- i_{2s} =2710 kJ/kg;
- i_{3s} =2245 kJ/kg;
- N_i = 5 MW;
- η_{iHP} = 0.76; η_{iLP} = 0.79;
- q_H = 1.4 MW; T_H = 333K;

Exergy (10)

- The general rule for the exergy balance in an open system is as follows

$$B_a = \Delta B_{sys} + B_e + L + \Delta B_{sources} + \delta B_{int\text{-}loss}$$

  - B_a – exergy of added material
  - B_e – exergy of extracted material
  - ΔB_{sys} – system exergy change
  - ΔB_{source} – exergy change due to heat sources/sinks
  - $\delta B_{int\text{-}loss}$ – internal exergy loss
  - L – work performed by the system

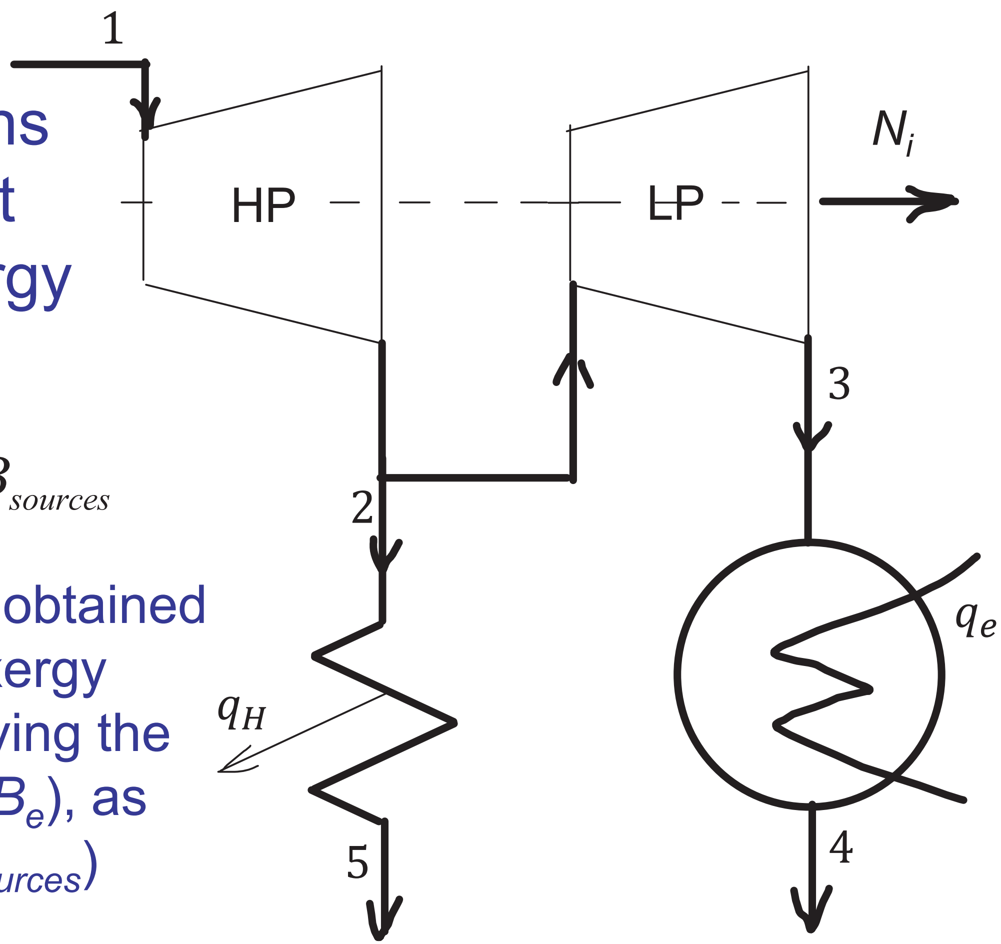


Exergy (11)

- For steady-state conditions the system exergy will not change, and internal exergy losses can be found as

$$\delta B_{int\text{-}loss} = B_a - B_e - L - \Delta B_{sources}$$

  - thus the exergy losses are obtained as a difference between exergy added (B_a) and exergy leaving the system with working fluid (B_e), as work (L) and as heat ($\Delta B_{sources}$)



Exergy (12)

- Expressed as time-rate loss of exergy, we have

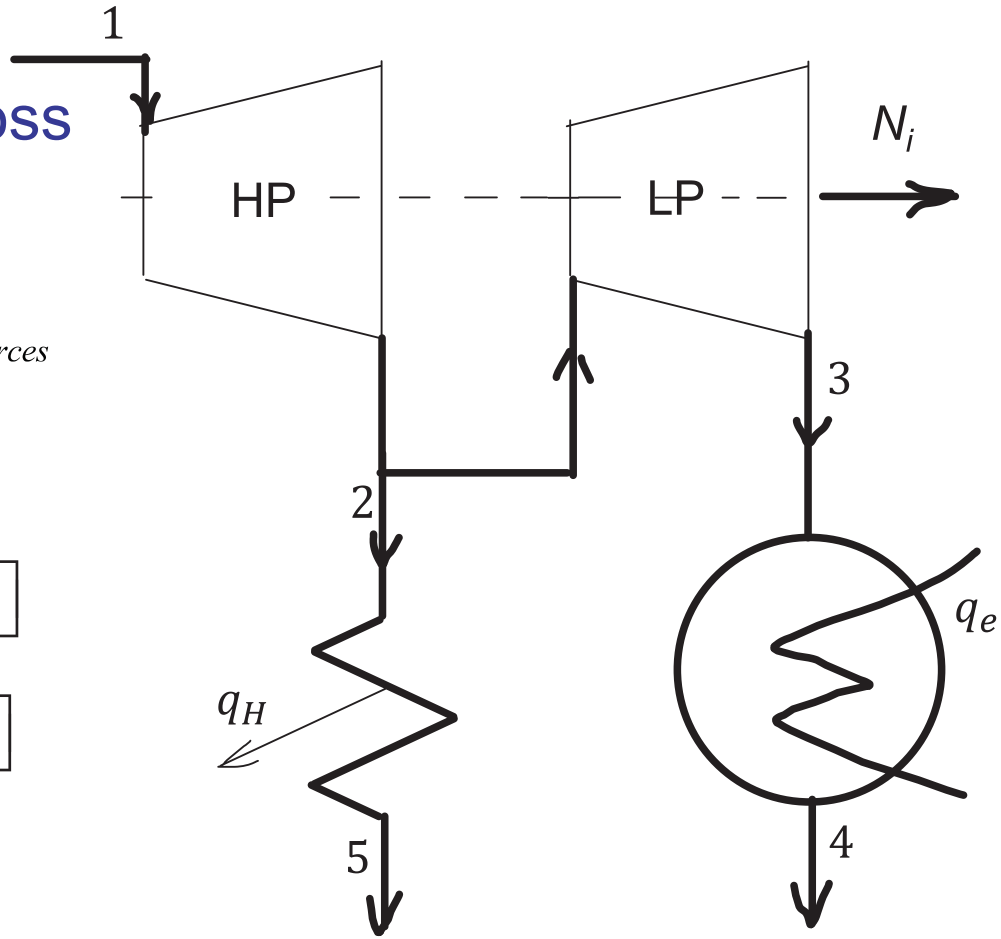
$$\delta \dot{B}_{int\text{-}loss} = \dot{B}_a - \dot{B}_e - N - \Delta \dot{B}_{sources}$$

  - where

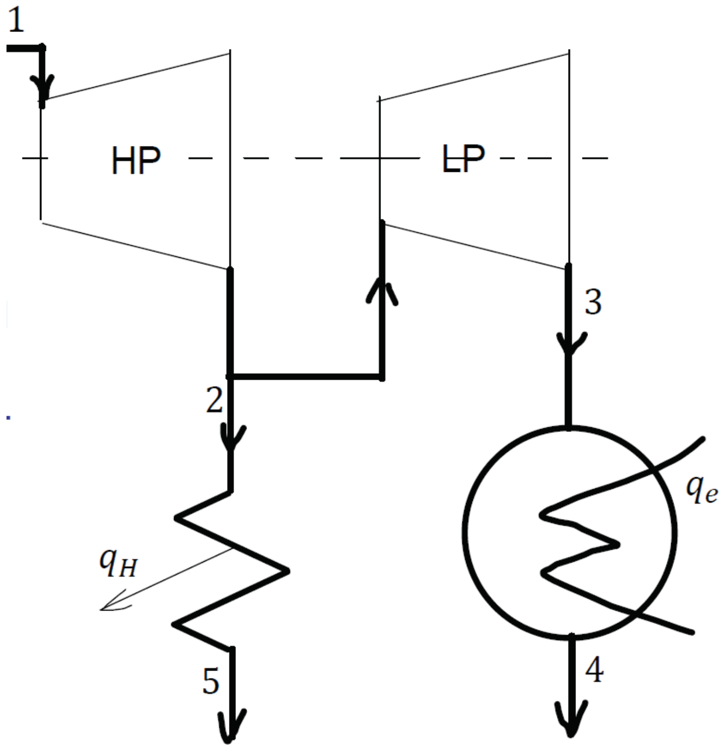
$$\dot{B}_a = W_a \left[i_a - i_0 - T_0 \left(s_a - s_0 \right) \right]$$

$$\dot{B}_e = W_e \left[i_e - i_0 - T_0 \left(s_e - s_0 \right) \right]$$

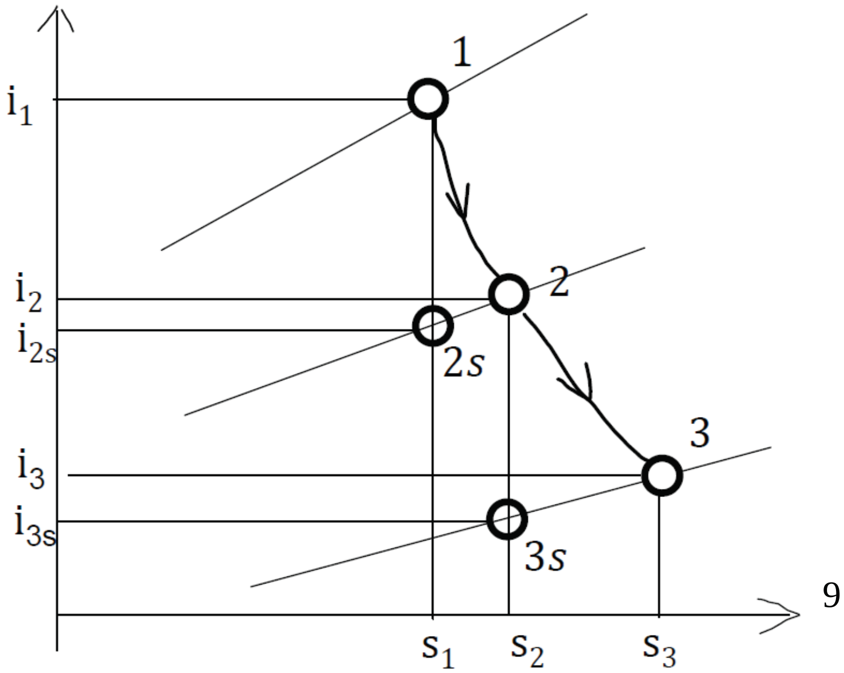
$$\Delta \dot{B}_{sources} = q_{sources} \frac{T_{sources} - T_0}{T_{sources}}$$



E01_P04



- Superheated steam with specific enthalpy i_1 flows into high-pressure turbine which has internal efficiency η_{iHP}. The isentropic expansion enthalpy is i_{2s}.
- After leaving the turbine, the steam is partly used for heating with thermal power q_H at temperature T_H, and the rest is feeding the low pressure turbine, which has internal efficiency η_{iLP}. The isentropic expansion enthalpy is i_{3s}.
- The exit specific enthalpy and entropy of bleeding steam are i_5 and s_5.
- Condensate leaving the condenser has a specific enthalpy i_4 and the specific entropy s_4.
- The total internal power of turbines is N_i.
- Heat is extracted in the condenser at temperature T_{amb}.
- Ambient steam specific enthalpy and entropy are i_{amb} and s_{amb}.
- Calculate the total exergy loss in the system.
-
- Solution
- $B_{loss} = B_a – B_e – N – dB_{sources}$
- $B = W*(i – i_{amb} – T_{amb}*(s – s_{amb}))$ for point 1, 4, 5
- $dB_{sources} = q*(T-T_{amb})/T$ for q_H and q_e



- $W_1 = W_2 + W_3$ (1)
- $q_H = W_2*(i_2 – i_5)$ (2)
- $\eta_{iHP} = (i_1-i_2)/(i_1-i_{2s})$ (3)
- $\eta_{iLP} = (i_2-i_3)/(i_2-i_{3s})$ (4)
- $N_i = W_1*(i_1-i_2) + W_3*(i_2-i_3)$ (5)

(5 unknowns: W_1, W_2, W_3, i_2, i_3)

- $W_1 = 6.85$ kg/s $W_2 = 0.556$ kg/s
- $B_{loss} = 2.187$ MW