Quiz 4

A flue gas is cooled from 1,200 to 120 °C, and the heat is used to generate saturated steam at 100 °C in a boiler. The flue gas has a heat capacity given by:

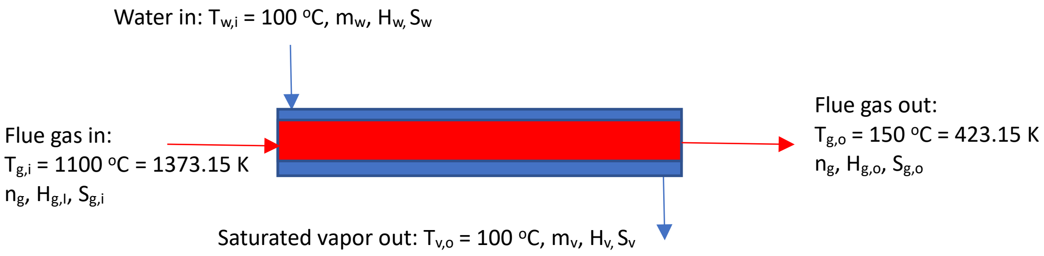
$C_P/R = 3.83 + 0.000551\ T\ (K)$

Water enters the boiler at 100 °C and is vaporized at this temperature; its latent heat of vaporization is 2,256.9 kJ kg^{-1}. With reference to a surroundings temperature of 25 °C,

a) What is the lost work of this process in kJ mol^{-1} of the flue gas?

b) What is the maximum work in kJ mol^{-1} of the flue gas that can be generated by the saturated steam at 100 °C if it condenses only (without subcooling)?

c) What is the maximum work in kJ mol^{-1} of the flue gas that can be generated by the flue gas in this process?



Answer:

This is an open flowing systems with two streams in and two streams out with uniform surroundings temperature (25°C). The calculations would be meaningful only at steady state.

Simplifying assumptions:

- The flue gas is an ideal gas, therefore we can calculate its entropy change using equation 5.10.
- There is no heat loss to the environment.
- The pressure drops at the both side of the heat exchanger are negligible (inlet pressure = outlet pressure).

If we write the first law of thermodynamics:

$$\frac{d(mU)_{CV}}{dt} + \Delta\left[\left(H + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} = \dot{Q} + \dot{W}$$

At steady state, $\frac{d(mU)_{CV}}{dt} = 0$. Also, we can assume that kinetic energy change, potential energy change, and heat loss to surroundings to be zero, the above equation is reduced to:

$$\Delta(\dot{m}H) = 0$$

Expanding the above equation for the given system:

$$-\dot{n}_g H_{g,i} + \dot{n}_g H_{g,o} - \dot{m}_w H_{w,i} + \dot{m}_w H_{s,o} = 0$$

$$\dot{n}_g \Delta H_g + \dot{m}_w \Delta H_{evap} = 0$$

The enthalpy change of the flue gas is mole-based and the one of steam is mass based.

$$\Delta H_g = \int_{T_{g,i}}^{T_{g,o}} C_p\, dT = \int_{1473.15}^{393.15} 8.314\,(3.83 + 0.000551T)\, dT = -39006.78\, J/mol$$

From the question (and also the saturated steam table at 100 °C):

$$\Delta H_{evap} = 2256.9\ kJ/kg$$

Using the first law of the thermodynamics simplified above:

$$\frac{\dot{m}_w}{\dot{n}_g} = -\frac{\Delta H_g}{\Delta H_{evap}} = 0.01728\ kg\ water/mol\ f$$

Work lost of the process (Eq. 5.29):

$$\dot{W} = T_\sigma\ \dot{S}_G$$

Entropy balance of the system:

$$\Delta(S_i \dot{m}_i)_{fs} + \frac{d(mS)_{cv}}{dt} - \sum_j \frac{\dot{Q}_j}{T_{\sigma,j}} = \dot{S}_G \geq 0$$

For an open flowing system at steady state $\frac{d(mS)_{cv}}{dt} = 0)$. Also, with uniform surroundings temperature $\sum_j \frac{\dot{Q}_j}{T_{\sigma,j}} = \frac{\dot{Q}}{T_\sigma}$. Because we have no heat transfer to the environment the equation is simplified as follows:

$$\dot{S}_G = \Delta(S_i \dot{m}_i)_{fs}$$

Expanding $\Delta(S_i \dot{m}_i)_{fs}$ for the system:

$$\Delta(S_i \dot{m}_i)_{fs} = -\dot{n}_g S_{g,i} + \dot{n}_g S_{g,o} - \dot{m}_w S_{w,i} + \dot{m}_w S_{s,i} = \dot{n}_g \Delta S_g + \dot{m}_w (S_{s,o} - S_{w,i})$$

Assume the flue gas to be at ideal gas state and constant pressure, i.e., $P_o/P_i = 1$:

$$\Delta S_g = \int_{T_{g,i}}^{T_{g,o}} \frac{C_p}{T} dT - R \int_{P_{g,i}}^{P_{g,o}} \frac{dP}{P} = \int_{T_{g,i}}^{T_{g,o}} \frac{C_p}{T} dT = \int_{1343.15}^{393.15} 8.314 \frac{(3.83 + 0.000551T)}{T}\ dT$$

$$\Delta S_g = -47.0105\ \text{J/mol K}$$

From the saturated steam table at 100 °C:

$$S_{s,o} - S_{w,i} = \Delta S_{evap} = 6.0485\ \text{kJ/kg K} = 6048.5\ \text{J/kg K}$$

On the basis of 1 mole of the flue gas:

$$S_G = \Delta S_g + \frac{m_w}{n_g}\ (S_{s,o} - S_{w,i}) = 57.5277\ J/mol_{flue\ gas}\ \ K$$

$$W = T_\sigma\ S_G = 17151.91\ J/mol_{flue\ gas}$$