

ME 354 Tutorial, Week#3

Application of the Second Law to an Open System

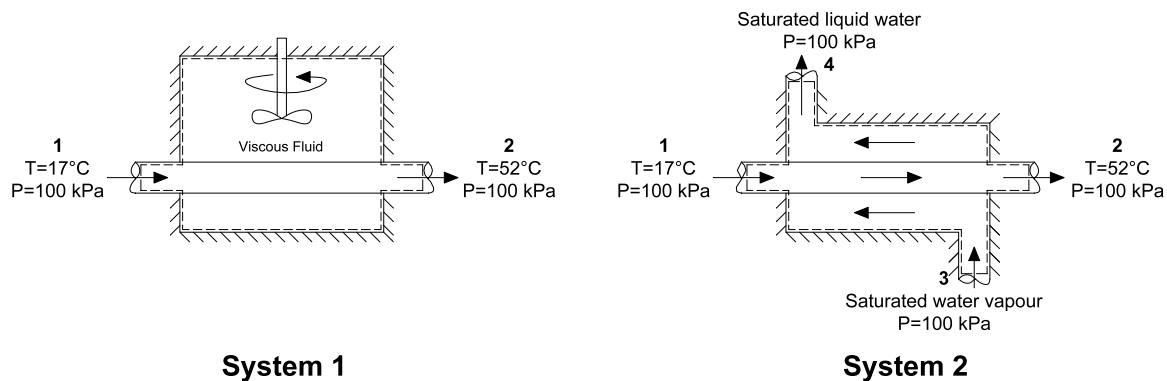
Two alternative systems are under consideration for bringing a stream of air from 17°C to 52°C at an essentially constant pressure of 100 kPa.

System 1: The air temperature is increased as a consequence of the stirring of a liquid surrounding the line carrying the air.

System 2: The air temperature is increased by passing it through one side of a counter-flow heat exchanger. On the other side, steam condenses at a pressure of 100kPa from a saturated vapour to a saturated liquid.

Both systems operate under steady conditions and are sufficiently insulated to prevent significant heat transfer with the surroundings. For each of the two systems, calculate the rate of entropy production, in kJ/K per kg of air passing through the system.

Step 1: Draw a diagram to represent the system showing control mass/volume of interest.



Step 2: Write out what you are required to solve for

Find:

Calculate the rate of entropy production for each of the two systems in kJ/K per kg of air passing through the system.

Step 3: Prepare a property table to keep track of the system's properties as you determine them

| <i>System 1</i> | Property | |
|-----------------|----------|--------|
| Location | T[K] | P[kPa] |
| 1 | 290 | 100 |
| 2 | 325 | 100 |

| <i>System 2</i> Location | Property | | | |
|------------------------------------|-----------------|---------------|-----------------|-------------------|
| | T[K] | P[kPa] | h[kJ/kg] | s[kJ/kg*K] |
| AIR | | | | |
| 1 | 290 | 100 | | |
| 2 | 325 | 100 | | |
| WATER | | | | |
| 3 (sat vapour) | | 100 | | |
| 4 (sat liquid) | | 100 | | |

Step 4: State your assumptions

Assumptions:

- 1) Both systems are operated under steady conditions.
- 2) Both systems are insulated – there is NO heat transfer to the surroundings.
- 3) Air is modelled as an ideal gas with constant specific heats
- 4) $\Delta k_e, \Delta p_e \approx 0$

Part a)

Step 5: Solve

System 1:

To determine the rate of entropy production in System 1, an entropy balance will be performed on the system as shown Eq1.

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \Delta \dot{S}_{system} \quad (\text{Eq1})$$

With our choice of the control volume boundary the only entropy brought into or out of the system is carried by mass flow. Note: there is shaft work into the system but work does not have a transfer of entropy associated with it. Since we have assumed the system is operated steadily, the rate of change of the change in the system's entropy will be zero and the mass flow of air in, m_1 , is equal to the mass flow of air out, m_2 . Using this information, Eq1 reduces to Eq2 as shown below.

$$\dot{m}_1 s_1 - \dot{m}_2 s_2 + \dot{S}_{gen} = 0 \rightarrow \frac{\dot{S}_{gen}}{\dot{m}_{air}} = (s_2 - s_1) \quad (\text{Eq2})$$

Since the air is modelled as an ideal gas, the change in entropy can be determined using the ideal gas relation for entropy change as a function of temperature and pressure as shown in Eq3.

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) \quad (\text{Eq3})$$

Substituting Eq3 into Eq2, the rate of entropy generation per kg of air can be expressed as Eq4.

$$\frac{\dot{S}_{gen}}{\dot{m}_{air}} = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) \quad (\text{Eq4})$$

Substituting in the values from the Property Table into Eq4 the rate of entropy production per kg of air can be determined as shown below. The specific heat of air at 300K is given as 1.005 kJ/kg*K in Table A-2.

$$\frac{\dot{S}_{gen}}{\dot{m}_{air}} = 1.005 \left[\frac{\text{kJ}}{\text{kg} * \text{K}} \right] \ln\left(\frac{325}{290}\right) - R \ln\left(\frac{100[\text{kPa}]}{100[\text{kPa}]}\right) = \mathbf{0.1145 \text{ kJ/kg*K} \quad \text{Answer}}$$

System 2:

To determine the rate of entropy production in System 2, an entropy balance will be performed on the system as shown Eq5.

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \Delta \dot{S}_{system} \quad (\text{Eq5})$$

With our choice of the control volume boundary the only entropy brought into or out of the system is carried by mass flow. Since we have assumed the system is operated steadily, the rate of change of the system's entropy will be zero, the mass flow of air in, \dot{m}_1 , is equal to the mass flow of air out, \dot{m}_2 and the mass flow of water in, \dot{m}_3 , is equal to the mass flow of water out, \dot{m}_4 . Using this information, Eq5 reduces to Eq6 as shown below.

$$\dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} = 0 \rightarrow \frac{\dot{S}_{gen}}{\dot{m}_{air}} = (s_2 - s_1) + \frac{\dot{m}_{water}}{\dot{m}_{air}} (s_4 - s_3) \quad (\text{Eq6})$$

Since the air temperatures and pressures are the same as in System 1, the entropy difference, $s_2 - s_1$, will be the same as calculated for System 1. The entropy difference, $s_4 - s_3$, for the water can be determined from Table A-4 using $-s_{fg}$ at 100kPa as shown in Eq7.

$$s_4 - s_3 = -s_{fg@100kPa} = -6.0480 \left[\frac{\text{kJ}}{\text{kg} * \text{K}} \right] \quad (\text{Eq7})$$

The ratio of the mass flow of water to the mass flow of air must be determined. Performing an energy balance on System 2, Eq8 is obtained.

$$\Delta \dot{E}_{system} = \dot{E}_{in} - \dot{E}_{out} \quad (\text{Eq8})$$

With our choice of the control volume boundary the only energy brought into or out of the system is carried by mass flow. Since we have assumed the system is operated steadily, the rate of change of the change in the system's energy will be zero, the mass flow of air in, \dot{m}_1 , is equal to the mass flow of air out, \dot{m}_2 and the mass flow of water in, \dot{m}_3 , is equal to the mass flow of water out, \dot{m}_4 . Using this information, Eq8 reduces to Eq9 as shown below.

$$\begin{aligned} \dot{m}_1(e + Pv)_1 + \dot{m}_3(e + Pv)_3 - \dot{m}_2(e + Pv)_2 - \dot{m}_4(e + Pv)_4 &= 0 \\ \rightarrow \frac{\dot{m}_{water}}{\dot{m}_{air}} &= \frac{(e + Pv)_2 - (e + Pv)_1}{(e + Pv)_3 - (e + Pv)_4} \end{aligned} \quad (\text{Eq9})$$

Since it has been assumed that changes in kinetic and potential energy are approximately equal to zero, the difference in $e + Pv$ terms are equivalent to the difference in enthalpies as shown in Eq10.

$$\frac{\dot{m}_{water}}{\dot{m}_{air}} = \frac{h_2 - h_1}{h_3 - h_4} \quad (\text{Eq10})$$

Since the air is modelled as an ideal gas, the change in enthalpy, $h_2 - h_1$, can be determined using the ideal gas relation for enthalpy change as a function of temperature only as shown in Eq11.

$$h_2 - h_1 = c_p(T_2 - T_1) \quad (\text{Eq11})$$

The enthalpy difference, $h_3 - h_4$, for the water can be determined from Table A-4 using h_{fg} at 100kPa as shown in Eq12.

$$h_3 - h_4 = h_{fg@100kPa} = 2257.0 \left[\frac{kJ}{kg} \right] \quad (\text{Eq12})$$

Substituting the answer to System 1, Eq7, Eq10, Eq11, Eq12 into Eq6, Eq13 is obtained.

$$\frac{\dot{S}_{gen}}{\dot{m}_{air}} = 0.1145 \left[\frac{kJ}{kg * K} \right] + \left(\frac{c_{p,air} (T_2 - T_1)}{2257 \left[\frac{kJ}{kg} \right]} \right) \left(-6.0480 \left[\frac{kJ}{kg * K} \right] \right) \quad (Eq13)$$

Substituting in values from the Property Table into Eq13 the rate of entropy production per kg of air can be determined as shown below.

$$\frac{\dot{S}_{gen}}{\dot{m}_{air}} = 0.1145 \left[\frac{kJ}{kg * K} \right] + \left(\frac{1.005 \left[\frac{kJ}{kg * K} \right] (325 - 290) [K]}{2257 \left[\frac{kJ}{kg} \right]} \right) (-6.0480) \left[\frac{kJ}{kg * K} \right] \quad \textbf{Answer}$$

$$= \mathbf{0.0202[kJ/kg*K]}$$

Step 6: Concluding Statement

The entropy production in System 1, 0.1145 kJ/kg*K, is greater than the entropy production in System 2, 0.0202 kJ/kg*K.