1) A 0.2 m³ rigid tank equipped with a pressure regulator contains steam (superheated water vapour) at 2 MPa and 300°C. The steam in the tank is heated. The regulator keeps the steam pressure constant by letting out some steam, but the temperature inside rises. Determine the amount of heat transferred when the steam temperature reaches 500°C.

2) Liquid water at 200 kPa and 20°C is heated in a chamber by mixing it with superheated steam at 200 kPa and 150°C. Liquid water enters the mixing chamber at a rate of 2.5 kg/s, and the chamber loses heat to the surrounding air at 25°C at a rate of 1200 kJ/minute. If the mixture leaves the chamber at 200 kPa and 60°C. Determine;
   a) the mass flow rate of the superheated steam,
   b) the rate of entropi generation during the mixing process.

3) A Carnot heat engine receives heat from a reservoir at 900°C at a rate of 800 kJ/minute and rejects the waste heat to the ambient air at 27°C. The entire work output of the heat engine is used to derive a refrigerator that removes heat from the refrigerated space at -5°C and transfers it to the same ambient air at 27°C. Determine;
   c) the maximum rate of heat removal from the refrigerated space,
   d) the total rate of heat rejection to the ambient air.

Exam duration is 100 minutes.
The marking of questions; Q1 is 30 points, Q2 and Q3 are 35 points each.
Good luck!
Solution 1:

5-137 A rigid tank initially contains superheated steam. A valve at the top of the tank is opened, and vapor is allowed to escape at constant pressure until the temperature rises to 500°C. The amount of heat transfer is to be determined.

**Assumptions** 1 This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform-flow process by using constant average properties for the steam leaving the tank. 2 Kinetic and potential energies are negligible. 3 There are no work interactions involved. 4 The direction of heat transfer is to the tank (will be verified).

**Properties** The properties of water are (Tables A-4 through A-5)

\[
\begin{align*}
P_1 &= 2 \text{ MPa} \quad \nu_1 = 0.12551 \text{ m}^3/\text{kg} \\
T_1 &= 300^\circ\text{C} \quad u_1 = 2773.2 \text{ kJ/kg}, \quad h_1 = 3024.2 \text{ kJ/kg} \\
P_2 &= 2 \text{ MPa} \quad \nu_2 = 0.17568 \text{ m}^3/\text{kg} \\
T_2 &= 500^\circ\text{C} \quad u_2 = 3116.9 \text{ kJ/kg}, \quad h_2 = 3468.3 \text{ kJ/kg}
\end{align*}
\]

**Analysis** We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the macroscopic energies of flowing and nonflowing fluids are represented by enthalpy $h$ and internal energy $u$, respectively, the mass and energy balances for this uniform-flow system can be expressed as

**Mass balance:**

\[m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \rightarrow m_{\text{e}} = m_1 - m_2\]

**Energy balance:**

\[
\frac{E_{\text{in}} - E_{\text{out}}}{\text{by heat, work, and mass}} = \frac{\Delta E_{\text{system}}}{\text{Change in internal, kinetic, potential, etc. energies}}
\]

\[Q_{\text{in}} = m_1 h_1 = m_2 u_2 - m_1 u_1 \quad \text{(since } W = ke = pe = 0)\]

The state and thus the enthalpy of the steam leaving the tank is changing during this process. But for simplicity, we assume constant properties for the exiting steam at the average values. Thus,

\[h_e = \frac{h_1 + h_2}{2} = \frac{3024.2 + 3468.3}{2} = 3246.2 \text{ kJ/kg}\]

The initial and the final masses in the tank are

\[m_1 = \frac{V_1}{\nu_1} = \frac{0.2 \text{ m}^3}{0.12551 \text{ m}^3/\text{kg}} = 1.594 \text{ kg}\]

\[m_2 = \frac{V_2}{\nu_2} = \frac{0.2 \text{ m}^3}{0.17568 \text{ m}^3/\text{kg}} = 1.138 \text{ kg}\]

Then from the mass and energy balance relations,

\[m_e = m_1 - m_2 = 1.594 - 1.138 - 0.456 \text{ kg}\]

\[Q_{\text{in}} = m_e h_e + m_2 u_2 - m_1 u_1\]

\[= (0.456 \text{ kg})(3246.2 \text{ kJ/kg}) + (1.138 \text{ kg})(3116.9 \text{ kJ/kg}) - (1.594 \text{ kg})(2773.2 \text{ kJ/kg})\]

\[= 606.8 \text{ kJ}\]
Solution 2:

7-168 Liquid water is heated in a chamber by mixing it with superheated steam. For a specified mixing temperature, the mass flow rate of the steam and the rate of entropy generation are to be determined.

**Assumptions** 1 This is a steady-flow process since there is no change with time. 2 Kinetic and potential energy changes are negligible. 3 There are no work interactions.

**Properties** Noting that \( T < T_{sat@200 \text{ kPa}} = 120.211 \text{°C} \), the cold water and the exit mixture streams exist as a compressed liquid, which can be approximated as a saturated liquid at the given temperature. From Tables A-4 through A-6,

\[
\begin{align*}
P_1 &= 200 \text{ kPa} \quad h_1 = h_{f@20°C} = 83.91 \text{ kJ/kg} \\
T_1 &= 20°C \quad s_1 = s_{f@20°C} = 0.2965 \text{ kJ/kg} \cdot \text{K} \\
P_2 &= 200 \text{ kPa} \quad h_2 = 2769.1 \text{ kJ/kg} \\
T_2 &= 150°C \quad s_2 = 7.2810 \text{ kJ/kg} \cdot \text{K} \\
P_3 &= 200 \text{ kPa} \quad h_3 = h_{f@60°C} = 251.18 \text{ kJ/kg} \\
T_3 &= 60°C \quad s_3 = s_{f@60°C} = 0.8313 \text{ kJ/kg} \cdot \text{K}
\end{align*}
\]

**Analysis** (a) We take the mixing chamber as the system, which is a control volume. The mass and energy balances for this steady-flow system can be expressed in the rate form as

**Mass balance:**

\[
\dot{m}_1 + \dot{m}_2 = \dot{m}_3
\]

**Energy balance:**

\[
\dot{E}_\text{in} - \dot{E}_\text{out} = \dot{\Delta E}_\text{system}^{\text{prob}} (\text{steady}) = 0 \quad \rightarrow \quad \dot{E}_\text{in} = \dot{E}_\text{out}
\]

Rate of energy transfer by heat, work, and mass

\[
\dot{E}_\text{in} - \dot{E}_\text{out} = \dot{\Delta E}_\text{system}^{\text{prob}} (\text{steady}) = 0
\]

\[
\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{Q}_\text{out} + \dot{m}_3 h_3
\]

Combining the two relations gives

\[
\dot{Q}_\text{out} = \dot{m}_1 h_1 + \dot{m}_2 h_2 - (\dot{m}_1 h_1 + \dot{m}_2 h_2) - \dot{m}_3 (h_1 - h_3)
\]

Solving for \( \dot{m}_2 \) and substituting, the mass flow rate of the superheated steam is determined to be

\[
\dot{m}_2 = \frac{\dot{Q}_\text{out} - \dot{m}_3 (h_1 - h_3)}{h_2 - h_3} = \frac{(1200/60 \text{kJ/s}) - (2.5 \text{kg/s})(83.91 - 251.18) \text{kJ/kg}}{(2769.1 - 251.18) \text{kJ/kg}} = 0.166 \text{ kg/s}
\]

Also,

\[
\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 2.5 + 0.166 = 2.666 \text{ kg/s}
\]

(b) The rate of total entropy generation during this process is determined by applying the entropy balance on an extended system that includes the mixing chamber and its immediate surroundings so that the boundary temperature of the extended system is 25°C at all times. It gives

\[
\dot{S}_\text{gen} = \dot{S}_\text{in} - \dot{S}_\text{out} - \dot{\Delta S}_\text{system}^{\text{prob}} = 0
\]

\[
\dot{S}_\text{gen} = \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_3 s_3 + \dot{Q}_\text{out} \frac{T_{B,\text{std}}}{T_{B,\text{std}}} = 0
\]

Substituting, the rate of entropy generation during this process is determined to be

\[
\begin{align*}
\dot{S}_\text{gen} &= \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_3 s_3 + \dot{Q}_\text{out} \frac{T_{B,\text{std}}}{T_{B,\text{std}}} \\
&= (2.666 \text{ kg/s})(0.8313 \text{ kJ/kg} \cdot \text{K}) - (0.166 \text{ kg/s})(7.2810 \text{ kJ/kg} \cdot \text{K}) \\
&= - (2.5 \text{ kg/s})(0.2965 \text{ kJ/kg} \cdot \text{K}) + \frac{1200/60 \text{kJ/s}}{298 \text{K}}
\end{align*}
\]

\[
= 0.333 \text{ kW/K}
\]
Solution 3:

6-111 A Carnot heat engine is used to drive a Carnot refrigerator. The maximum rate of heat removal from the refrigerated space and the total rate of heat rejection to the ambient air are to be determined.

**Assumptions** The heat engine and the refrigerator operate steadily.

**Analysis** (a) The highest thermal efficiency a heat engine operating between two specified temperature limits can have is the Carnot efficiency, which is determined from

\[ \eta_{th, max} = \eta_{th, C} = 1 - \frac{T_L}{T_H} = 1 - \frac{300 \text{ K}}{1173 \text{ K}} = 0.744 \]

Then the maximum power output of this heat engine is determined from the definition of thermal efficiency to be

\[ \dot{w}_{net, out} = \eta_{th} \dot{Q}_H = (0.744)(800 \text{ kJ/min}) = 595.2 \text{ kJ/min} \]

which is also the power input to the refrigerator, \( \dot{w}_{net, in} \).

The rate of heat removal from the refrigerated space will be a maximum if a Carnot refrigerator is used. The COP of the Carnot refrigerator is

\[ \text{COP}_{R, rev} = \frac{1}{(T_H / T_L) - 1} = \frac{1}{(27 + 273 \text{ K}) / (-5 + 273 \text{ K}) - 1} = 8.37 \]

Then the rate of heat removal from the refrigerated space becomes

\[ \dot{Q}_{L, R} = (\text{COP}_{R, rev}) \dot{w}_{net, in} = (8.37)(595.2 \text{ kJ/min}) = 4982 \text{ kJ/min} \]

(b) The total rate of heat rejection to the ambient air is the sum of the heat rejected by the heat engine (\( \dot{Q}_{L, HE} \)) and the heat discarded by the refrigerator (\( \dot{Q}_{H, R} \)),

\[ \dot{Q}_{L, HE} = \dot{Q}_{H, HE} - \dot{w}_{net, out} = 800 - 595.2 = 204.8 \text{ kJ/min} \]
\[ \dot{Q}_{H, R} = \dot{Q}_{L, R} + \dot{w}_{net, in} = 4982 + 595.2 = 5577.2 \text{ kJ/min} \]

and

\[ \dot{Q}_{ambient} = \dot{Q}_{L, HE} + \dot{Q}_{H, R} = 204.8 + 5577.2 = 5782 \text{ kJ/min} \]