Chapter 4

Worksheet: First Law of Thermodynamics for Closed Systems

4–5 A piston–cylinder device initially contains 0.07 m³ of nitrogen gas at 130 kPa and 120°C. The nitrogen is now expanded polytropically to a state of 100 kPa and 100°C. Determine the boundary work done during this process.

Properties The gas constant for nitrogen is 0.2968 kJ/kg.K (Table A-2).

Analysis The mass and volume of nitrogen at the initial state are

\[
m = \frac{P_1 V_1}{RT_1} = \frac{(130 \text{ kPa})(0.07 \text{ m}^3)}{(0.2968 \text{ kJ/kg.K})(120 + 273 \text{ K})} = 0.07802 \text{ kg}
\]

\[
V_2 = \frac{mRT_2}{P_2} = \frac{(0.07802 \text{ kg})(0.2968 \text{ kJ/kg.K})(100 + 273 \text{ K})}{100 \text{ kPa}} = 0.08637 \text{ m}^3
\]

The polytropic index is determined from

\[
P_1 V_1^n = P_2 V_2^n \rightarrow (130 \text{ kPa})(0.07 \text{ m}^3)^n = (100 \text{ kPa})(0.08637 \text{ m}^3)^n \rightarrow n = 1.249
\]

The boundary work is determined from

\[
W_b = \frac{P_2 V_2 - P_1 V_1}{1 - n} = \frac{(100 \text{ kPa})(0.08637 \text{ m}^3) - (130 \text{ kPa})(0.07 \text{ m}^3)}{1 - 1.249} = 1.86 \text{ kJ}
\]

4–30 A well-insulated rigid tank contains 5 kg of a saturated liquid–vapor mixture of water at 100 kPa. Initially, three-quarters of the mass is in the liquid phase. An electric resistor placed in the tank is connected to a 110-V source, and a current of 8 A flows through the resistor when the switch is turned on. Determine how long it will take to vaporize all the liquid in the tank. Also, show the process on a \(T-v\) diagram with respect to saturation lines.
**Assumptions**

1. The tank is stationary and thus the kinetic and potential energy changes are zero.  
2. The device is well-insulated and thus heat transfer is negligible.  
3. The energy stored in the resistance wires, and the heat transferred to the tank itself is negligible.

**Analysis**

We take the contents of the tank as the system. This is a closed system since no mass enters or leaves. Noting that the volume of the system is constant and thus there is no boundary work, the energy balance for this stationary closed system can be expressed as

\[ E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \]

Net energy transfer by heat, work, and mass  
\[ W_{\text{cin}} = \Delta U = m(u_f - u_i) \]  
(since \( Q = KE = PE = 0 \))  
\[ VIT = m(u_f - u_i) \]

The properties of water are (Tables A-4 through A-6)

\[ P_1 = 100 \text{kPa}, \quad \rho_f = 0.001043, \quad \rho_g = 1.6941 \text{ m}^3/\text{kg}, \quad u_f = 417.40, \quad u_g = 2088.2 \text{ kJ/kg} \]
\[ x = 0.25 \]

\[ \rho_1 = \rho_f + x\rho_g = 0.001043 + 0.25 \times (1.6941 - 0.001043) = 0.42431 \text{ m}^3/\text{kg} \]
\[ u_1 = u_f + xu_g = 417.40 + 0.25 \times 2088.2 = 939.4 \text{ kJ/kg} \]

Substituting,

\[ \Delta t = 9186 \text{ s} \approx 153.1 \text{ min} \]

A 3-m³ rigid tank contains hydrogen at 250 kPa and 550 K. The gas is now cooled until its temperature drops to 350 K. Determine (a) the final pressure in the tank and (b) the amount of heat transfer.

**Assumptions**

1. Hydrogen is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -240°C and 1.30 MPa.  
2. The tank is stationary, and thus the kinetic and potential energy changes are negligible, \( \Delta ke \approx \Delta pe \approx 0 \).
**Properties** The gas constant of hydrogen is \( R = 4.124 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K} \) (Table A-1). The constant volume specific heat of hydrogen at the average temperature of 450 K is \( c_{v_{avg}} = 10.377 \text{ kJ/kg} \cdot \text{K} \) (Table A-2).

**Analysis**

(a) The final pressure of hydrogen can be determined from the ideal gas relation,

\[
\frac{P_1 V}{T_1} = \frac{P_2 V}{T_2} \quad \Rightarrow \quad P_2 = \frac{T_2}{T_1} P_1 = \frac{350 \text{ K}}{550 \text{ K}} (250 \text{ kPa}) = 159.1 \text{ kPa}
\]

(b) We take the hydrogen in the tank as the system. This is a *closed system* since no mass enters or leaves. The energy balance for this stationary closed system can be expressed as

\[
E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}
\]

Net energy transfer by heat, work, and mass

\[
-Q_{\text{out}} = \Delta U
\]

\[
Q_{\text{out}} = -\Delta U = -m(u_2 - u_1) \equiv mC_v(T_1 - T_2)
\]

where

\[
m = \frac{P_1 V}{RT_1} = \frac{(250 \text{ kPa})(3.0 \text{ m}^3)}{(4.124 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(550 \text{ K})} = 0.3307 \text{ kg}
\]

Substituting into the energy balance,

\[
Q_{\text{out}} = (0.33307 \text{ kg})(10.377 \text{ kJ/kg} \cdot \text{K})(550 - 350)\text{K} = 686.2 \text{ kJ}
\]