INDIAN INSTITUTE OF TECHNOLOGY KANPUR

ESO 201A: Thermodynamics

(2023-24 I Semester)

Instructor: Dr Avinash Kumar Agarwal

Tutorial 5

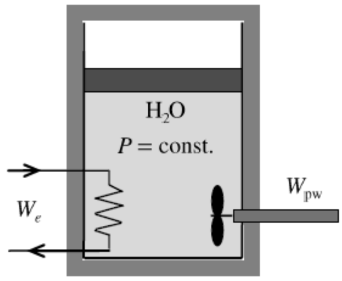
Question 1: An insulated piston–cylinder device contains 5 L of saturated liquid water at a constant pressure of 175 kPa. Water is stirred by a paddle wheel while a current of 8 A flows for 45 min through a resistor placed in the water. If one-half of the liquid is evaporated during this constant-pressure process and the paddle-wheel work amounts to 400 kJ, determine the voltage of the source. Also, show the process on a p-V diagram with respect to saturation lines.

Solution:

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis We take the contents of the cylinder 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

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$



$$W_{e,in} + W_{pw,in} - W_{b,out} = \Delta U \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$

$$W_{e,in} + W_{pw,in} = m(h_2 - h_1)$$

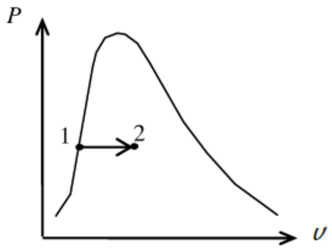
$$(\mathbf{V}I\Delta t) + W_{pw,in} = m(h_2 - h_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The properties of water are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 175 \text{ kPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_1 = h_{f@175\text{ kPa}} = 487.01 \text{ kJ/kg} \\ v_1 = v_{f@175\text{ kPa}} = 0.001057 \text{ m}^3\text{/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 175 \text{ kPa} \\ x_2 = 0.5 \end{array}\right\} h_2 = h_f + x_2 h_{fg} = 487.01 + (0.5 \times 2213.1) = 1593.6 \text{ kJ/kg}$$

$$m = \frac{V_1}{v_1} = \frac{0.005 \text{ m}^3}{0.001057 \text{ m}^3\text{/kg}} = 4.731 \text{ kg}$$



Substituting,

$$\mathbf{V}I\Delta t + (400 \text{ kJ}) = (4.731 \text{ kg})(1593.6 - 487.01)\text{kJ/kg}$$

$$\mathbf{V}I\Delta t = 4835 \text{ kJ}$$

$$\mathbf{V} = \frac{4835 \text{ kJ}}{(8 \text{ A})(45 \times 60 \text{ s})}\left(\frac{1000 \text{ VA}}{1 \text{ kJ/s}}\right) = \mathbf{223.9 \text{ V}}$$

Question 2: Steam at 75 kPa and 8 percent quality is contained in a spring-loaded piston–cylinder device, as shown in Fig.1, with an initial volume of 2 m³. Steam is now heated until its volume is 5 m³ and its pressure is 225 kPa. Determine the heat transferred to and the work produced by the steam during this process.

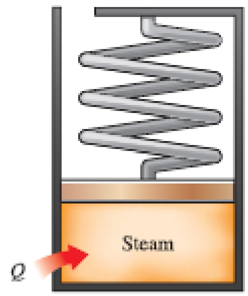


Figure 1.

Analysis We take the contents of the cylinder 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

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

$$Q_{in} - W_{b,\text{out}} = \Delta U = m(u_2 - u_1) \quad (\text{since KE} = \text{PE} = 0)$$

$$Q_{in} = W_{b,\text{out}} + m(u_2 - u_1)$$

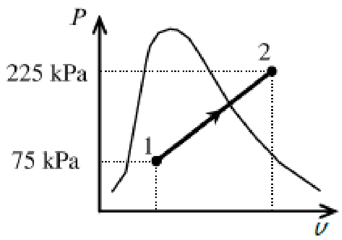
The initial state is saturated mixture at 75 kPa. The specific volume and internal energy at this state are (Table A-5),

$$v_1 = v_f + x v_{fg} = 0.001037 + (0.08)(2.2172 - 0.001037) = 0.1783 \text{ m}^3/\text{kg}$$

$$u_1 = u_f + x u_{fg} = 384.36 + (0.08)(2111.8) = 553.30 \text{ kJ/kg}$$

The mass of water is

$$m = \frac{V_1}{v_1} = \frac{2 \text{ m}^3}{0.1783 \text{ m}^3/\text{kg}} = 11.22 \text{ kg}$$



The final specific volume is

$$v_2 = \frac{V_2}{m} = \frac{5 \text{ m}^3}{11.22 \text{ kg}} = 0.4458 \text{ m}^3/\text{kg}$$

The final state is now fixed. The internal energy at this specific volume and 225 kPa pressure is (Table A-6)

$$u_2 = 1650.4 \text{ kJ/kg}$$

Since this is a linear process, the work done is equal to the area under the process line 1-2:

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1) = \frac{(75 + 225)\text{kPa}}{2}(5 - 2)\text{m}^3 \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = \mathbf{450 \text{ kJ}}$$

Substituting into energy balance equation gives

$$Q_{in} = W_{b,\text{out}} + m(u_2 - u_1) = 450 \text{ kJ} + (11.22 \text{ kg})(1650.4 - 553.30) \text{ kJ/kg} = \mathbf{12{,}750 \text{ kJ}}$$

Question 3: Air enters the 1-m^2 inlet of an aircraft engine at 100 kPa and 20°C with a velocity of 180 m/s. Determine the volume flow rate, in m^3/s, at the engine's inlet and the mass flow rate, in kg/s, at the engine's exit.

Assumptions **1** Air is an ideal gas. **2** The flow is steady.

Properties The gas constant of air is $R = 0.287$ kPa·m³/kg·K (Table A-1).

Analysis The inlet volume flow rate is

$$\dot{V}_1 = A_1 V_1 = (1\ \text{m}^2)(180\ \text{m/s}) = \mathbf{180\ m^3/s}$$

The specific volume at the inlet is

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(20+273\ \text{K})}{100\ \text{kPa}} = 0.8409\ \text{m}^3/\text{kg}$$

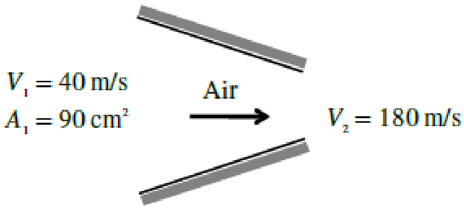
Since the flow is steady, the mass flow rate remains constant during the flow. Then,

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{180\ \text{m}^3/\text{s}}{0.8409\ \text{m}^3/\text{kg}} = \mathbf{214.1\ kg/s}$$

Question4: Air enters a nozzle steadily at 2.21 kg/m3 and 40 m/s and leaves at 0.762 kg/m3 and 180 m/s. If the inlet area of the nozzle is 90 cm2, determine (a) the mass flow rate through the nozzle, and (b) the exit area of the nozzle. **(0.796 kg/s and 58.0 cm²)**

Assumptions Flow through the nozzle is steady.

Properties The density of air is given to be 2.21 kg/m³ at the inlet, and 0.762 kg/m³ at the exit.



Analysis (a) The mass flow rate of air is determined from the inlet conditions to be

$$\dot{m} = \rho_1 A_1 V_1 = (2.21\ \text{kg/m}^3)(0.009\ \text{m}^2)(40\ \text{m/s}) = \mathbf{0.796\ kg/s}$$

(*b*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Then the exit area of the nozzle is determined to be

$$\dot{m} = \rho_2 A_2 V_2 \longrightarrow A_2 = \frac{\dot{m}}{\rho_2 V_2} = \frac{0.796\ \text{kg/s}}{(0.762\ \text{kg/m}^3)(180\ \text{m/s})} = 0.00580\ \text{m}^2 = \mathbf{58.0\ cm^2}$$

Question5: A spherical hot-air balloon is initially filled with air at 120 kPa and 20°C with an initial diameter of 5 m. Air enters this balloon at 120 kPa and 20°C with a velocity of 3 m/s through a 1-m-diameter opening. How many minutes will it take to inflate this balloon to a 17-m diameter when the pressure and temperature of the air in the balloon remain the same as the air entering the balloon?

Assumptions **1** Air is an ideal gas.

Properties The gas constant of air is $R = 0.287$ kPa·m³/kg·K (Table A-1).

Analysis The specific volume of air entering the balloon is

$$v = \frac{RT}{P} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(20+273\ \text{K})}{120\ \text{kPa}} = 0.7008\ \text{m}^3/\text{kg}$$

The mass flow rate at this entrance is

$$\dot{m} = \frac{A_c V}{v} = \frac{\pi D^2}{4}\frac{V}{v} = \frac{\pi(1.0\ \text{m})^2}{4}\frac{3\ \text{m/s}}{0.7008\ \text{m}^3/\text{kg}} = 3.362\ \text{kg/s}$$

The initial mass of the air in the balloon is

$$m_i = \frac{V_i}{v} = \frac{\pi D^3}{6v} = \frac{\pi(5\ \text{m})^3}{6(0.7008\ \text{m}^3/\text{kg})} = 93.39\ \text{kg}$$

Similarly, the final mass of air in the balloon is

$$m_f = \frac{V_f}{v} = \frac{\pi D^3}{6v} = \frac{\pi(17\ \text{m})^3}{6(0.7008\ \text{m}^3/\text{kg})} = 3671\ \text{kg}$$

The time it takes to inflate the balloon is determined from

$$\Delta t = \frac{m_f - m_i}{\dot{m}} = \frac{(3671 - 93.39)\ \text{kg}}{3.362\ \text{kg/s}} = 1064\ \text{s} = \mathbf{17.7\ min}$$

Question6: Refrigerant-134a enters a diffuser steadily as saturated vapor at 600 kPa with a velocity of 160 m/s, and it leaves at 700 kPa and 40°C. The refrigerant is gaining heat at a rate of 2 kJ/s as it passes through the diffuser. If the exit area is 80 percent greater than the inlet area, determine (a) the exit velocity and (b) the mass flow rate of the refrigerant.

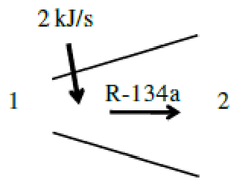
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Potential energy changes are negligible. **3** There are no work interactions.

Properties From the R-134a tables (Tables A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 600\ \text{kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} v_1 = 0.034335\ \text{m}^3/\text{kg} \\ h_1 = 262.46\ \text{kJ/kg} \end{array}$$

and

$$\left.\begin{array}{l} P_2 = 700\ \text{kPa} \\ T_2 = 40^\circ\text{C} \end{array}\right\} \begin{array}{l} v_2 = 0.031696\ \text{m}^3/\text{kg} \\ h_2 = 278.59\ \text{kJ/kg} \end{array}$$



Analysis (*a*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Then the exit velocity of R-134a is determined from the steady-flow mass balance to be

$$\frac{1}{v_2}A_2V_2 = \frac{1}{v_1}A_1V_1 \longrightarrow V_2 = \frac{v_2}{v_1}\frac{A_1}{A_2}V_1 = \frac{1}{1.8}\frac{(0.031696\ \text{m}^3/\text{kg})}{(0.034335\ \text{m}^3/\text{kg})}(160\ \text{m/s}) = 82.06\ \text{m/s} \cong \mathbf{82.1\ m/s}$$

(*b*) We take diffuser as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}{}^{\nearrow 0\ \text{(steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{Q}_{\text{in}} + \dot{m}(h_1 + V_1^2/2) = \dot{m}(h_2 + V_2^2/2) \quad (\text{since } \dot{W} \cong \Delta \text{pe} \cong 0)$$

$$\dot{Q}_{\text{in}} = \dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}\right)$$

Substituting, the mass flow rate of the refrigerant is determined to be

$$2 \text{ kJ/s} = \dot{m}\left[(278.59 - 262.46)\text{kJ/kg} + \frac{(82.06 \text{ m/s})^2 - (160 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right]$$

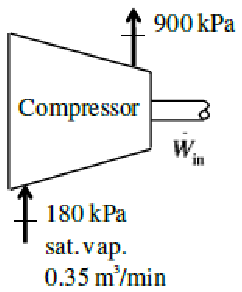
It yields

$$\dot{m} = \mathbf{0.298 \text{ kg/s}}$$

Question7: Refrigerant-134a enters a compressor at 180 kPa as a saturated vapor with a flow rate of 0.35 m3/min and leaves at 900 kPa. The power supplied to the refrigerant during the compression process is 2.35 kW. What is the temperature of R-134a at the exit of the compressor?

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** Heat transfer with the surroundings is negligible.

Analysis We take the compressor as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters and leaves the compressor, the energy balance for this steady-flow system can be expressed in the rate form as



$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{\text{system}}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{W}_{\text{in}} + \dot{m}h_1 = \dot{m}h_2 \quad (\text{since } \Delta ke \cong \Delta \text{pe} \cong 0)$$

$$\dot{W}_{\text{in}} = \dot{m}(h_2 - h_2)$$

From R134a tables (Table A-12)

$$\left.\begin{array}{l} P_1 = 180 \text{ kPa} \\ x_1 = 0 \end{array}\right\} \begin{array}{l} h_1 = 242.86 \text{ kJ/kg} \\ v_1 = 0.1104 \text{ m}^3/\text{kg} \end{array}$$

The mass flow rate is

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{(0.35/60) \text{ m}^3/\text{s}}{0.1104 \text{ m}^3/\text{kg}} = 0.05283 \text{ kg/s}$$

Substituting for the exit enthalpy,

$$\dot{W}_{\text{in}} = \dot{m}(h_2 - h_1)$$

$$2.35 \text{ kW} = (0.05283 \text{ kg/s})(h_2 - 242.86)\text{kJ/kg} \longrightarrow h_2 = 287.34 \text{ kJ/kg}$$

From Table A-13,

$$\left.\begin{array}{l} P_2 = 900 \text{ kPa} \\ h_2 = 287.34 \text{ kJ/kg} \end{array}\right\} T_2 = \mathbf{52.5°C}$$