ESO201A Thermodynamics
Instructor: Jishnu Bhattacharya
Mid Semester Exam
Maximum points: 120

Date: 21st Feb 2023 (Tuesday)
Venue: L18 (Sections G1, G2, G3)
L19 (Sections G4, G5, G6) - all OROS
Allotted time: 120 minutes (13:00-15:00)

Important instructions:

-You must write your **name**, **roll number** and **section**, and put your **signature** in the answer sheet.

-Please return the property tables after the exam.

Q1 (30 points). If sufficient data are provided, complete the blank cells in the following table of properties of water. In the last column describe the condition of water as compressed liquid, saturated mixture, superheated vapour or insufficient information; and, if applicable, mention the quality of vapour. Showing calculation for each value of missing property and the reasoning behind the description in the last column are mandatory for full credit.

P, kPa	T, °C	v, m^3/kg	u, kJ/kg	Phase description
	250		2728.9	
300			1560.0	
101.325	**99.97**			
3000	180			

Figure for Q1

Q2 (30 points). Consider a well-insulated horizontal rigid cylinder that is divided into two compartments by a piston that is free to move but does not allow either gas to leak into the other side. Initially, one side of the piston contains 1 m^3 of N_2 gas at 500 kPa and 120 °C while the other side contains 1 m^3 of He gas at 500 kPa and 40 °C. Now thermal equilibrium is established in the cylinder as a result of heat transfer through the piston. Using constant specific heats at room temperature, determine the final equilibrium temperature (in °C) in the cylinder. What would your answer be if the piston were not free to move?

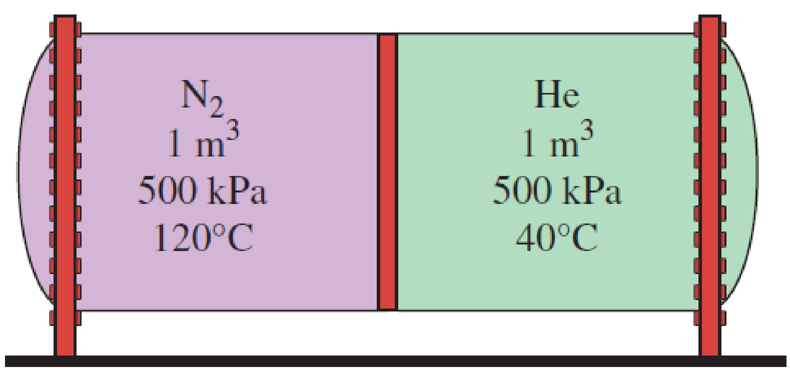


Figure for Q2

Q3 (30 points). A piston-cylinder device initially contains 2 kg of refrigerant-134a at 800 kPa and 80 °C. At this state, the piston is touching on a pair of stops at the top. The mass of the piston is such that 500 kPa pressure is required to move it. A valve at the bottom of the tank is opened, and R-134a is withdrawn from the cylinder. After a while, the piston is observed to move and the valve is closed when half of the refrigerant is withdrawn from the tank and the temperature in the tank drops to 20 °C. Determine (a) the work done (in kJ) and (b) the heat transfer (in kJ).

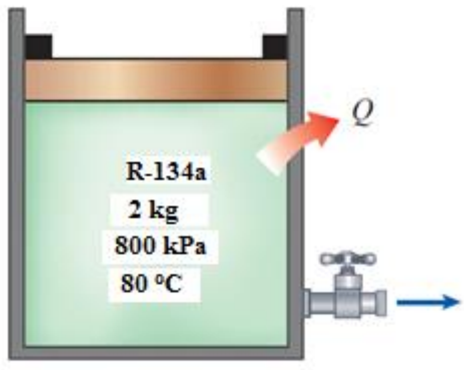


Figure for Q3

Q4 (30 points). An air-conditioner with refrigerant-134a as the working fluid is used to keep a room at 23 °C by rejecting waste heat to the outdoor air at 34 °C. The room gains heat through the walls and the windows at a rate of 250 kJ/min while the heat generated by the computer, TV and lights amounts to 900 W. The refrigerant enters the compressor at 400 kPa as a saturated vapour at the rate of 80 L/min and leaves at 1200 kPa and 70 °C. Determine (a) the actual COP, (b) the maximum COP and (c) the minimum volume flow rate (in L/min) of the refrigerant at the compressor inlet for the same compressor inlet and exit conditions.

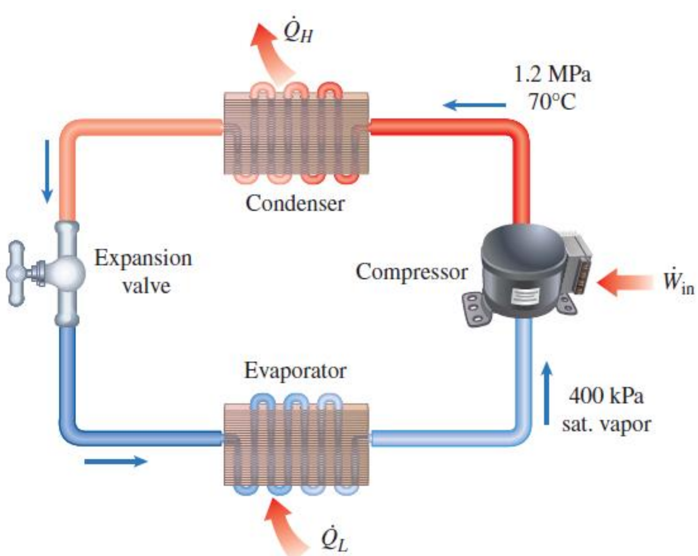


Figure for Q4

Q 1 The table is completed as follows:

P, kPa	T, °C	v, m^3/kg	u, kJ/kg	Condition description and quality, if applicable
300	250	**0.79645**	2728.9	**Superheated vapor**
300	**133.52**	**0.30479**	1560.0	**x = 0.504, Two-phase mixture**
101.325	**99.97**	-	-	**Insufficient information**
3000	180	**0.001127***	**761.92***	**Compressed liquid**

* Approximated as saturated liquid at the given temperature of 180°C

Q2 An insulated cylinder is divided into two parts. One side of the cylinder contains N_2 gas and the other side contains He gas at different states. The final equilibrium temperature in the cylinder when thermal equilibrium is established is to be determined for the cases of the piston being fixed and moving freely.

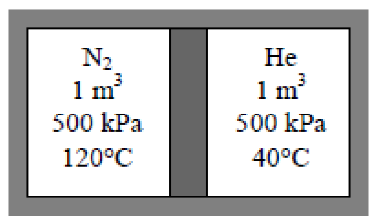
Assumptions **1** Both N_2 and He are ideal gases with constant specific heats. **2** The energy stored in the container itself is negligible. **3** The cylinder is well-insulated and thus heat transfer is negligible.

Properties The gas constants and the constant volume specific heats are R = 0.2968 kPa.m^3/kg.K is c_v = 0.743 kJ/kg·°C for N_2, and R = 2.0769 kPa.m^3/kg.K is c_v = 3.1156 kJ/kg·°C for He (Tables A-1 and A-2)

Analysis The mass of each gas in the cylinder is

$$m_{N_2} = \left(\frac{P_1 V_1}{RT_1}\right)_{N_2} = \frac{(500\ \text{kPa})(1\ \text{m}^3)}{(0.2968\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(393\ \text{K})} = 4.287\ \text{kg}$$

$$m_{He} = \left(\frac{P_1 V_1}{RT_1}\right)_{He} = \frac{(500\ \text{kPa})(1\ \text{m}^3)}{(2.0769\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(313\ \text{K})} = 0.7691\ \text{kg}$$



Taking the entire contents of the cylinder as our system, the 1st law relation can be written as

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

$$0 = \Delta U = (\Delta U)_{N_2} + (\Delta U)_{He}$$

$$0 = [mc_v(T_2 - T_1)]_{N_2} + [mc_v(T_2 - T_1)]_{He}$$

Substituting,

$$(4.287\ \text{kg})(0.743\ \text{kJ/kg}\cdot°\text{C})(T_f - 120)°\text{C} + (0.7691\ \text{kg})(3.1156\ \text{kJ/kg}\cdot°\text{C})(T_f - 40)°\text{C} = 0$$

It gives

T_f = **85.4°C**

where T_f is the final equilibrium temperature in the cylinder.

The answer would be the **same** if the piston were not free to move since it would effect only pressure, and not the specific heats.

Discussion Using the relation $PV = NR_uT$, it can be shown that the total number of moles in the cylinder is 0.153 + 0.192 = 0.345 kmol, and the final pressure is 515 kPa. **Not asked to find out**

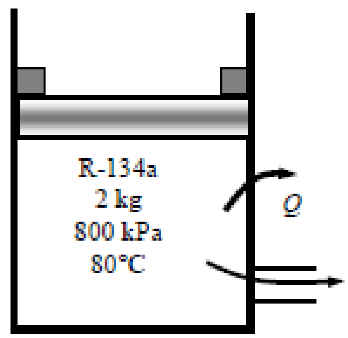
Q 3 R-134a is allowed to leave a piston-cylinder device with a pair of stops. The work done and the heat transfer are to be determined.

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 since the state of fluid leaving the device is assumed to be constant. **2** Kinetic and potential energies are negligible.

Properties The properties of R-134a at various states are (Tables A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 800\text{ kPa} \\ T_1 = 80°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 0.032659\text{ m}^3/\text{kg} \\ u_1 = 290.86\text{ kJ/kg} \\ h_1 = 316.99\text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 500\text{ kPa} \\ T_2 = 20°\text{C} \end{array}\right\} \begin{array}{l} v_2 = 0.042115\text{ m}^3/\text{kg} \\ u_2 = 242.42\text{ kJ/kg} \\ h_2 = 263.48\text{ kJ/kg} \end{array}$$



Analysis (*a*) We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic 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:

$$m_{in} - m_{out} = \Delta m_{system} \rightarrow m_e = m_1 - m_2$$

Energy balance:

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

$$W_{b,in} - Q_{out} - m_e h_e = m_2 u_2 - m_1 u_1 \quad (\text{since ke} \cong \text{pe} \cong 0)$$

The volumes at the initial and final states and the mass that has left the cylinder are

$$V_1 = m_1 v_1 = (2\text{ kg})(0.032659\text{ m}^3/\text{kg}) = 0.06532\text{ m}^3$$

$$V_2 = m_2 v_2 = (1/2)m_1 v_2 = (1/2)(2\text{ kg})(0.042115\text{ m}^3/\text{kg}) = 0.04212\text{ m}^3$$

$$m_e = m_1 - m_2 = 2 - 1 = 1\text{ kg}$$

The enthalpy of the refrigerant withdrawn from the cylinder is assumed to be the average of initial and final enthalpies of the refrigerant in the cylinder

$$h_e = (1/2)(h_1 + h_2) = (1/2)(316.99 + 263.48) = 290.23\text{ kJ/kg}$$

Noting that the pressure remains constant after the piston starts moving, the boundary work is determined from

$$W_{b,in} = P_2(V_1 - V_2) = (500\text{ kPa})(0.06532 - 0.04212)\text{m}^3 = \mathbf{11.6\ kJ}$$

(*b*) Substituting,

$$11.6\text{ kJ} - Q_{out} - (1\text{ kg})(290.23\text{ kJ/kg}) = (1\text{ kg})(242.42\text{ kJ/kg}) - (2\text{ kg})(290.86\text{ kJ/kg})$$

$$Q_{out} = \mathbf{60.7\ kJ}$$

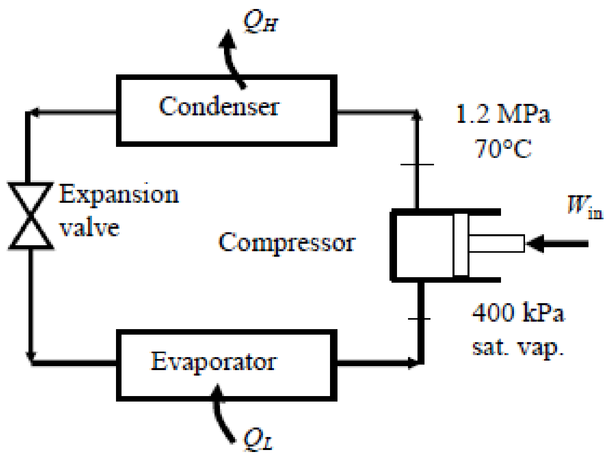
Q4 An air-conditioner with R-134a as the working fluid is considered. The compressor inlet and exit states are specified. The actual and maximum COPs and the minimum volume flow rate of the refrigerant at the compressor inlet are to be determined.

Assumptions **1** The air-conditioner operates steadily. **2** The kinetic and potential energy changes are zero.

Properties The properties of R-134a at the compressor inlet and exit states are (Tables A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 400\text{ kPa} \\ x_1 = 1 \end{array}\right\} \begin{array}{l} h_1 = 255.61\text{ kJ/kg} \\ v_1 = 0.05127\text{ m}^3\text{/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1.2\text{ MPa} \\ T_2 = 70°\text{C} \end{array}\right\} h_2 = 300.63\text{ kJ/kg}$$



Analysis (*a*) The mass flow rate of the refrigerant and the power consumption of the compressor are

$$\dot{m}_R = \frac{\dot{V}_1}{v_1} = \frac{80\text{ L/min}\left(\frac{1\text{ m}^3}{1000\text{ L}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)}{0.05127\text{ m}^3\text{/kg}} = 0.02601\text{ kg/s}$$

$$\dot{W}_{in} = \dot{m}_R(h_2 - h_1) = (0.02601\text{ kg/s})(300.63 - 255.61)\text{ kJ/kg} = 1.171\text{ kW}$$

The heat gains to the room must be rejected by the air-conditioner. That is,

$$\dot{Q}_L = \dot{Q}_{heat} + \dot{Q}_{equipment} = (250\text{ kJ/min})\left(\frac{1\text{ min}}{60\text{ s}}\right) + 0.9\text{ kW} = 5.067\text{ kW}$$

Then, the actual COP becomes

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{5.067\text{ kW}}{1.171\text{ kW}} = \mathbf{4.33}$$

(*b*) The COP of a reversible refrigerator operating between the same temperature limits is

$$\text{COP}_{max}\ \frac{1}{T_H/T_L - 1} = \frac{1}{(34+273)/(23+273) - 1} = \mathbf{26.91}$$

(*c*) The minimum power input to the compressor for the same refrigeration load would be

$$\dot{W}_{in,min} = \frac{\dot{Q}_L}{\text{COP}_{max}} = \frac{5.067\text{ kW}}{26.91} = 0.1883\text{ kW}$$

The minimum mass flow rate is

$$\dot{m}_{R,min} = \frac{\dot{W}_{in,min}}{h_2 - h_1} = \frac{0.1883\text{ kW}}{(300.63 - 255.61)\text{ kJ/kg}} = 0.004182\text{ kg/s}$$

Finally, the minimum volume flow rate at the compressor inlet is

$$\dot{V}_{min,1} = \dot{m}_{R,min} v_1 = (0.004182\text{ kg/s})(0.05127\text{ m}^3\text{/kg}) = 0.0002144\text{ m}^3\text{/s} = \mathbf{12.9\ L/min}$$