Given
Heating of liquid CO_2 at constant pressure

Find
(a) Change in specific internal energy ($\frac{kJ}{kg}$) using:
- Property Table
- Saturated liquid approximation
- Specific heat at average temperature

(b) Change in specific enthalpy ($\frac{kJ}{kg}$) using:
- Property table
- Saturated liquid approximation
- Specific heat at average temperature

System
N/A

Assumptions
- Liquid CO_2 is incompressible
- Specific heat constant with Temperature change

Basic Equations
N/A

Solution

CO_2, $P_1 = 20\ bar$, $T_1 = -40°C$ $\longrightarrow$ $P_2 = 20\ bar$, $T_2 = -20°C$

$T_{sat}(20\ bar) = -19.503°C \Rightarrow T < T_{sat} \Rightarrow$ sub-cooled (compressed) liquid

(a) Compressed liquid table:

$u_1 = -1.641\ \frac{kJ}{kg}$, $u_2 = 39.601\ \frac{kJ}{kg}$

$\Delta u = u_2 - u_1 \Rightarrow \boxed{\Delta u = 41.242\ \frac{kJ}{kg}}$

Saturated liquid approximation:

$u_1 \cong u_f(-40°C) = -0.8997\ \frac{kJ}{kg}$, $u_2 \cong u_f(-20°C) = 39.636\ \frac{kJ}{kg}$

$\Delta u = u_2 - u_1 \Rightarrow \boxed{\Delta u = 40.536\ \frac{kJ}{kg}}$

Specific heat:

$c_{CO_2} = 2.082\ \frac{kJ}{kg-K}$ $\Rightarrow \boxed{\Delta u = 41.64\ \frac{kJ}{kg}}$

$\Delta u = c_{CO_2}(T_2 - T_1) = 2.082\ \frac{kJ}{kg-K} * (-20 - (-40))\ K$

(b) Compressed liquid table:

$h_1 = 0.146 \frac{kJ}{kg}$, $h_2 = 41.540 \frac{kJ}{kg}$

$\Delta h = h_2 - h_1 \Rightarrow \boxed{\Delta h = 41.394 \frac{kJ}{kg}}$

Saturated liquid approximation:

$h_1 \cong h_f(-40°C) + v_f(-40°C)[P_1 - P_{sat}(-40°C)]$

$= 0 \frac{kJ}{kg} + 0.0008957 \frac{m^3}{kg} * (20 - 10.045) \times 100\ kPa$

$= 0.89167 \frac{kJ}{kg}$

$h_2 \cong h_f(-20°C) + v_f(-20°C)[P_2 - P_{sat}(-20°C)]$

$= 41.546 \frac{kJ}{kg} + 0.0009693 \frac{m^3}{kg} * (20 - 19.696) \times 100\ kPa$

$= 41.575 \frac{kJ}{kg}$

$\Delta h = h_2 - h_1 \Rightarrow \boxed{\Delta h = 40.683 \frac{kJ}{kg}}$

Specific heat:

$\Delta h = \Delta u + v\cancel{\Delta P}^{0} \Rightarrow \boxed{\Delta h = 41.64 \frac{kJ}{kg}}$

Given

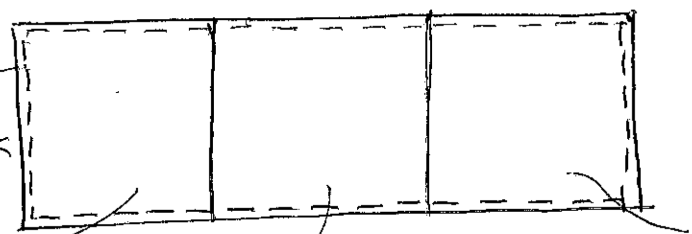
Heat transfer among three liquids inside a well-insulated, closed rigid tank

Find

Temperature (°C) at equilibrium

System

Liquid inside the rigid tank is the system



$m_A = 5$ kg, $C_A = 2 \frac{kJ}{kg-K}$, $T_{A,i} = 100°C$

$m_B = 2$ kg, $C_B = 4 \frac{kJ}{kg-K}$, $T_{B,i} = 50°C$

$m_C = 1$ kg, $C_C = 7 \frac{kJ}{kg-K}$, $T_{C,i} = 40°C$

Assumptions

- Closed system (m = constant)
- Rigid tank : $W_{boundary} = 0$
- Insulated : $Q = 0$
- Ignore change in KE and PE
- Liquids are incompressible
- Specific heat constant with temperature change

Basic Equations

$$\cancel{Q}^{0} - \cancel{W}^{0} = \Delta E = \Delta U + \Delta \cancel{KE}^{\approx 0} + \Delta \cancel{PE}^{\approx 0}$$

$$W \to (\cancel{W_{boundary}}^{0} + \cancel{W_{other}}^{0})$$

Solution

Considering energy balance : $\Delta U = 0$

$$\Delta U_A + \Delta U_B + \Delta U_C = 0$$

$$m_A c_A (T_f - T_{A,i}) + m_B c_B (T_f - T_{B,i}) + m_C c_C (T_f - T_{C,i}) = 0$$

Temperature at equilibrium :

$$T_f = \frac{m_A c_A T_{A,i} + m_B c_B T_{B,i} + m_C c_C T_{C,i}}{m_A c_A + m_B c_B + m_C c_C}$$

$$\boxed{T_f = 67.2°C}$$

Given

Air inside a closed, rigid tank

Find

(a) Temperature (K) of air at State 2

(b) Heat transfer (kJ) during the process

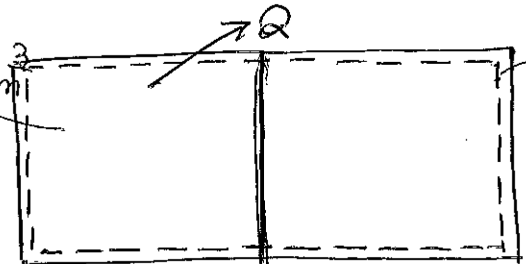
System

$P_1 = 5$ bar, $V_1 = 0.2 m^3$

$T_1 = 500 K$

↓

$P_2 = 1.25$ bar, $V_2 = 0.4 m^3$



Air inside the tank is the system

Assumptions

- Closed system (m = constant)
- Rigid tank : $W_{boundary} = 0$
- Ignore change in KE and PE
- Air behaves as an ideal gas
- Specific heat constant with temperature change

Basic Equations

$$Q - \cancel{W}^{0} = \Delta E = \Delta U + \cancel{\Delta KE}^{no} + \cancel{\Delta PE}^{no}$$

$$\hookrightarrow (\cancel{W_{boundary}}^{0} + \cancel{W_{other}}^{0})$$

Solution

(a) State 1 $\quad P_1 = 5$ bar, $V_1 = 0.2 m^3$, $T_1 = 500 K$

Ideal gas equation: $P_1 V_1 = m_1 R_{air} T_1$

$$R_{air} = \frac{\bar{R}}{M_{air}} = \frac{8.314 \frac{kJ}{kmol-K}}{28.97 \frac{kg}{kmol}} = 0.287 \frac{kJ}{kg-K}$$

$$m_1 = \frac{P_1 V_1}{R_{air} T_1} = \frac{(5 \times 100)\, \cancel{kPa} * 0.2\, \cancel{m^3}}{0.287 \frac{\cancel{kJ}}{kg-\cancel{K}} * 500\, \cancel{K}} = 0.697 \text{ kg}$$

State 2 $\quad P_2 = 1.25$ bar, $V_2 = 0.4 m^3$, $m_2 = m_1$

Ideal gas equation: $P_2 V_2 = m_2 R_{air} T_2$

Temperature at ~~State~~ State 2: $T_2 = \frac{P_2 V_2}{m_2 R_{air}}$

$$T_2 = \frac{(1.25 \times 100)\, \cancel{kPa} * 0.4\, \cancel{m^3}}{0.697\, \cancel{kg} * 0.287\, \frac{\cancel{kJ}}{\cancel{kg}-K}} \Rightarrow \boxed{T_2 \cong 250\ K}$$

(b) Considering energy balance, heat transfer during the process: $Q = \Delta U = U_2 - U_1 = m_2 u_2 - m_1 u_1$

$$Q = (m_1 = m_2)(u_2 - u_1) = (m_1 = m_2)\, c_{v_{air}} (T_2 - T_1)$$

For an ideal gas: $c_p - c_v = R$

$$c_{v_{air}} = c_{p_{air}} - R_{air} = 1.017 \frac{kJ}{kg-K} - 0.287 \frac{kJ}{kg-K}$$
$$= 0.730 \frac{kJ}{kg-K}$$

$$Q = 0.697\ kg * 0.730 \frac{kJ}{kg-K} * (250 - 500)\ K$$

$\boxed{Q = -127.2\ kJ}$ $Q < 0$ heat transfer out of the system

Given

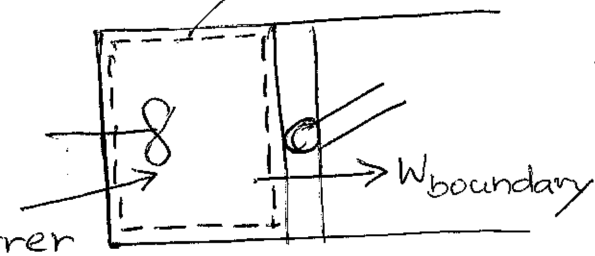
Air inside a closed insulated piston-cylinder device with a stirrer

Find

Work (kJ) for the stirrer

System

Air inside the cylinder is the system



$P_1 = 1.5$ bar, $V_1 = 0.02\,m^3$
$T_1 = 400K$
$\downarrow$
$P_2 = P_1$, $T_2 = 950\,K$

Assumptions

- Closed system (m = constant)
- Quasi-equilibrium process
- Ignore change in KE and PE
- Air behaves as an ideal gas
- Insulated: $Q = 0$

Basic Equations

$$W_{boundary} = \int P dV$$

$$\cancel{Q}^{0} - W = \Delta E = \Delta U + \Delta \cancel{KE}^{no} + \Delta \cancel{PE}^{no}$$

$\hookrightarrow (W_{boundary} + W_{other})$

Solution

Considering energy balance, work during the process: $-W = \Delta U = U_2 - U_1 = m_2 u_2 - m_1 u_1$

$-(W_{boundary} + W_{other}) = (m_1 = m_2)(u_2 - u_1)$

State 1 $P_1 = 1.5$ bar, $V_1 = 0.02\,m^3$, $T_1 = 400\,K$

Ideal gas equation: $P_1 V_1 = m_1 R_{air} T_1$

$$R_{air} = \frac{\bar{R}}{M_{air}} = \frac{8.314\,\frac{kJ}{kmol\text{-}K}}{28.97\,\frac{kg}{kmol}} = 0.287\,\frac{kJ}{kg\text{-}K}$$

$$m_1 = \frac{P_1 V_1}{R_{air} T_1} = \frac{(1.5 \times 100)\,\cancel{kPa} * 0.02\,m^3}{0.287\,\frac{\cancel{kJ}}{kg\text{-}\cancel{K}} * 400\,\cancel{K}} = 0.0261\,kg$$

State 2 $P_2 = P_1 = 1.5$ bar, $T_2 = 950$ K, $m_2 = m$,

Ideal gas equation: $P_2 V_2 = m_2 R_{air} T_2$

$$V_2 = \frac{m_2 R_{air} T_2}{P_2} = \frac{0.0261\ \cancel{kg} * 0.287 \frac{kJ}{\cancel{kg}-\cancel{K}} * 950\cancel{K}}{(1.5 \times 100)\ kPa}$$

$$= 0.0474\ m^3$$

Boundary work during the process:

$$W_{boundary} = \int_{V_1}^{V_2} P dV = (P_1 = P_2)(V_2 - V_1) = (1.5 \times 100) kPa * (0.0474 - 0.02) m^3$$

$$= +4.11\ kJ \qquad W > 0 \text{ work done by air}$$

$T_1 = 400$ K, $u_1 = 286.1 \frac{kJ}{kg}$

$T_2 = 950$ K, $u_2 = 716.5 \frac{kJ}{kg}$

Work for the stirrer:

$$-W_{stirrer} = -W_{other} = (m_1 = m_2)(u_2 - u_1) + W_{boundary}$$

$$= 0.0261\ kg * (716.5 - 286.1) \frac{kJ}{kg} + 4.11\ kJ$$

$$= 15.3\ kJ$$

$$\Rightarrow \boxed{W_{stirrer} = -15.3\ kJ} \qquad W < 0 \text{ work done on air}$$

Given

Air inside a closed piston-cylinder device undergoing four processes

Find

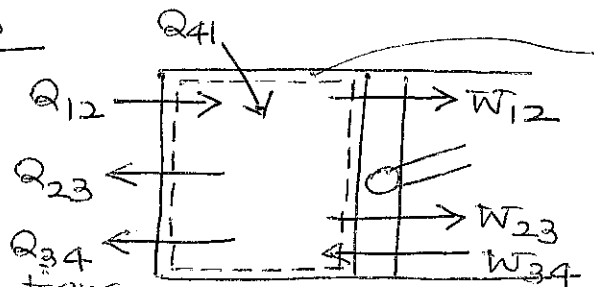
(a) Temperature (K) at State 3 and State 4

(b) Work (kJ) for each process

(c) Heat transfer (kJ) for each process

(d) P-V diagram

System



Air inside the cylinder is the system

$m_{air} = 2\ kg$

Assumptions

- Closed system (m = constant)
- Quasi-equilibrium process
- Ignore KE and PE change
- Air behaves as an ideal gas

Basic Equations

$$W_{boundary} = \int P\,dV$$

$$Q - W = \Delta E = \Delta U + \cancel{\Delta KE}^{\,no} + \cancel{\Delta PE}^{\,no}$$

$$W = (W_{boundary} + \cancel{W_{other}}^{\,0})$$

Solution

(a) State 1 $\quad P_1 = 5\ bar,\ T_1 = 600\ K$

Ideal gas equation: $P_1 V_1 = m_{air} R_{air} T_1$

$$R_{air} = \frac{\bar{R}}{M_{air}} = \frac{8.314\ \frac{kJ}{kmol\text{-}K}}{28.97\ \frac{kg}{kmol}} = 0.287\ \frac{kJ}{kg\text{-}K}$$

$$V_1 = \frac{m_{air} R_{air} T_1}{P_1} = \frac{2\ \cancel{kg} * 0.287\ \frac{kJ}{\cancel{kg\text{-}K}} * 600\ \cancel{K}}{(5 \times 100)\ kPa}$$

$V_1 = 0.689\ m^3$

State 2 $\quad P_2 = 4\text{ bar},\ T_2 = T_1 = 600\text{ K}$

$$V_2 = \frac{m_{air} R_{air} T_2}{P_2} = \frac{2\,\cancel{kg} * 0.287\,\frac{kJ}{\cancel{kg\text{-}K}} * 600\,\cancel{K}}{(4\times 100)\,kPa}$$

$V_2 = 0.861\ m^3$

State 3 $\quad P_3 = 3\text{ bar},\ P_2 V_2^{1.4} = P_3 V_3^{1.4} \Rightarrow V_3 = 1.06\ m^3$

$$T_3 = \frac{P_3 V_3}{m_{air} R_{air}} = \frac{(3\times 100)\,\cancel{kPa} * 1.06\,\cancel{m^3}}{2\,\cancel{kg} * 0.287\,\frac{\cancel{kJ}}{\cancel{kg}\text{-}K}}$$

Temperature at State 3 : $\boxed{T_3 = 554\text{ K}}$

Alternatively

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} \Rightarrow T_3 = 600\text{ K} * \left(\frac{3\text{ bar}}{4\text{ bar}}\right)^{\frac{1.4-1}{1.4}} \Rightarrow T_3 \simeq 554\text{ K}$$

State 4 $\quad P_4 = P_3 = 3\text{ bar},\ V_4 = V_1 = 0.689\ m^3$

$$T_4 = \frac{P_4 V_4}{m_{air} R_{air}} = \frac{(3\times 100)\,\cancel{kPa} * 0.689\,\cancel{m^3}}{2\,\cancel{kg} * 0.287\,\frac{\cancel{kJ}}{\cancel{kg}\text{-}K}}$$

Temperature at State 4 : $\boxed{T_4 = 360\text{ K}}$

Alternatively

$$\frac{T_4}{T_3} = \frac{V_4}{V_3} \Rightarrow T_4 = 554\text{ K} * \frac{0.689\ m^3}{1.060\ m^3} \Rightarrow T_4 \simeq 360\text{ K}$$

(b) Boundary work for each process:

$$W_{12} = \int_{V_1}^{V_2} P\,dV \qquad m_{air} = \frac{P_1 V_1}{\cancel{R_{air}}\,\cancel{T_1}} = \frac{P_2 V_2}{\cancel{R_{air}}\,\cancel{T_2}} \Rightarrow PV = \text{constant}$$

$$W_{12} = \int_{V_1}^{V_2} \left(\frac{\text{constant}}{V}\right) dV = \underbrace{(P_1 V_1 = P_2 V_2)}_{m_{air} R_{air} (T_1 = T_2)} \ln\frac{V_2}{V_1} \;;\; \frac{V_2}{V_1} = \frac{P_1}{P_2}$$

$$= 2\text{ kg} * 0.287\,\frac{kJ}{kg\text{-}K} * 600\text{ K}\ \ln\frac{5\text{ bar}}{4\text{ bar}}$$

$\boxed{W_{12} = +76.8\text{ kJ}}$ $\quad W > 0 \Rightarrow$ work done by the system

$$W_{23} = \int_{V_2}^{V_3} \left(\frac{\text{constant}}{V^{1.4}}\right) dV = \frac{P_2 V_2 - P_3 V_3}{n-1} = \frac{m_{air} R_{air} (T_2 - T_3)}{n-1}$$

$$= \frac{2\,kg * 0.287 \frac{kJ}{kg-K} * (600 - 554)\,K}{1.4 - 1}$$

$\boxed{W_{23} = +66\ kJ}$ $W > 0 \Rightarrow$ work done by the system

$$W_{34} = \int_{V_3}^{V_4} P\,dV = (P_3 = P_4)(V_4 - V_3) = (3 \times 100)\ kPa * (0.889 - 1.060)\ m^3$$

$\boxed{W_{34} = -111.3\ kJ}$ $W < 0 \Rightarrow$ work done on the system

$$W_{41} = \int_{V_4}^{V_1} P\,\cancel{dV}^{\,0} \Rightarrow \boxed{W_{41} = 0}$$

(c) Considering energy balance, heat transfer for each process: $Q = W + \Delta U$

$$Q_{12} = W_{12} + (U_2 - U_1) = W_{12} + m_{air}\cancel{(u_2 - u_1)}^{\,0}$$

$T_1 = T_2$
$u = f(T)$ only for ideal gas

$\boxed{Q_{12} = +76.8\ kJ}$ $Q > 0 \Rightarrow$ heat transfer into the system

$$Q_{23} = W_{23} + (U_3 - U_2) = W_{23} + m_{air}(u_3 - u_2)$$

$T_2 = 600\ K \Rightarrow u_2 = 434.8\ \frac{kJ}{kg}$

$T_3 = 554\ K$ Interpolating: $u_3 = 399.9\ \frac{kJ}{kg}$.

$$Q_{23} = +66\ kJ + 2\,kg * (399.9 - 434.8)\ \frac{kJ}{kg}$$

$\boxed{Q_{23} = -3.8\ kJ}$ $Q < 0 \Rightarrow$ heat transfer out of the system

$$Q_{34} = W_{34} + (U_4 - U_3) = W_{34} + m_{air}(u_4 - u_3)$$

$T_4 = 360\ K \Rightarrow u_4 = 257.2\ \frac{kJ}{kg}$

$$Q_{34} = -111.3\ kJ + 2\,kg * (257.2 - 399.9)\ \frac{kJ}{kg}$$

$\boxed{Q_{34} = -396.7\ kJ}$ $Q < 0 \Rightarrow$ heat transfer out of the system

$$Q_{41} = \cancelto{0}{W_{41}} + (U_1 - U_4) = m_{air}(u_1 - u_4)$$

$$Q_{41} = 2\,kg * (434.8 - 257.2)\ \frac{kJ}{kg}$$

$\boxed{Q_{41} = +355.2\ kJ}$ $Q > 0 \Rightarrow$ heat transfer into the system

Note

$$W_{net} = W_{12} + W_{23} + W_{34} + \cancelto{0}{W_{41}} = +31.5\ kJ$$

$$Q_{net} = Q_{12} + Q_{23} + Q_{34} + Q_{41} = +31.5\ kJ$$

$$\Delta U_{net} = \Delta U_{12} + \Delta U_{23} + \Delta U_{34} + \Delta U_{41} = 0$$

$$Q_{net} - W_{net} = \cancelto{0}{\Delta U_{net}} \implies Q_{net} = W_{net}$$

This is a "cyclic" system

(d)