Thermodynamics (ME2121)
Tutorial 2

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Outline and objectives of Tutorial 2

Outline

1. A brief summary of chapters 3&4
2. Four selected tutorial problems

Objectives

1. Intensifying the understanding of first law of thermodynamics---Energy balance principle
2. Applying energy and mass balance principles to solve practical problems

One useful link

http://serve.me.nus.edu.sg/arun/proj_undergrad.htm

You are strongly encouraged to obtain raw solution before attendance of each tutorial!

Summary of Chapter 3&4

* Moving Boundary Work $W_b = \int_1^2 P dV$
* Mass Balance Principle $m_{in} - m_{out} = \Delta m_{system}$
* Total energy of a non-flowing fluid (P147) $\theta = u + ke + pe = u + \frac{V^2}{2} + gz$
* Total energy of a flowing fluid (P147) $\theta = h + ke + pe = h + \frac{V^2}{2} + gz$
* The general form of conservation of energy principle (P167) $E_{in} - E_{out} = \Delta E_{system}$
* The conservation of energy principle during a process non-involving mass flow (P169)

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = \Delta E_{sys} = E_{final} - E_{initial}$$

* The conservation of energy principle during a process involving mass flow (P169)

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{sys} = E_{final} - E_{initial}$$

Summary of Chapter 3&4

* The conservation of energy principle for steady flow systems (P181-184)

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system} = 0 \qquad \text{(in rate form)}$$

* Applications of the conservation of energy principle (P184-197)

Nozzles and Diffusers, Compressor, Steam Turbine, Throttling Valves, Mixing Chambers, Heat exchangers (Please drop by the website of Prof Mujumdar or IVLE to download the file for further information)

* Concepts of steady(P14, P181) , unsteady (P197), uniform flow process(P198), quasi-equilibrium state (P13)

* Energy balance for uniform flow process (P198)

$$\left(Q_{in} + W_{in} + \sum m_i \theta_i\right) - \left(Q_{out} + W_{out} + \sum m_e \theta_e\right) = \Delta E_{system}$$

$$\Delta E_{system} = (E_{final} - E_{initial})_{system} = (m_2 u_2 - m_1 u_1)_{system}$$

Problem 1

Problem B1 (Problem 3-88)
A mass of 5 kg of saturated liquid-vapor mixture of water is contained in a piston-cylinder device at 100 kPa. Initially, 2 kg of the water is in the liquid phase and the rest is in the vapor phase. Heat is now transferred to the water, and the piston, which is resting on a set of stops, starts moving when the pressure inside reaches 200 kPa. Heat transfer continues until the total volume increases by 20 percent. Determine **(a) the initial and final temperatures,** (b) the mass of liquid water when the piston first starts moving, and (c) the work done during this process. Also, show the process on a P-v diagram.

Solution

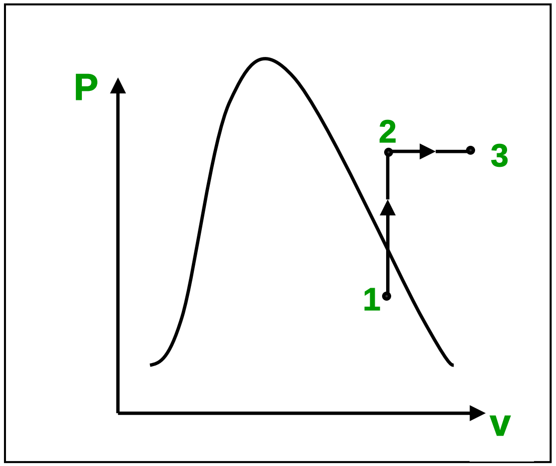
Assumption: The process is **quasi-equilibrium**.

(a) Initially the system is a saturated mixture at 100 kPa pressure, and thus the initial temperature is (Table A-5)

$$T_1 = T_{sat@100\ kPa} = \mathbf{99.63\ ^0C}$$

The total initial volume is (v_f and v_g from **Table A-5)**

$$V_1 = m_f v_f + m_g v_g = 2 \times 0.001043 + 3 \times 1.6940 = 5.084\ m^3$$



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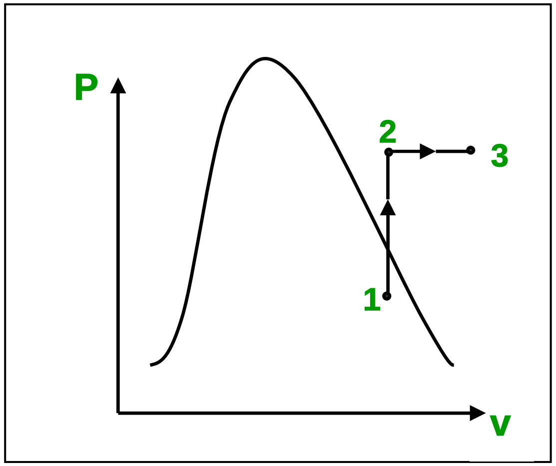
Solution



Then the total and specific volumes at the final state are
$V_3 = 1.2\ V_1 = 1.2 \times 5.084 = 6.101\ m^3$

$$v_3 = \frac{V_3}{m} = \frac{6.101\ m^3}{5\ kg} = 1.220\ m^3/kg$$

Thus, at state 3, $P_3 = 200$ kPa, $v_3 = 1.220\ m^3/kg$

Since, $v_3 > v_g$ at 200 kPa (v_g **=** 0.8857m3/kg from **Table A-5),** state 3 is in superheated region**.**

So, $T_3 = 259.0\ ^0C$ (from superheated **Table A-6,** by interpolation)

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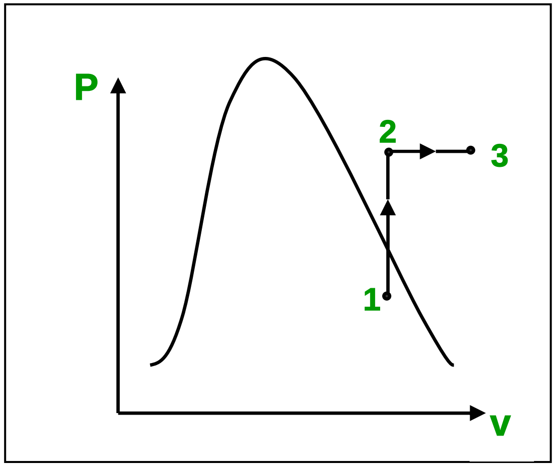
Solution

(b) When the piston first starts moving, P_2 = 200 kPa and V_2 = V_1 = 5.084 m^3, the specific volume at this state is

$$v_2 = \frac{V_2}{m} = \frac{5.084\ m^3}{5\ kg} = 1.017\ m^3/kg$$

which is greater than v_g = 0.8857 m3/kg at 200 kPa and state 2 is in superheated region.

Thus, no liquid is left in the cylinder when the piston starts moving.



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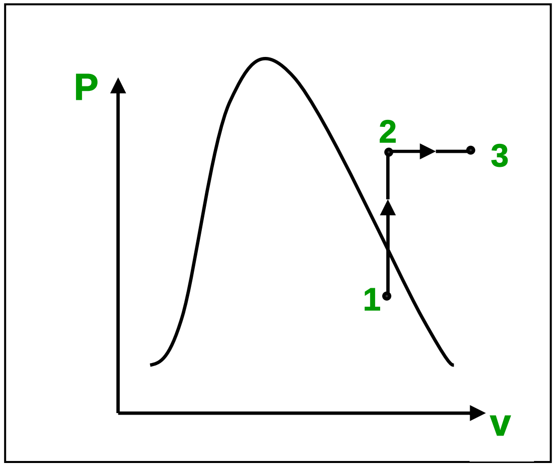
Solution

(c) No work is done during the process 1-2 since $V_1 = V_2$.

The pressure remains constant during process 2-3 and the work done during the process is

$$W_b = \int_2^3 P dV = P_2 (V_3 - V_2) = (200\ kPa)(6.101 - 5.084)m^3 \left(\frac{1\ kJ}{1\ kPa\ .m^3} \right)$$

$$= 203\ kJ$$

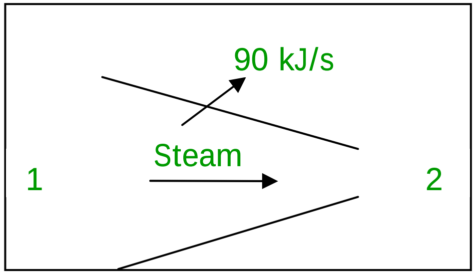


Problem 2

Problem B2 (Problem 4-63)

Steam at 5 MPa and 500^{o}C enters a nozzle steadily with a velocity of 80 m/s, and it leaves at 2 MPa and 400^{o}C. The inlet area of the nozzle is 50 cm^2, and heat is being lost at a rate of 90 kJ/s. Determine (a) the mass flow rate of the steam, (b) the exit velocity of the steam, and (c) the exit area of the nozzle.

<u>Solutions:</u>



<u>Assumptions</u>

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.

<u>Properties:</u> From steam Table A-6

$$\left.\begin{array}{l} P_1 = 5MPa \\ T_1 = 500^o C \end{array}\right\} \Rightarrow \left\{\begin{array}{l} v_1 = 0.06857 m^3/kg \\ h_1 = 3433.8 kJ/kg \end{array}\right.$$

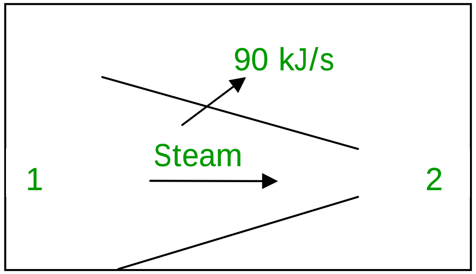
$$\left.\begin{array}{l} P_2 = 2MPa \\ T_2 = 400^o C \end{array}\right\} \Rightarrow \left\{\begin{array}{l} v_2 = 0.1512 m^3/kg \\ h_2 = 3247.6 kJ/kg \end{array}\right.$$

Problem 2

Problem B2(Problem 4-63)

Steam at 5 MPa and 500ºC enters a nozzle steadily with a velocity of 80 m/s, and it leaves at 2 MPa and 400?C. The inlet area of the nozzle is 50 cm^2, and heat is being lost at a rate of 90 kJ/s. Determine **(a) the mass flow rate of the steam, (b) the exit velocity of the steam,** and (c) the exit area of the nozzle.

Solutions:



(a) There is only one inlet and one exit, so, $\dot{m}_1 = \dot{m}_2 = \dot{m}$.

So, mass flow rate of the steam, $\dot{m} = \frac{1}{v_1} V_1 A_1 = 5.833 kg/s$

where, V_1 = inlet velocity

(b) Taking nozzle as the system, energy balance for this steady-flow system can be expressed in the rate form as,

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

Rate of net energy transfer by heat, work and mass   *Rate of change in internal, kinetic, potential, etc. energies*

Problem 2

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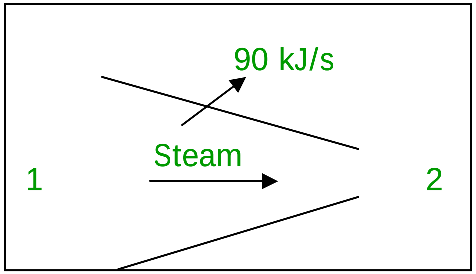
Steam at 5 MPa and 500°C enters a nozzle steadily with a velocity of 80 m/s, and it leaves at 2 MPa and 400°C. The inlet area of the nozzle is 50 cm^2, and heat is being lost at a rate of 90 kJ/s. Determine (a) the mass flow rate of the steam, **(b) the exit velocity of the steam**, and (c) the exit area of the nozzle.

Solutions:



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

Since $\dot{W} \cong \Delta pe = 0$

$$\dot{m}(h_1 + V_1^2/2) = \dot{Q}_{out} + \dot{m}(h_2 + V_2^2/2)$$

Substituting, the exit velocity of the steam is determined to be

$$-90kJ/s = (5.833kg/s)[3247.6kJ/kg - 3433.8kJ/kg + \frac{V_2^2 - (80m/s)^2}{2}(\frac{1kJ/kg}{1000m^2/s^2})]$$

It yields $V_2 = 589.9$m/s

Problem 2

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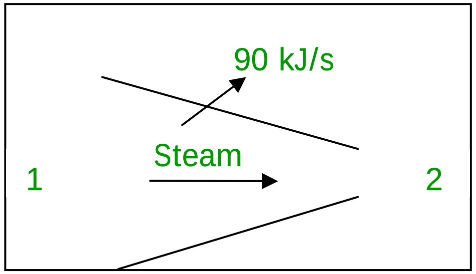
Solutions:



(c) The exit area of the nozzle can be found from,

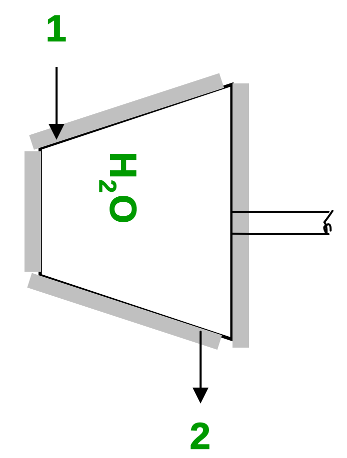
$$\dot{m} = \frac{1}{v_2} V_2 A_2$$

It gives

$$A_2 = \frac{\dot{m} v_2}{V_2} = \frac{(5.833 kg/s)(0.1512 m^3/kg)}{589.9 m/s} = 15.0 \times 10^{-4} m^2$$

Problem 3

Problem B3 (Problem 4-81)
Steam enters an adiabatic turbine at 10 MPa and 400°C and leaves at 20 kPa with a quality of 90 percent. Neglecting the changes in kinetic and potential energies, determine the mass flow rate required for a power output of 5 MW.



<u>Solutions</u>

<u>Assumptions</u>

1. This is a steady-flow process since there is no change with time.
2. Kinetic and potential energy changes are negligible.
3. The device is adiabatic and thus heat transfer is negligible.

<u>Properties</u>

From the steam tables (**Tables A-4 through 6)**

$$\left.\begin{aligned} P_1 &= 10MPa \\ T_1 &= 400^o C \end{aligned}\right\} \Rightarrow \left\{ h_1 = 3096.5kJ/kg \right.$$

$$\left.\begin{aligned} P_1 &= 20kPa \\ x_2 &= 0.9 \end{aligned}\right\} \Rightarrow \left\{ h_2 = h_f + x_2 h_{fg} = 251.4 + 0.9 \times 2358.3 = 2373.9kJ/kg \right.$$

Problem 3

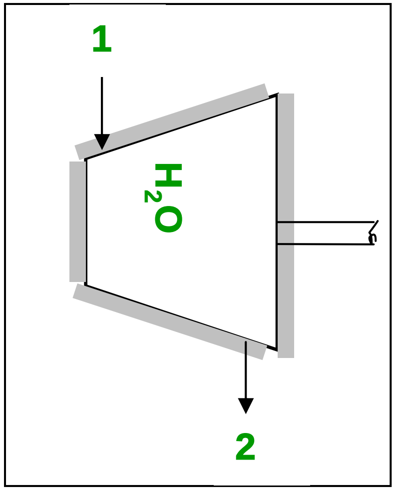
Problem B3 (Problem 4-81)
Steam enters an adiabatic turbine at 10 MPa and 400ºC and leaves at 20 kPa with a quality of 90 percent. Neglecting the changes in kinetic and potential energies, determine the mass flow rate required for a power output of 5 MW.

Solutions

There is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.

We take the turbine as the control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

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



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

Since $\Delta ke \cong \Delta pe = 0$

$$\dot{m} h_1 = \dot{W}_{out} + \dot{m} h_2$$

Problem 3

Problem B3 (Problem 4-81)

Steam enters an adiabatic turbine at 10 MPa and 400°C and leaves at 20 kPa with a quality of 90 percent. Neglecting the changes in kinetic and potential energies, determine the mass flow rate required for a power output of 5 MW.

Solutions

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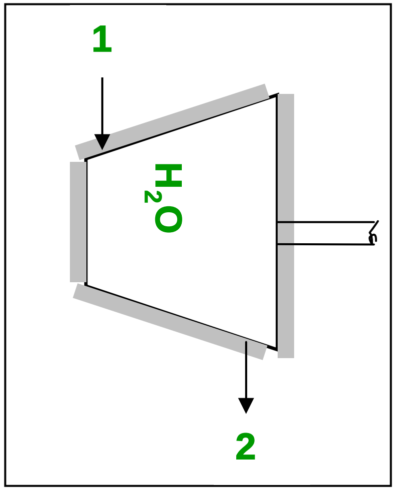
$$\dot{W}_{out} = -\dot{m}(h_2 - h_1)$$



Substituting the values, the required mass flow rate of the steam is determined to be

$$5000 kJ/s = -\dot{m}(2373.9 - 3096.5) kJ/kg$$

It yields

$$\dot{m} = 6.919 kg/s$$

Problem 4

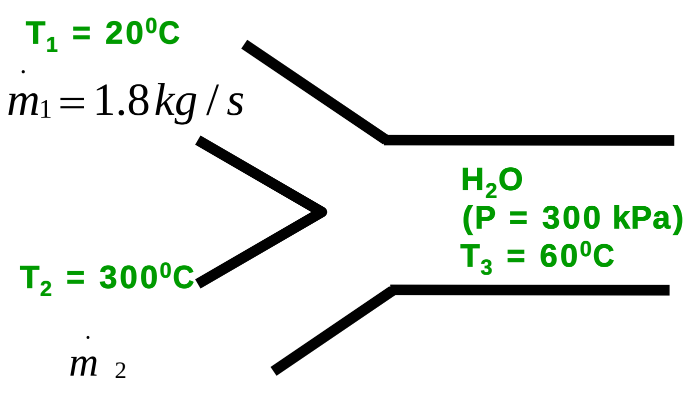
Problem B4(Problem 4-105)
Liquid water at 300 kPa and 20^{o}C is heated in chamber by mixing it with superheated steam at 300 kPa and 300^{o}C. Cold water enters the chamber at a rate of 1.8 kg/s. If the mixture leaves the mixing chamber at 60^{o}C, determine the mass flow rate of the superheated steam required.

Solution:

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.
4. The device is adiabatic and thus heat transfer is negligible.

Properties
Since $T<T_{sat@300\ kPa} = 133.55^0C$, the cold water stream and the mixture exist as a compressed liquid, which can be approximated as a saturated liquid at the given temperature. (**Tables A-4 through 6)** Thus



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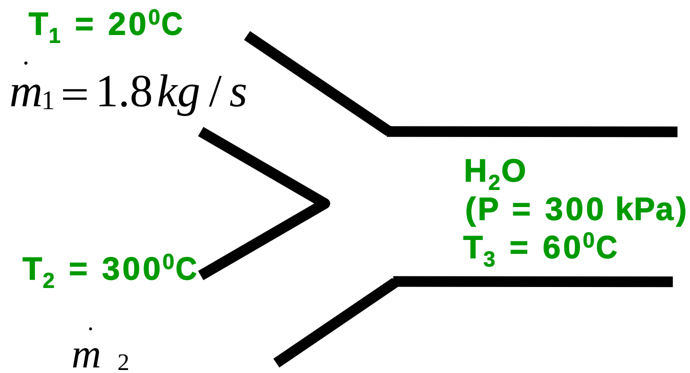

Solution:

$$h_1 \cong h_{f\,@\,20^0C} = 83.96\ kJ/kg$$

$$h_3 \cong h_{f\,@\,60^0C} = 251.13\ kJ/kg$$

$$\left.\begin{array}{l} P_2 = 300kPa \\ T_2 = 300^oC \end{array}\right\} \Rightarrow h_2 = 3069.3kJ/kg$$

Taking the mixing chamber as the system, which is a control volume since mass crosses the boundary. The mass and energy balances for this steady-flow system can be expressed in the rate form as,

Mass balance: $\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{system} = 0$ (0(steady))

$$\dot{m}_{in} = \dot{m}_{out} \quad \text{Or} \quad \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

Problem 4

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Solution:

Energy balance:

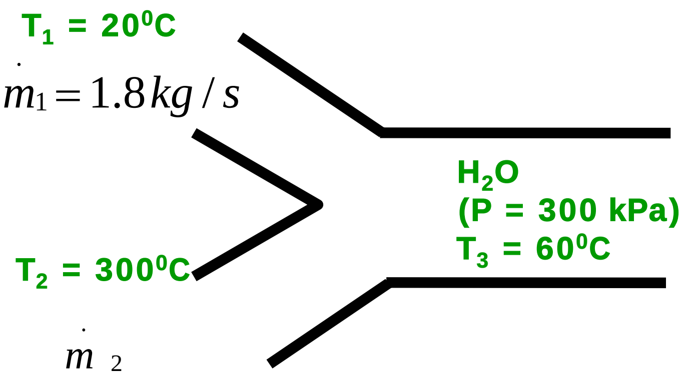
$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work and mass}} = \underbrace{\Delta \dot{E}_{system}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0$$

0(steady)

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

Since $\dot{W} \cong \Delta pe = \Delta ke = 0$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$



Problem 4

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Solution:

Combining the mass and energy balance equations,

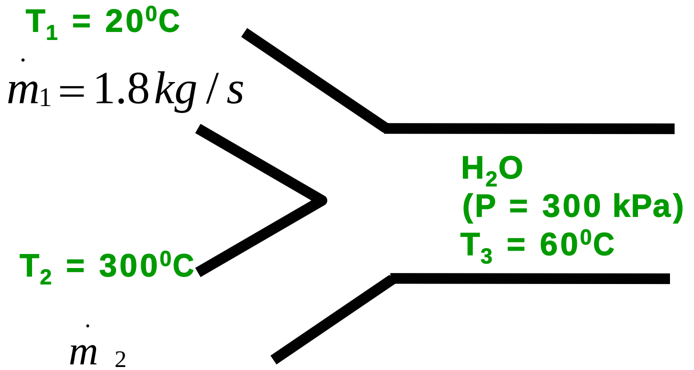
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2) h_3$$

Solving for $\dot{m}_2$

$$\dot{m}_2 = \frac{h_1 - h_3}{h_3 - h_2} \dot{m}_1$$

Substituting

$$\dot{m}_2 = \frac{83.96 - 251.13}{251.13 - 3069.3}(1.8 kg/s) = 0.107 kg/s$$



Problem 5

Problem B5 (Problem 4-156)

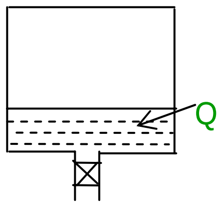
A 0.1m^3 rigid tank initially contains saturated liquid-vapor mixture of refrigerant-134a at 800kPa. Initially, 40 percent of the volume is occupied by liquid and the rest by vapor. A valve at the bottom of the tank is now opened, and the liquid is withdrawn from the tank. Heat is transferred to the refrigerant such that the pressure inside the tank remains constant. The valve is closed when no liquid remains inside. The amount of heat transfer is to be determined.

Solution:

Assumptions

1. It is an unsteady process since the conditions within the device are continuously changing during the process, but it can be analyzed as a uniform-flow process since the state of fluid leaving the device remains constant.
2. Kinetic and potential energies are negligible.
3. There are no work interactions involved.

Properties



The properties of R-134a are (**Tables A-11 through A-13**)

$$P_1 = 800kPa \rightarrow v_f = 0.0008454m^3/kg, v_g = 0.0255m^3/kg$$

$$u_f = 92.75kJ/kg, u_g = 243.78kJ/kg$$

Problem 5

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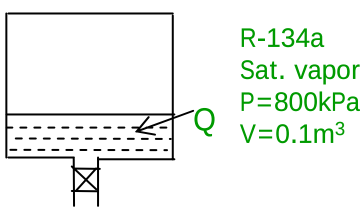
A $0.1m^3$ rigid tank initially contains saturated liquid-vapor mixture of refrigerant-134a at 800kPa. Initially, 40 percent of the volume is occupied by liquid and the rest by vapor. A valve at the bottom of the tank is now opened, and the liquid is withdrawn from the tank. Heat is transferred to the refrigerant such that the pressure inside the tank remains constant. The valve is closed when no liquid remains inside. The amount of heat transfer is to be determined.

Properties

The properties of R-134a are (**Tables A-11 through A-13**)

$$\left.\begin{array}{l} P_2 = 800kPa \\ sat.vapr \end{array}\right\} \Rightarrow \left\{\begin{array}{l} v_2 = v_{g@800kPa} = 0.0255m^3/kg \\ u_2 = u_{g@800kPa} = 243.78kJ/kg \end{array}\right.$$

$$\left.\begin{array}{l} P_e = 800kPa \\ sat.liquid \end{array}\right\} \Rightarrow h_e = h_{f@800kPa} = 93.42kJ/kg$$



Analysis

We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the total 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

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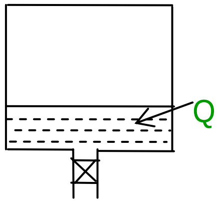
Solution:

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

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

Net energy transfer
By heat, work, and mass

Change in internal, kinetic,
Potential, etc. energies



$$Q_{in} - m_e h_e = m_2 u_2 - m_1 u_1 (Since W \cong ke \cong pe \cong 0)$$

The initial mass, internal energy, and final mass in the tank are

$$m_1 = m_f + m_g = \frac{V_f}{v_f} + \frac{V_g}{v_g} = \frac{0.1 \times 0.4 m^3}{0.000845 m^3/kg} + \frac{0.1 \times 0.6 m^3}{0.0255 m^3/kg} = 47.32 + 2.35 = 49.67 kg$$

$$U_1 = m_1 u_1 = m_f u_f + m_g u_g = (47.32)(92.75) + (2.35)(243.78) = 4962 kJ$$

Problem 5

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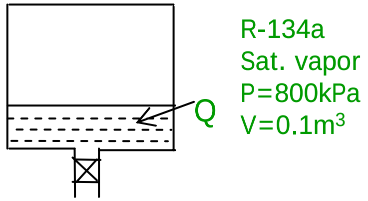
Solution:

$$m_2 = \frac{V}{v_2} = \frac{0.1m^3}{0.0255m^3/kg} = 3.92kg$$



Then from the mass and energy balances,

$$m_e = m_1 - m_2 = 49.67 - 3.92 = 45.75kg$$

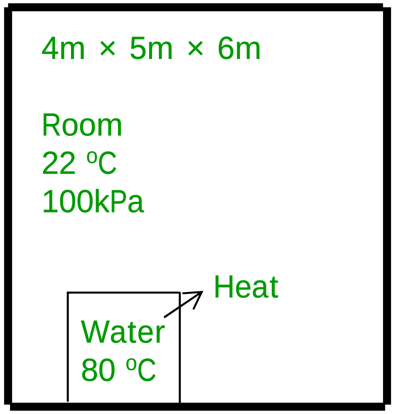
$$Q_{in} = (45.75kg)(93.42kJ/kg) + (3.92kg)(243.78kJ/kg) - 4962kJ = 267.6kJ$$

Problem 6

Problem B6 (Problem 4-194)

One ton (1000 kg) of liquid water at 80°C is brought into a well-insulated and well-sealed 4m*5m*6m room initially at 22°C. Assuming constant specific heats for both air and water at room temperature, determine the final equilibrium temperature in the room is to be determined.

Solution:



Assumptions

1. The room is well insulated and well sealed.
2. The thermal properties of water and air are constant.
3. Air is well-mixed.

Properties

The gas constant of air is R = 0.287kPa.m^3/kg.K (**Table A-1**). The specific heat of water at room temperature is C = 4.18kJ/kg. °C (**Table A-3**).

Analysis

The volume and the mass of the air in the room are

$V = 4×5×6 = 120\ m^3$

Problem 6

Problem B6 (Problem 4-194)

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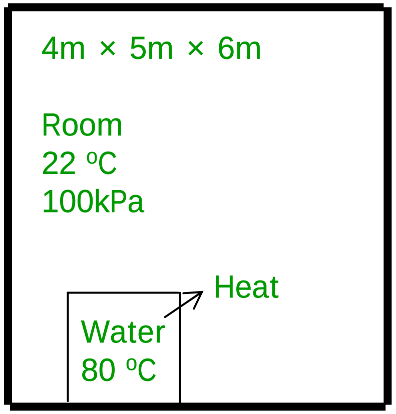
Solution:



$$m_{air} = \frac{P_1 V_1}{RT_1} = \frac{(100kPa)(120m^3)}{(0.287kPa \cdot m^3/kg \cdot K)(295K)} = 141.7kg$$

Taking the contents of the room, including the water, as our system,

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

Net energy transfer
By heat, work, and mass

Change in internal, kinetic,
Potential, etc. energies

So

$$0 = \Delta U = (\Delta U)_{water} + (\Delta U)_{air} \quad \text{Or} \quad [mC(T_2 - T_1)]_{water} + [mC_v(T_2 - T_1)]_{air} = 0$$

Substituting,

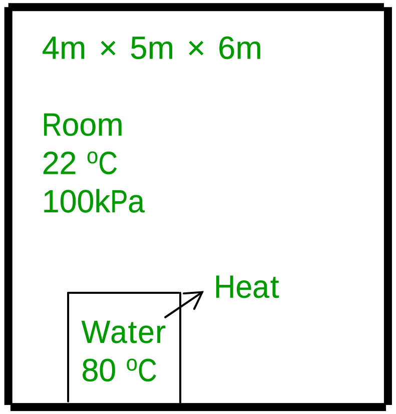
$$(1000kg)(4.181kJ/kg \cdot {}^\circ C)(T_f - 80)^\circ C + (141.7kg)(0.718kJ/kg \cdot {}^\circ C)(T_f - 22)^\circ C = 0$$

It gives $T_f = 78.6^\circ C$

where T_f is the final equilibrium temperature in the room.

Problem 6

Problem B6 (Problem 4-194)
One ton (1000 kg) of liquid water at 80^{o}C is brought into a well-insulated and well-sealed 4m*5m*6m room initially at 22^{o}C. Assuming constant specific heats for both air and water at room temperature, determine the final equilibrium temperature in the room is to be determined.



<u>Further discussions</u>

1. What if there are heat losses from the room?
2. Initially dry air. What if air humidity effect is included? is then a function of humidity.
3. Is room pressure affected by vaporization?
4. What if we have 10 tons of water? Will it all vaporize? What is the humidity condition?

Thank you for your attendance!