ESO201A

Lecture#24

(Class Lecture)

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By

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Example Problem #1

Refrigerant R-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. See Fig. 1. Neglecting pressure drops, determine (a) the mass flow rate of the cooling water required and (b) the heat transfer rate from the refrigerant to water.

Solution

Assumptions:

1. Steady flow
2. $\Delta ke = 0$, $\Delta pe = 0$
3. $\dot{Q} = 0$ (considering the entire system as the control volume)
4. $\dot{W} = 0$

Assumption # 3 is used to solve part (a).

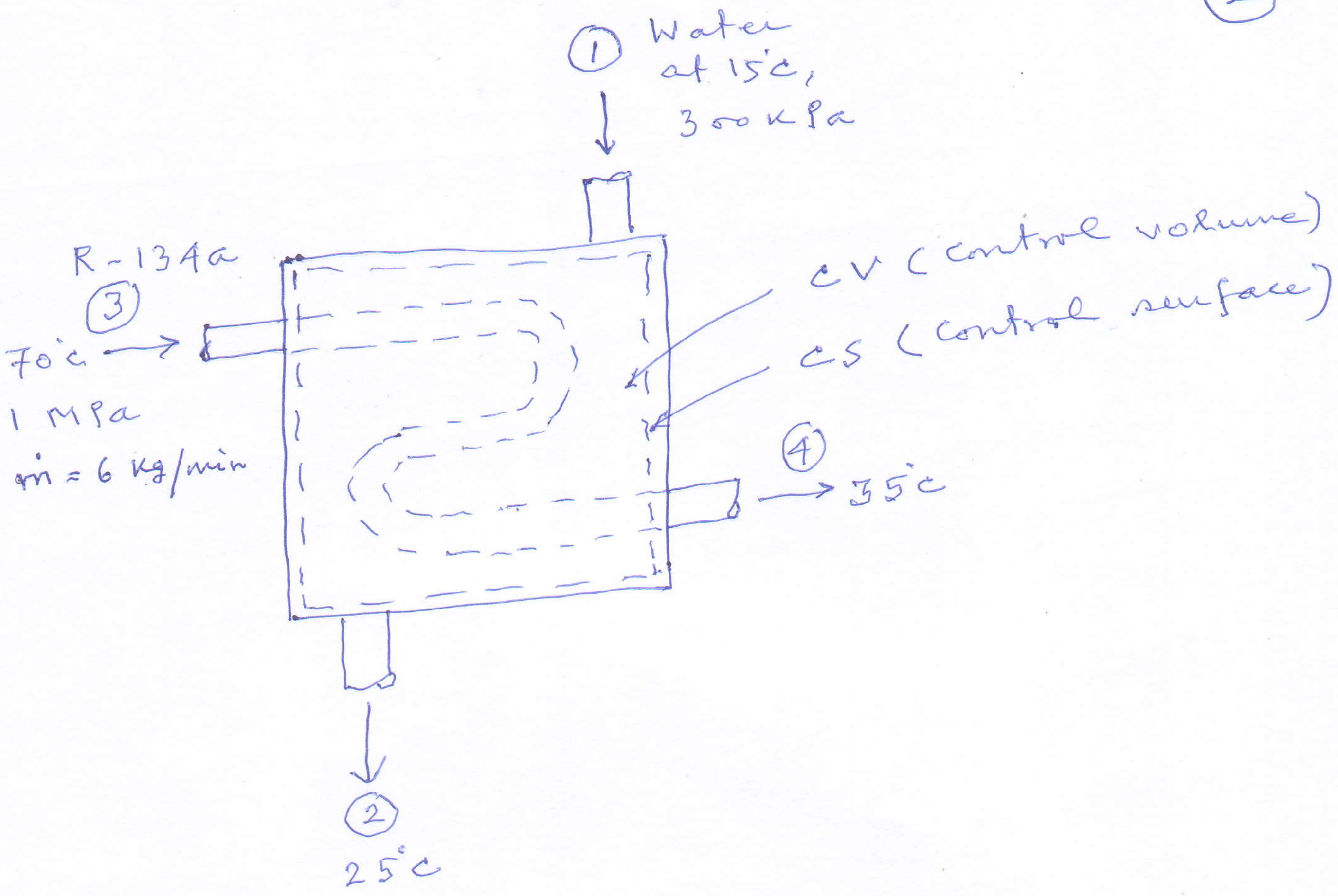


Fig. 1

(a) Mass balance

$\dot{m}_{in} = \dot{m}_{out}$ for each fluid stream

Thus,

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$$
$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

w ← Water

R ← Refrigerant

Energy balance

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

$$\Rightarrow \dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

$$\Rightarrow \dot{m}_w h_1 + \dot{m}_R h_3 = \dot{m}_w h_2 + \dot{m}_R h_4$$

$$\Rightarrow \dot{m}_w (h_1 - h_2) = \dot{m}_R (h_4 - h_3)$$

Water

At $P = 300$ kPa, $T_{sat} = 133.52°C$ (Table A-5)

$T_{w_1} = 15°C$, and $T_{w_2} = 25°C$,

$T_{w_1} < T_{sat}$, $T_{w_2} < T_{sat}$

Hence, both inlet and exit water streams are compressed liquid.

Since compressed liquid property data at 300 kPa (0.3 MPa) are not available in Table A-7, we calculate h_1 and h_2 as follows.

$$h_1 = h_{f@15^\circ C} + v_{f@15^\circ C}(P - P_{sat@15^\circ C})$$

$$= 62.982 + 0.001001(300 - 1.7057)$$

$$= 62.982 + 0.001001(298.2943)$$

$$= 62.982 + 0.2985925943$$

$$= 63.2805925943$$

$$\simeq \boxed{63.28 \text{ kJ/kg}}$$

(see Table A-4)

$$h_2 = h_{f@25^\circ C} + v_{f@25^\circ C}(P - P_{sat@25^\circ C})$$

$$= 104.83 + 0.001003(300 - 3.1698)$$

$$= 104.83 + 0.001003(296.8302)$$

$$= 104.83 + 0.2977206906$$

$$= 105.1277206906$$

$$\simeq \boxed{105.13 \text{ kJ/kg}}$$

(see Table A-4)

R-134a

$$\left.\begin{array}{l} P_3 = 1\ MPa \\ T_{sat@P_3} = 39.37^\circ C \end{array}\right\} \text{Table A-12}$$

$T_3 = 70^\circ C$

Since $T_{sat@P_3} < T_3$, the refrigerant is superheated at the inlet.

$$\left.\begin{array}{l} P_3 = 1\ MPa \\ T_3 = 70^\circ C \end{array}\right\} h_3 = 303.85\ kJ/kg$$

(Table A-13)

$P_4 = 1\ MPa$

$T_{sat@P_4} = 39.37^\circ C$

$T_4 = 35^\circ C$

Since $T_{sat@P_4} > T_4$, the refrigerant is subcooled at the outlet.

Hence,

$$h_4 = h_{f@35^\circ C} + v_{f@35^\circ C}(P - P_{sat@35^\circ C})$$

Table A-11 by interpolation

$$= 100.8 + 0.00085965(1000 - 887.73)$$

$$= 100.865 + 0.00085965(112.27)$$

$$= 100.865 + 0.0965129055$$

$$= 100.9615129055 \approx \boxed{100.96\ kJ/kg}$$

R-134a

	P_{sat} (kPa)	v_f (m^3/kg)	h_f (kJ/kg)
34°C	863.11	0.0008536	99.40
36°C	912.35	0.0008657	102.33

Substituting,

$$\dot{m}_w (63.28 - 105.13) = (6)(100.96 - 303.85)$$

$$= (6)(-202.89)$$

$$\Rightarrow \dot{m}_w (-41.85) = (6)(-202.89)$$

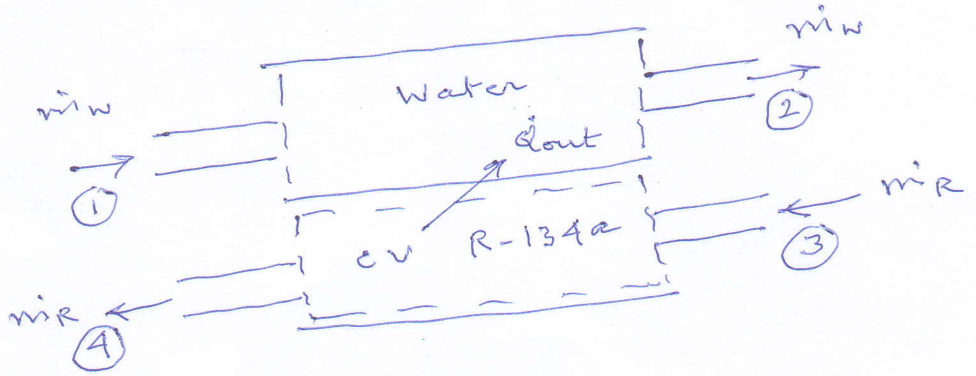
$$\Rightarrow \dot{m}_w = \frac{(6)(202.89)}{41.85}$$

$$= 29.0881720\,43$$

$$\simeq \boxed{29.088 \text{ kg/min}}$$

(b) To determine the heat transfer from the refrigerant to the water, we have to select a control volume whose boundary lies across the path of heat transfer. We can choose the volume occupied by either fluid as our control volume.

R-134a as CV



Energy balance

$$\dot{m}_R h_3 = \dot{m}_R h_4 + \dot{Q}_{out}$$

$$\Rightarrow \dot{Q}_{out} = \dot{m}_R (h_3 - h_4)$$
$$= (6)(303.85 - 100.96)$$
$$= (6)(202.89)$$
$$= 1217.34$$
$$= \boxed{1217.3 \text{ kJ/min}}$$

Water as CV

$$\dot{Q}_{in} + \dot{m}_w h_1 = \dot{m}_w h_2 .$$

$$\Rightarrow \dot{Q}_{in} = \dot{m}_w (h_2 - h_1)$$

$$= (29.088)(105.13 - 63.28)$$

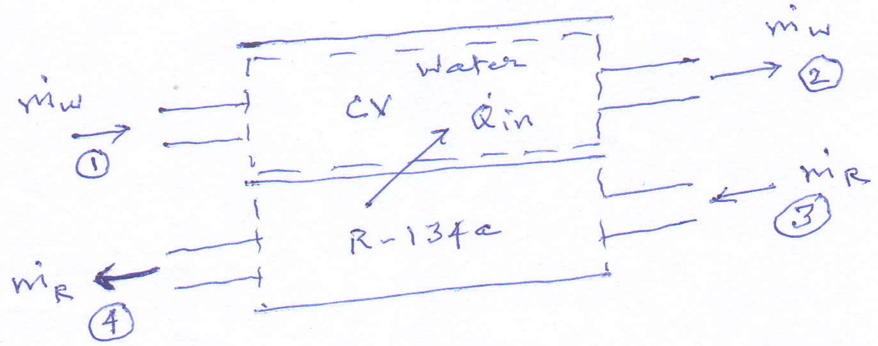
$$= (29.088)(41.85)$$

$$= 1217.3328$$

$$\approx \boxed{1217.3 \text{ kJ/min}}$$

Thus, $\dot{Q}_{in} = \dot{Q}_{out}$.

That is, heat gained by the water is equal to the heat lost by the refrigerant.



Example Problem #2

Consider a duct in which air is heated electrically by a 15 kW heater. Air enters the duct at 100 kPa and 17°C with a volume flow rate of 150 m³/min. If heat is lost from the air in the duct to the surroundings at a rate of 200 W, determine the exit temperature of air. See Fig. 1. Compare the result obtained using constant cp for air = 1.005 kJ/kg°C and that obtained by taking data from the table.

Solution

Assumptions

1. Steady flow.
2. Air is an ideal gas.
3. $\Delta ke = 0$, $\Delta pe = 0$

Justifications for Assumption #2

$P_{cr\,Air} = 3.77$ MPa

$T_{cr\,Air} = 132.5$ K

$P = 100$ kPa $= 0.1$ MPa

$T = 17°C = 290$ K

Since $P << P_{cr}$ and $T >> T_{cr}$ the ideal gas assumption for the air is valid.

Energy balance

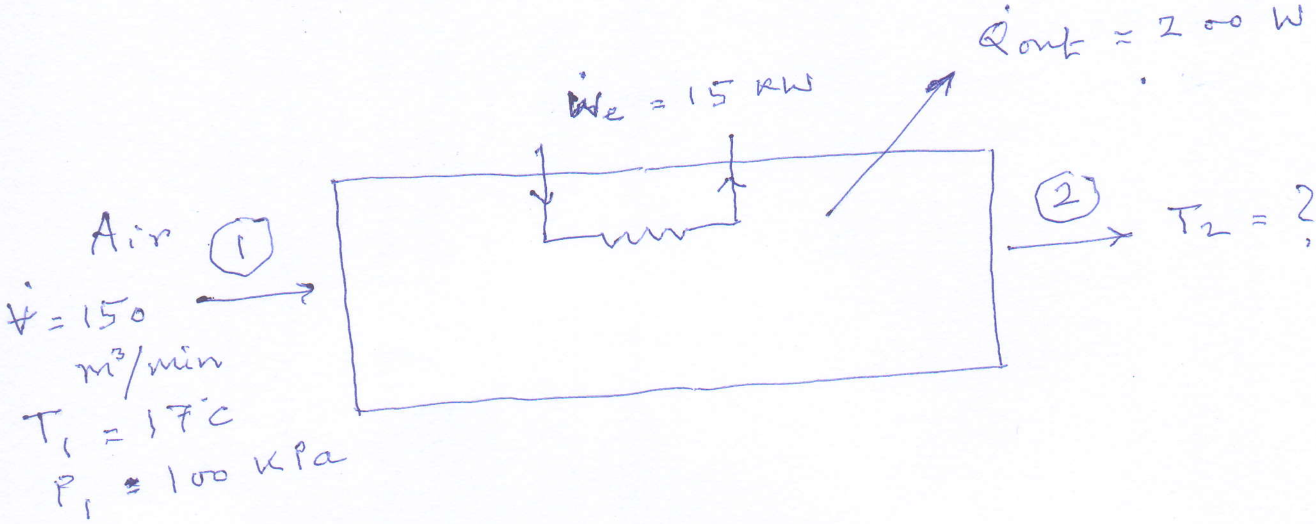


Fig. 1

Using c_p

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

$$\Rightarrow \dot{W}_{e,in} + \dot{m} h_1 = \dot{Q}_{out} + \dot{m} h_2$$

$$\Rightarrow \dot{W}_{e,in} - \dot{Q}_{out} = \dot{m}(h_2 - h_1)$$

$$\Rightarrow \dot{W}_{e,in} - \dot{Q}_{out} = \dot{m} c_p (T_2 - T_1)$$

$$\Rightarrow \dot{W}_{e,in} - \dot{Q}_{out} \qquad (\because \Delta h = c_p \Delta T)$$

From the ideal gas equation,

$$P_1 v_1 = R T_1$$

$$\Rightarrow v_1 = \frac{R T_1}{P_1}$$

$$= \frac{(0.287)(290)}{100}$$

$$= 0.832 \text{ m}^3/\text{kg}$$

For air,
$R = 0.287 \frac{\text{kPa} \cdot \text{m}^3}{\text{kg K}}$
(from Table A-1)

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{150 \text{ m}^3/\text{min}}{0.832 \text{ m}^3/\text{kg}} \cdot \frac{1 \text{ min}}{60 \text{ s}}$$

$$= 3.004807692 3$$

$$= 3.0 \text{ kg/s}$$

We know, from the energy balance,

$$\dot{W}_{e\,in} - \dot{Q}_{out} = \dot{m}\, c_p\, (T_2 - T_1)$$

$$\Rightarrow 15 - 0.2 = (3)(1.005)(T_2 - 17)$$

$$\Rightarrow T_2 - 17 = \frac{14.8}{3.015}$$

$$= 4.908789386 4$$

$$\Rightarrow T_2 = 21.908789386 4$$

$$= \boxed{21.91^\circ C}$$

Using Ideal-Gas Air Property Table (Table A-17)

$$\dot{W}_{e,in} - \dot{Q}_{out} = \dot{m}(h_2 - h_1)$$

$$\Rightarrow h_2 - h_1 = \frac{\dot{W}_{e,in} - \dot{Q}_{out}}{\dot{m}}$$

$$\Rightarrow h_2 = h_1 + \frac{\dot{W}_{e,in} - \dot{Q}_{out}}{\dot{m}}$$

$$= 290.16 + \frac{15 - 0.2}{3}$$

$$= 290.16 + \frac{14.8}{3}$$

$$= 290.16 + 4.93$$

$$= 295.09 \text{ kJ/kg}$$

Since $h = f(T)$ for ideal gases

$$h_2 = f(T_2)$$

h (kJ/kg)	T (K)
290.16	290
295.17	295

By interpolation

$$T_{@h=295.09\ \text{kJ/kg}} = 294.92\ \text{K}$$

$$= \boxed{21.92\,^\circ\text{C}}$$

$$\% \text{ error} = \left| \frac{21.91 - 21.92}{21.92} \right| \times 100$$

$$= 0.0456\%$$

Thus, the error is negligibly small.

It may be noted that $c_p = 1.005$ kJ/kg°C for air can be used in the range of -20°C to 70°C with negligible error in the calculation of Δh.

Energy Analysis of Unsteady-Flow Processes

- During a steady-flow process, no changes occur within the control volume.
- Many processes of interest, however, involve changes within the control volume with time.
- Such processes are called unsteady-flow, or transient-flow processes. In this case, it is important to keep track of the mass and energy contents of the control volume as well as the energy interactions across the boundary.

Some Examples of Unsteady-flow processes

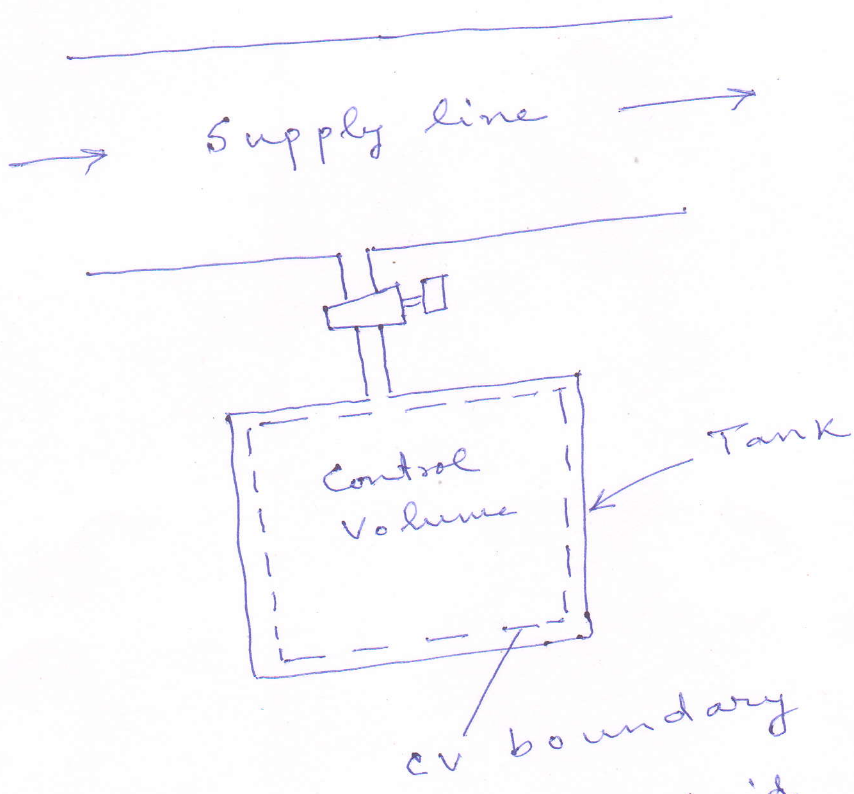


Fig. 1 charging of a rigid tank from a supply line

Some Examples of Unsteady-flow Processes (Contd.)

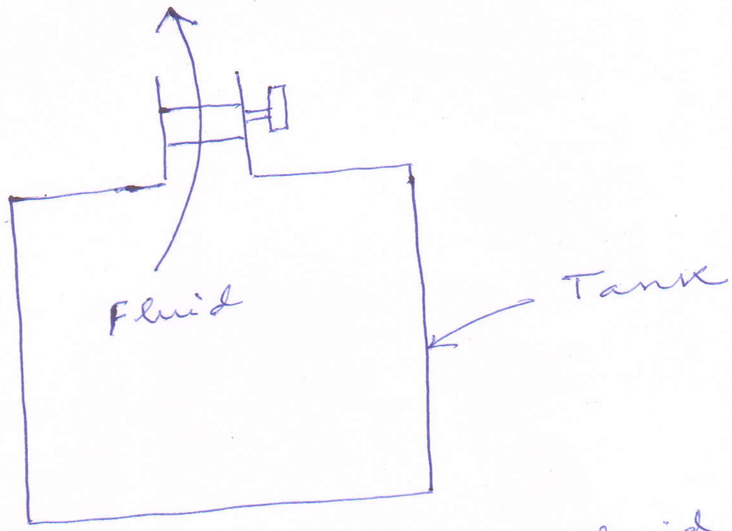


Fig. 2 Discharging of a fluid from a tank

Differences between Steady and Unsteady-flow Processes

- Unlike steady-flow processes, unsteady-flow processes start and end over some finite time period instead of continuing indefinitely.

- Another difference between steady and unsteady-flow systems is that steady-flow systems are fixed in space, size and shape. Unsteady-flow systems may not be so (Fig. 3). They are usually stationary; that is, they are fixed in space, but may involve moving boundaries and thus boundary work.

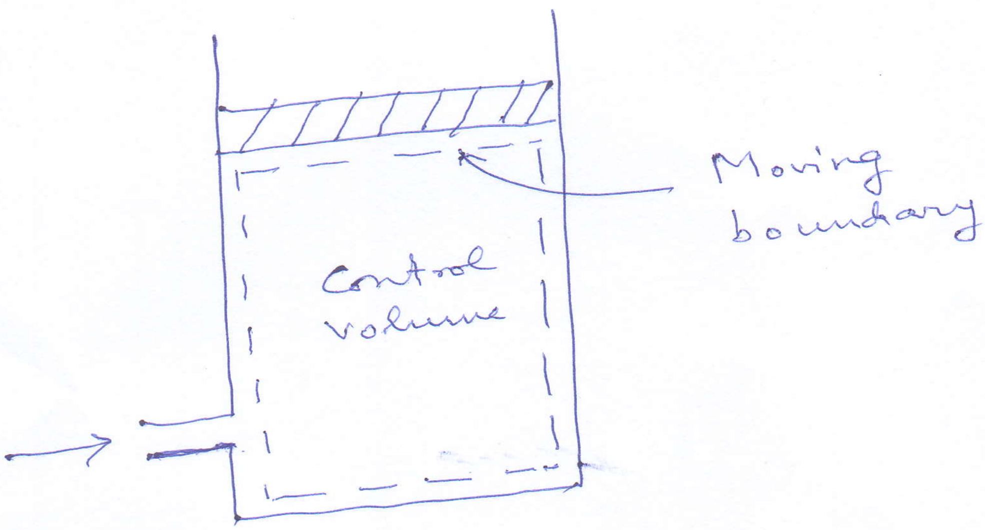


Fig. 3 The shape and size of a control volume may change during an unsteady-flow process.

Assumptions in modelling unsteady-flow processes

1. The control volume is stationary.

2. The state of mass within the control volume may change with time, but at any instant of time the state is uniform throughout the entire volume.

3. At any instant of time the flow is uniform at the inlet(s) and exit(s) although the mass flow rates may vary with time.