Problem 4.10

**KNOWN:** Data are provided for a crude oil storage tank.

**FIND:** After 24 h, determine the mass and volume of oil in the tank.

**SCHEMATIC & GIVEN DATA:**

![Diagram showing a storage tank with dimensions and flow rates.]

**ENERGY MODEL**

1. As shown by the sketch, a control volume encloses the storage tank.
2. The specific volume of the oil is constant: \( V = 0.0015 \text{ m}^3/\text{kg} \)

---

(a) **Mass rate balance:**

\[
\frac{dm_v}{dt} = m_{\text{in}} - m_{\text{out}}, \quad \text{where}
\]

\[
m_{\text{in}} = \frac{(AV)}{\nu} = \frac{(2 \text{ m}^3/\text{min})}{(0.0015 \text{ m}^3/\text{kg})} \cdot \frac{60 \text{ min}}{1 \text{ h}} = 8 \times 10^4 \text{ kg/h}
\]

\[
m_{\text{out}} = \frac{A_2 V}{\nu} = \frac{\pi D_2^2 / 4 \cdot (1.15 \text{ m/h})}{\nu} = \frac{\pi (0.15 \text{ m})^2 (1.15 \text{ m/h})}{4 (0.0015 \text{ m}^3/\text{kg})} \cdot \frac{3600 \text{ s}}{1 \text{ h}} = 6.36 \times 10^4 \text{ kg/h}
\]

\[
\Rightarrow \quad \frac{dm_v}{dt} = 1.64 \times 10^4 \text{ kg/h}
\]

Integrating

\[
m_v = m_{\text{in}}(0) = (1.64 \times 10^4 \text{ kg/h}) (24 \text{ h}) = 39.36 \times 10^4 \text{ kg}
\]

\[
\Rightarrow \quad \frac{m_v}{V} = \frac{1000 \text{ kg}}{(0.0015 \text{ m}^3/\text{kg})} = 66.67 \times 10^4 \text{ kg}
\]

So,

\[
m_v(24h) = (66.67 \times 3936) \times 10^4 \text{ kg} = 1.06 \times 10^6 \text{ kg}
\]

(b) \[
V(24h) = \frac{m_v(24h)}{V_m} = \frac{(0.0015 \text{ m}^3/\text{kg})}{(1.06 \times 10^6 \text{ kg})}
\]

\[
= 1590 \text{ m}^3
\]

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As shown in Fig. P4.25, air enters a pipe at 25°C, 100 kPa with a volumetric flow rate of 23 m³/h. On the outer pipe surface is an electrical resistor covered with insulation. With a voltage of 120 V, the resistor draws a current of 4 amps. Assuming the ideal gas model with \(c_p = 1.005 \text{ kJ/kg} \cdot \text{K}\) for air and ignoring kinetic and potential energy effects, determine (a) the mass flow rate of the air, in kg/h, and (b) the temperature of the air at exit, in °C.

**Schematic & Given Data:**

- Air
  - \(T_1 = 25°C\),
  - \(p_1 = 100 \text{ kPa}\)
  - \(\text{AV} = 23 \text{ m}^3/\text{h}\)

**Problem 4.25**

**Analysis:**

(a) \[m = \frac{\text{AV}}{R_1} = \frac{p_1 \cdot \text{AV}}{R_1} = \frac{(10^5 \text{ kPa})(23 \text{ m}^3/\text{h})}{(821 \text{ Nm}^2/\text{kg} \cdot \text{K})(298 \text{ K})} = 26.89 \text{ kg/h} \]

(b) Reducing Eq. 4.2a using listed assumptions,

\[\dot{Q}_{\text{ev}} = \dot{W}_{\text{ev}} + m\left[h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + g (Z_1 - Z_2)\right]\]

where \((h_1 - h_2) = \text{cp} (T_1 - T_2)\)

\[\dot{W}_{\text{ev}} = -(\text{voltage})(\text{Current})\]

\[= -(120 \text{ V})(4 \text{amps}) = -480 \text{ W} = -0.48 \text{ kW}\]

Collecting results, and solving for \(T_2\),

\[T_2 = T_1 - \frac{\dot{W}_{\text{ev}}}{m \cdot \text{cp}}\]

\[= 298 - \frac{-0.48 \text{ kW}}{(24.8 \text{ kJ/kg} \cdot \text{K})(1005 \text{ kJ/kg} \cdot \text{K})} = 362 \text{ K} (89°C)\]

**Energy Model:**

1. The control volume shown in the sketch is at steady state.
2. For the control volume, strong heat transfer and kinetic and potential energy effects can be ignored.
3. The air can be modeled as an ideal gas with constant specific heat \(c_p\).
Problem 4.30

**KNOWN:**
Data are provided for electronic components mounted on a plate that are cooled by convection to the surroundings and water circulating through a tube bonded to the plate. Operation is at steady state.

**EQUIPMENT:**
Determine the tube diameter.

**SCHEMATIC & GIVEN DATA:**

**ENGR. MODEL:**
1. A control volume encloses the plate-mounted electronic components with an inlet at 1 and an exit at 2. The control volume is at steady state.
2. For the water entering and exiting, $h_m = h_f(T_1), v_m = v_f(T_1)$.
3. Kinetic and potential energy effects can be ignored.

**ANALYSIS:**
At steady state, $\dot{m}_1 = \dot{m}_2 \equiv \dot{m}$. Also,

$$\dot{m} = \frac{A_1 V_1}{V_1} = \frac{(\pi D^2/4) V_1}{V_f(T_1)}$$

An energy balance yields

$$0 = \dot{Q}_c - \dot{W}_{cv} + \dot{m} \left[ (h_1 - h_2) + \left( \frac{v_1^2 - v_2^2}{2} \right) + g(z_1 - z_2) \right]$$

Or

$$\dot{m} = \frac{\dot{Q}_c - \dot{W}_{cv}}{h_2 - h_1} = \frac{\dot{Q}_c - \dot{W}_{cv}}{h_f(T_1) - h_f(T_i)}$$

**Collecting results**

$$D = \sqrt{\frac{4V_f(T_i)}{\pi \sqrt{\dot{m}}}} \left[ \frac{\left( \dot{Q}_c - \dot{W}_{cv} \right)}{h_f(T_1) - h_f(T_i)} \right]$$

With data from Table A-2:
- $\dot{V}_f(20^\circ C) = (1.0018/18^3) m^3/kg$
- $h_f(T_i) = 83.96 \times 10^3 kJ/kg$
- $h_f(T_1) = 100.7 \times 10^3 kJ/kg$

$$D = \sqrt{\frac{4 \times (1.0018/18^3) m^3/15}{\pi (0.4 m/s)}} \left[ \frac{(-0.08 - (-0.5))kJ/s}{(100.7 - 83.96) \times 10^3 kJ/kg} \right]$$

$$= 0.0089 \text{ m} \left| \frac{10^3 \text{ cm}}{\text{m}} \right|$$

$$= 0.89 \text{ cm}$$

1. Alternatively, the incompressible model can be used with Eq 3.20b and c from Table A-19.
4.33 Air enters a nozzle operating at steady state at 720°F with negligible velocity and exits the nozzle at 500°F with a velocity of 1450 ft/s. Assuming ideal gas behavior and neglecting potential energy effects, determine the heat transfer, in Btu per lb of air flowing.

**KNOWN:** Air flows through a nozzle with known temperature and velocity at the inlet and exit.

**FIND:** Determine the heat transfer per unit mass of air flowing.

**SCHEMATIC AND GIVEN DATA:**

![Schematic Diagram](image)

1. \( T_1 = 720°F \)
2. \( V_1 = 0 \) ft/s
3. \( T_2 = 500°F \)
4. \( V_2 = 1450 \) ft/s

**ENGINEERING MODEL:**
1. The control volume shown on the accompanying figure is at steady state.
2. Change in potential energy from inlet to exit can be neglected.
3. \( W_{ce} = 0 \).
4. Air can be modeled as an ideal gas.
5. The inlet velocity is negligible.

**ANALYSIS:**
Since enthalpy of an ideal gas is a function of only temperature, the enthalpy values at State 1 and State 2 are determined from Table A-22E: \( h_1 = 172.39 \) Btu/lb and \( h_2 = 119.48 \) Btu/lb.

The steady-state, one-inlet, one-exit energy balance gives

\[
0 = \dot{Q}_{cv} - \dot{W}_{ce} + \dot{m} \left[ (h_1 - h_2) + \frac{1}{2} (V_1^2 - V_2^2) + g(z_1 - z_2) \right]
\]

Neglecting potential energy change, setting \( V_1 = 0 \), recognizing no work is associated with a nozzle, solving for rate of heat transfer, and dividing by the mass flow rate, the energy balance simplifies to

\[
\frac{\dot{Q}_{cv}}{m} = (h_2 - h_1) + \frac{1}{2} V_2^2
\]

Substituting values and applying the appropriate conversion factors give

\[
\frac{\dot{Q}_{cv}}{m} = \left( \frac{119.48 \text{ Btu}}{\text{lb}} - 172.39 \frac{\text{Btu}}{\text{lb}} \right) + \left( \frac{1450}{s} \right)^2 \left( \frac{\text{ft}}{2} \right) \left( \frac{778 \text{ lb} \cdot \text{ft}}{\text{Btu}} \right) \left( \frac{32.2 \text{ ft} \cdot \text{lb}}{s^2} \right) = -10.9 \text{ Btu/lb}
\]

The negative sign indicates energy transfer by heat from the nozzle.
PROBLEM 4.50

KNOWN: Steady-state operating data are provided for a two-stage turbine with a reheater.

FIND: Determine the steam mass flow rate, the total power developed, and the rate of heat transfer for the steam flowing through the reheater.

SCHEMATIC & GIVEN DATA:

![Diagram of a two-stage turbine with a reheater]

- Steam: \( p_1 = 40 \text{ bar}, T_1 = 500^\circ \text{C} \)
- (AV)_1 = 90 \text{ m}^3/\text{min}
- Sat. vapor, \( p_a = 0.6 \text{ bar} \)
- \( p_2 = 20 \text{ bar} \)
- \( T_2 = 400^\circ \text{C} \)
- Reheated: \( p_3 = 20 \text{ bar} \)
- \( T_3 = 500^\circ \text{C} \)

Fig. P4.50

ENERG. MODEL:
1. As shown in the sketch, two control volumes are under consideration.
2. Each control volume is at steady state.
3. Kinetic and potential energy effects can be ignored.
4. For control volume #1, Stany heat transfer can be ignored.

ANALYSIS: (a) The mass flow rate at inlet 1 is found from \( \dot{m}_1 = \frac{(AV)_1}{60} \).

From Table A-4, at 40 bar, 580°C, \( u_1 = 0.08643 \text{ m}^3/\text{kg} \). Then,

\[
\dot{m}_1 = \frac{90 \text{ m}^3/\text{min}}{0.08643 \text{ m}^3/\text{kg}} \times \frac{60 \text{ s}}{1 \text{ h}} = 2.48 \times 10^4 \text{ kg/h}
\]

(b) An energy rate balance for control volume #1 reads

\[
0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_1 [h_1 - h_2] + \dot{m}_1 [h_4 - h_5]
\]

\[
\dot{W}_{cv} = \dot{m}_1 [h_1 - h_2] + (h_3 - h_4)
\]

With data from Tables A-3 and A-4, \( h_1 = 3.445.3 \text{ kJ/kg}, h_2 = 3247.6 \text{ kJ/kg}, h_3 = 3467.6 \text{ kJ/kg}, h_4 = 2652.5 \text{ kJ/kg} \).

\[
\dot{W}_{cv} = \dot{m}_1 \left[ (3.445.3 - 3247.6) + (3467.6 - 2652.5) \right] \text{ kJ/kg}
\]

\[
= 6.298 \times 10^4 \text{ kg} \times \frac{1 \text{ kW}}{1 \text{ kJ/kg}} = 17,936.8 \text{ kW}
\]

(c) An energy rate balance for control volume #2 reads

\[
0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_1 [h_5 - h_4] \Rightarrow \dot{Q}_{cv} = \dot{m}_1 [h_5 - h_4]
\]

\[
\dot{Q}_{cv} = \dot{m}_1 \left[ (3467.6 - 3247.6) \right] \text{ kJ/kg}
\]

\[
= 3.819 \text{ kW}
\]
4.57 At steady state, a well-insulated compressor takes in nitrogen at 60°F, 14.2 lb/in.², with a volumetric flow rate of 1200 ft³/min. Compressed nitrogen exits at 500°F, 120 lb/in.². Kinetic and potential energy changes from inlet to exit can be neglected. Determine the compressor power, in hp, and the volumetric flow rate at the exit, in ft³/min.

**KNOWN:** Nitrogen with known inlet and exit conditions flows through a well-insulated compressor operating at steady state.

**FIND:** Determine the compressor power, in hp, and the volumetric flow rate at the exit, in ft³/min.

**SCHEMATIC AND GIVEN DATA:**

Nitrogen

1. $p_1 = 14.2$ lb/in.²
2. $T_1 = 60°F$
3. $A_1V_1 = 1200$ ft³/min
4. $T_2 = 500°F$
5. $p_2 = 120$ lb/in.²

**ENGINEERING MODEL:**
(1) The control volume shown in the accompanying schematic operates at steady state.
(2) Heat transfer can be neglected.
(3) Nitrogen behaves as an ideal gas.
(4) Potential and kinetic energy changes from inlet to exit can be neglected.

**ANALYSIS:**
To determine the power, begin with the steady state mass and energy balances.

$m_1 = m_2 = \dot{m}$

$0 = \dot{Q}_c - \dot{W}_c + \dot{m} \left[ (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right]$

With listed assumptions, we solve for $\dot{W}_c$. 
\[ \dot{W}_o = \dot{m}(h_1 - h_2) \]

Note that \( \bar{h} \) equals \((h/M)\), where \( M \) is the molecular weight for nitrogen and \( \bar{h} \) is from Table A-23E: \( \bar{h}_1 = 3611.3 \text{ Btu/lbmol} \) and \( \bar{h}_2 = 6693.1 \text{ Btu/lbmol} \).

\[ \dot{W}_o = \dot{m}(h_1 - h_2) \rightarrow \dot{W}_o = \frac{\dot{m}}{M} (\bar{h}_1 - \bar{h}_2) \tag{1} \]

Obtain \( \dot{m} \), in lb/h, using the ideal gas equation of state.

\[ \dot{m} = \frac{(AV)_h}{v_i} = \frac{(AV)_h P_i}{RT_1} = \frac{(1200 \, \text{ft}^3/\text{min})(14.2 \, \text{lb} \cdot \text{ft}^2/\text{in}^2)}{(1545 \, \text{ft} \cdot \text{lb} \cdot \text{R}) (520^\circ \text{R})} \times \frac{1 \text{ h}}{1 \text{ ft}^2} \times \frac{144 \text{ in}^2}{60 \text{ min}} = 5133 \, \text{lb} \cdot \text{h} \]

Using Eq. (1), solve for \( \dot{W}_o \), in hp.

\[ \dot{W}_o = \frac{5133 \, \text{lb} \cdot \text{h}}{28.01 \, \text{lbmol}} \left(3611.3 - 6693.1\right) \frac{\text{Btu}}{\text{lbmol}} \times \frac{1 \text{ hp}}{2545 \, \text{Btu}} = -221.9 \, \text{hp} \]

The exit volumetric flow rate, in ft³/min, is as follows:

\[ (AV)_o = \dot{m}v_o = \dot{m} \left( \frac{RT_1}{P_2} \right) = \frac{5133 \, \text{lb} \cdot \text{h}}{28.01 \, \text{lb} \cdot \text{ft}^2/\text{in}^2} \left( \frac{1545 \, \text{ft} \cdot \text{lb} \cdot \text{R}}{960^\circ \text{R}} \right) \times \frac{1 \text{ h}}{60 \text{ min}} \times \frac{1 \text{ ft}^3}{144 \text{ in}^2} = 262.2 \, \text{ft}^3/\text{min} \]

1. Table A-1E gives \( p_o = 33.5 \, \text{atm} = 492.32 \, \text{lbf/in}^2 \), \( T_o = 227^\circ \text{R} \) for nitrogen. Therefore, \( p_{R1} = 0.029 \), \( T_{R1} = 2.29 \). Referring to Fig. A-1, the value of the compressibility factor at this state is \( Z = 1 \). The same conclusion results when state 2 is checked. Accordingly, \( pv = RT \) adequately describes the \( p-v-T \) relation for the air at those states.

2. \( \dot{W}_o \) is negative, as expected for a compressor. Here, energy is added to the system through work.