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Chapter 11. Changes in Thermodynamic Properties

Practice Problems

1.

Which statement is FALSE?

(A)

The availability of a system depends on the location of the system.

(B)

A heat engine cycle can have a thermal efficiency of 100% given that the transfer of heat to the working fluid is at a constant temperature in a reversible process over a reasonably finite time.

(C)

The gas temperature always decreases when the gas expands isentropically.

(D)

Water in a liquid state cannot exist at any temperature if the pressure is less than the triple point pressure.

2.

Which statement is true?

(A)

Entropy does not change in an adiabatic process.

(B)

The entropy of a closed system cannot decrease.

(C)

Entropy increases when a refrigerant passes through a throttling valve.

(D)

The entropy of air inside a closed room with a running, electrically driven fan will always increase over time.

3.

Which process CANNOT be modeled as an isenthalpic process?

(A)

viscous drag on an object moving through air

(B)

an ideal gas accelerating to supersonic speed through a converging-diverging nozzle

(C)

refrigerant passing through a pressure-reducing throttling valve
(D)

high-pressure steam escaping through a spring-loaded pressure-relief (safety) valve
4.

Air expands isentropically in a steady-flow process from 700°F and 400 psia to 50 psia. Based on the specific heat capacity at room temperature, what is most nearly the change in enthalpy per lbm assuming air as an ideal gas and the ratio of heat capacities is 1.4.?

(A)

–680 Btu/lbm

(B)

–120 Btu/lbm

(C)

–90 Btu/lbm

(D)

–14 Btu/lbm

5.

A perfectly insulated, rigid enclosure contains 0.60 kg of air (c_p = 1.005 kJ/kg·K; c_v = 0.718 kJ/kg·K). The ambient conditions outside the enclosure are 95 kPa and 20°C. The air inside the enclosure is initially at 200 kPa and 20°C. Subsequently, an internal impeller within the enclosure raises the air's pressure to 230 kPa through a shaft from an external motor with a motor efficiency of 65%. Approximately how much shaft work is required to raise the pressure from 200 kPa to 230 kPa?

(A)

19 kJ

(B)

25 kJ

(C)

32 kJ

(D)

140 kJ

6.

Cast iron is heated from 80°F to 780°F (27°C to 416°C). The heat required per unit mass is most nearly

(A)

70 Btu/lbm (160 kJ/kg)

(B)

120 Btu/lbm (280 kJ/kg)

(C)

170 Btu/lbm (390 kJ/kg)

(D)

320 Btu/lbm (740 kJ/kg)
7.

The ventilation rate in a building is 3×10^5 ft^3/hr (2.4 m^3/s). The air is heated from 35°F to 75°F (2°C to 24°C) by water whose temperature decreases from 180°F to 150°F (82°C to 66°C). The water flow rate in gal/min (L/s) is most nearly

(A)

9 gal/min (0.58 L/s)

(B)

13 gal/min (0.83 L/s)

(C)

15 gal/min (0.96 L/s)

(D)

22 gal/min (1.4 L/s)

8.

8.0 ft^3 (0.25 m^3) of 180°F, 14.7 psia (82°C, 101.3 kPa) air is cooled to 100°F (38°C) in a constant-pressure process. The amount of work done is most nearly

(A)

−2100 ft-lbf (−3.1 kJ)

(B)

−1500 ft-lbf (−2.3 kJ)

(C)

−1100 ft-lbf (−1.5 kJ)

(D)

−900 ft-lbf (−1.3 kJ)

9.

Most nearly, the enthalpy change of an isentropic process using steam with an initial quality of 95% and operating between 300 psia and 50 psia (2 MPa and 0.35 MPa) is

(A)

100 Btu/lbm (230 kJ/kg)

(B)

130 Btu/lbm (300 kJ/kg)
(C)

210 Btu/lbm (480 kJ/kg)

(D)

340 Btu/lbm (780 kJ/kg)
10.

A closed air heater receives 540°F, 100 psia (280°C, 700 kPa) air and heats it to 1540°F (840°C). The outside temperature is 100°F (40°C). The pressure of the air drops 20 psi (150 kPa) as it passes through the heater. The heat transfer can be approximated as the outside temperature times the change in entropy. The percentage loss in available energy due to the pressure drop is most nearly

(A)

6%

(B)

12%

(C)

18%

(D)

34%

11.

Carbon dioxide gas at 20 psia and 70°F (150 kPa and 21°C) is compressed to 3800 psia and 70°F (25 MPa and 21°C) by a compressor/heat exchanger combination. The compressed gas is stored at 70°F (21°C) in a 100 ft^3 (3 m^3) rigid tank initially charged with carbon dioxide gas at 20 psia (150 kPa). The average mass flow rate of carbon dioxide gas into the tank if the compressor fills the tank in exactly one hour is most nearly

(A)

6500 lbm/hr (0.8 kg/s)

(B)

9700 lbm/hr (1.3 kg/s)

(C)

12,000 lbm/hr (1.6 kg/s)

(D)

14,000 lbm/hr (1.9 kg/s)

12.

The mass of an insulated 20 ft^3 (0.6 m^3) steel tank is 40 lbm (20 kg). The steel has a specific heat of 0.11 Btu/lbm-°R (0.46 kJ/kg·K). The tank is placed in a room where the surrounding air is 70°F and 14.7 psia (21°C and 101.3 kPa). After the tank is evacuated to 1 psia and 70°F (7 kPa and 21°C), a valve is suddenly opened, allowing the tank to fill with room air. The air enters the tank in a well-mixed, turbulent condition and increases the system's final temperature to 300°F (149°C). The work performed by the room air entering the tank is most nearly

(A)

−42 Btu (−49 000 J)

(B)

−34 Btu (−38 000 J)

(C)

−8 Btu (−9500 J)

(D)

−4 Btu (−4700 J)

Solutions

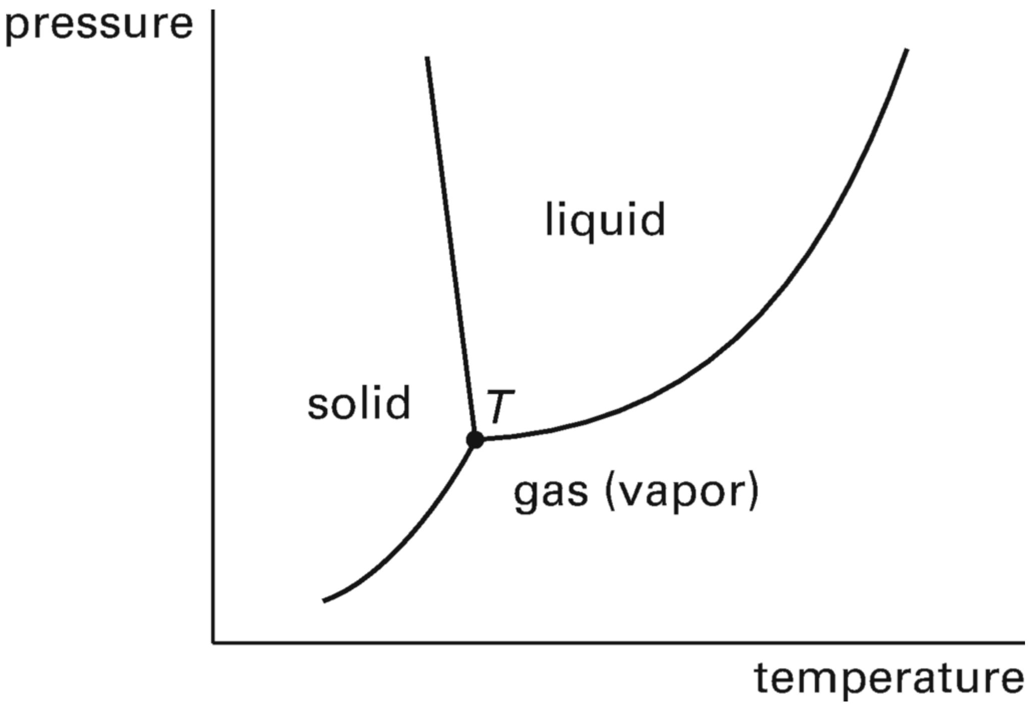
1.

Availability depends on the temperature of the environment, T_L. Option A is true.

A heat engine's maximum efficiency is that of a Carnot engine cycle, which is always less than 100%. Option B is false.

An expansion includes a drop in enthalpy, and since $h = u + pv$, both u (manifested as temperature) and p decrease. Option C is true.

Liquid water cannot exist below the triple point pressure. Option D is true.



The answer is (B).

2.

Entropy does not change in an isentropic (reversible adiabatic) process. However, not all adiabatic processes are reversible. Option A is false.

The entropy of a closed system can be decreased by decreasing the temperature. Option B is false.

When a refrigerant is throttled, the enthalpy remains constant, the pressure drops, and the entropy increases. Option C is true.

The fan and motor will certainly increase the entropy of the air inside the room. However, if the air temperature is decreased by heat loss to the outside, the entropy will decrease. Option D is false.

The answer is (C).
3.

A throttling process (including flow through a control valve, safety relief valve, throttling valve, nozzle, or orifice) is modeled as an isenthalpic process. Consider steam expanding through a safety relief valve. To squeeze through the narrow restriction between the disk and the valve seat, steam has to accelerate to a high speed. It does so by converting enthalpy into kinetic energy. The process is not frictionless, but passage past the valve seat occurs so quickly as to be essentially so, and the process is considered to be isentropic. Once past the narrow restriction, the steam expands into the lower pressure region in the valve outlet. The steam decelerates as the flow area increases from the valve passageway to the downstream pipe. This decrease in velocity (kinetic energy) is manifested as an increase in temperature and enthalpy. The enthalpy drop associated with the initial increase in kinetic energy is reclaimed (except for a small portion lost due to the effects of friction). Therefore, the final process is essentially isenthalpic.

Viscous drag of an object in any fluid is an adiabatic process without work being performed on or by the fluid. The duration of the contact between fluid and object is short. Therefore, viscous drag is isenthalpic.

The increase in velocity in a supersonic nozzle comes entirely at the expense of enthalpy.

The answer is (B).

4.

From equationMERM25093 (also the *NCEES Handbook:* section titled “Closed Thermodynamic Systems”) (applicable to both closed and open systems),

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (1160^\circ\text{R})\left(\frac{50\ \frac{\text{lbf}}{\text{in}^2}}{400\ \frac{\text{lbf}}{\text{in}^2}}\right)^{\frac{1.4-1}{1.4}} = 640.4^\circ\text{R}$$

As in the *NCEES Handbook:* section titled “Temperature-Dependent Properties of Air (U.S. Customary Units),” $c_p = 0.240$ Btu/lbm-°R.

From equationMERM25121 (also the *NCEES Handbook:* section titled “Turbines”), for turbines (i.e., gas expansion), the change in enthalpy is

$$\begin{aligned}\Delta h &= c_p\Delta T = \left(0.240\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{R}}\right)(640.4^\circ\text{R} - 1160^\circ\text{R}) \\ &= -124.7\ \text{Btu/lbm} \quad (-120\ \text{Btu/lbm})\end{aligned}$$

The answer is (B).

5.

Using the ideal gas law (see *NCEES Handbook:* Ideal Gas Law),

$$\begin{aligned}T_2 &= \frac{T_1 p_2}{p_1} = \frac{(20^\circ\text{C} + 273^\circ)(230\ \text{kPa})}{200\ \text{kPa}} = 337\text{K} \\ T_{2,^\circ\text{C}} &= 337\text{K} - 273^\circ = 64^\circ\text{C}\end{aligned}$$

This is a closed system. The first law of thermodynamics is applicable.

$$Q = \Delta U + W$$

Since the system is insulated, it is adiabatic, and $Q = 0$.

$$W = -\Delta U$$

Work on a unit mass (not molar) basis. Use equationMERM25047 (also *NCEES Handbook:* Closed Thermodynamic Systems), valid for any process.

$$\begin{aligned} W &= -\Delta U = -(m)(c_v)(T_2 - T_1) \\ &= (0.6\ \text{kg})\left(0.718\ \frac{\text{kJ}}{\text{kg·K}}\right)(64^\circ\text{C} - 20^\circ\text{C}) \\ &= 19\ \text{kJ} \end{aligned}$$

The answer is (A).

6.

Customary U.S. Solution

From tableMERM24002 (also *NCEES Handbook* table "Physical Properties of Metals at 68°F (U.S. Units)"), the approximate value of specific heat for cast iron is $c_p = 0.10$ Btu/lbm-°F.

The heat required per unit mass is

$$\begin{aligned} q &= c_p\,(T_2 - T_1) = \left(0.10\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)(780^\circ\text{F} - 80^\circ\text{F}) \\ &= 70\ \text{Btu/lbm} \end{aligned}$$

The answer is (A).

SI Solution

From tableMERM24002 (also *NCEES Handbook* table "Physical Properties of Metals at 20°C (SI Units)"), the approximate value of specific heat of cast iron is $c_p = 0.42$ kJ/kg·K.

The heat required per unit mass is

$$\begin{aligned} q &= c_p\,(T_2 - T_1) \\ &= \left(0.42\ \frac{\text{kJ}}{\text{kg·K}}\right)(416^\circ\text{C} - 27^\circ\text{C}) \\ &= 163.4\ \text{kJ/kg} \quad (160\ \text{kJ/kg}) \end{aligned}$$

The answer is (A).

7.

Customary U.S. Solution

First calculate the mass flow rate of air to be heated by using the ideal gas law. (Usually the air mass would be evaluated at the entering conditions. This problem is ambiguous. The building conditions are used because a building ventilation rate was specified.)

$$\dot{m}_{\text{air}} = \frac{p\dot{V}}{RT}$$

As in *NCEES Handbook:* Temperature, the absolute temperature is

$$
\begin{aligned}
T &= 75^\circ\text{F} + 460^\circ = 535^\circ\text{R} \\
\dot{m}_{air} &= \frac{\left(14.7\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2\left(3\times10^5\ \frac{\text{ft}^3}{\text{hr}}\right)\left(29\ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545.35\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(535^\circ\text{R})} \\
&= 2.227 \times 10^4\ \text{lbm/hr}
\end{aligned}
$$

As in *NCEES Handbook:* Ideal Gas Law, the heat lost by the water is equal to the heat gained by the air.

$$
\begin{aligned}
&\dot{m}_w c_{p,w}\left(T_{1,w} - T_{2,w}\right) = \dot{m}_{\text{air}} c_{p,\text{air}}\left(T_{2,\text{air}} - T_{1,\text{air}}\right) \\
&\dot{m}_w \left(1\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)(180^\circ\text{F} - 150^\circ\text{F}) \\
&\quad = \left(2.227 \times 10^4\ \frac{\text{lbm}}{\text{hr}}\right)\left(0.241\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)(75^\circ\text{F} - 35^\circ\text{F}) \\
&\dot{m}_w = 7156.1\ \text{lbm/hr}
\end{aligned}
$$

From appendixMERM35A (also *NCEES Handbook* table “Physical Properties of Liquid Water (U.S. Units)”), the density of water at 165°F is approximately 61 lbm/ft^3. The water volume flow rate is

$$
\begin{aligned}
\dot{V}_w &= \frac{\dot{m}}{\rho} = \frac{\left(7156.1\ \frac{\text{lbm}}{\text{hr}}\right)\left(7.481\ \frac{\text{gal}}{\text{ft}^3}\right)}{\left(61\ \frac{\text{lbm}}{\text{ft}^3}\right)\left(60\ \frac{\text{min}}{\text{hr}}\right)} \\
&= 14.63\ \text{gal/min} \quad (15\ \text{gal/min})
\end{aligned}
$$

The answer is (C).

SI Solution

First calculate the mass flow rate of air to be heated by using the ideal gas law. (Usually the air mass would be evaluated at the entering conditions. This problem is ambiguous. The building conditions are used because a building ventilation rate was specified.)

$$
\dot{m}_{\text{air}} = \frac{p\dot{V}}{RT}
$$

As in *NCEES Handbook* table “Conversion Table for Temperature Units,” the absolute temperature is

$$
\begin{aligned}
T &= 24^\circ\text{C} + 273^\circ = 297\text{K} \\
\dot{m}_{air} &= \frac{(101\ 300\ \text{Pa})\left(2.4\ \frac{\text{m}^3}{\text{s}}\right)\left(29\ \frac{\text{g}}{\text{mol}}\right)}{\left(8314.5\ \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(297\text{K})} \\
&= 2.85\ \text{kg/s}
\end{aligned}
$$

As in *NCEES Handbook:* Ideal Gas Law, the heat lost by the water is equal to the heat gained by the air.

$$
\begin{aligned}
&\dot{m}_w c_{p,w}\left(T_{1,w} - T_{2,w}\right) = \dot{m}_{\text{air}} c_{p,\text{air}}\left(T_{2,\text{air}} - T_{1,\text{air}}\right) \\
&\dot{m}_w \left(4.190\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)(82^\circ\text{C} - 66^\circ\text{C}) \\
&\quad = \left(2.85\ \frac{\text{kg}}{\text{s}}\right)\left(1.005\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)(24^\circ\text{C} - 2^\circ\text{C}) \\
&\dot{m}_w = 0.940\ \text{kg/s}
\end{aligned}
$$

From appendixMERM35B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”), the density of water at 74°C is approximately 976 kg/m^3. The water volume flow rate is

$$\dot{V}_w = \frac{\dot{m}}{\rho} = \frac{\left(0.940\ \frac{\text{kg}}{\text{s}}\right)\left(1000\ \frac{\text{L}}{\text{m}^3}\right)}{976\ \frac{\text{kg}}{\text{m}^3}} = 0.963\ \text{L/s} \quad (0.96\ \text{L/s})$$

The answer is (C).

8.

Customary U.S. Solution

As in *NCEES Handbook:* Ideal Gas Law, the mass of air is

$$\begin{aligned} m &= \frac{pV}{RT} = \frac{\left(14.7\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2\left(8\ \text{ft}^3\right)\left(29\ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545.35\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(640^\circ\text{R})} \\ &= 0.4964\ \text{lbm} \end{aligned}$$

For a constant pressure process from equationMERM25051 (also *NCEES Handbook:* Closed Thermodynamic Systems), on a per unit mass basis,

$$W = p(v_2 - v_1) = R(T_2 - T_1)$$

Since $\Delta T_{^\circ\text{R}} = \Delta T_{^\circ\text{F}}$, the total work for m in lbm is

$$\begin{aligned} W &= mR(T_2 - T_1) \\ &= \frac{(0.4964\ \text{lbm})\left(1545.35\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(100^\circ\text{F} - 180^\circ\text{F})}{29\ \frac{\text{lbm}}{\text{lbmol}}} \\ &= -2116.6\ \text{ft-lbf} \quad (-2100\ \text{ft-lbf}) \end{aligned}$$

This is negative because work is done on the system.

The answer is (A).

SI Solution

As in *NCEES Handbook:* Ideal Gas Law, the mass of air is

$$\begin{aligned} m &= \frac{pV}{RT} = \frac{(101\,300\ \text{Pa})(0.25\ \text{m}^3)\left(29\ \frac{\text{g}}{\text{mol}}\right)}{\left(8314.5\ \frac{\text{J}}{\text{kmol·K}}\right)(355\text{K})} \\ &= 0.2486\ \text{kg} \end{aligned}$$

For a constant pressure process from equationMERM25051 (also *NCEES Handbook:* Closed Thermodynamic Systems), on a per unit mass basis,

$$W = p(v_2 - v_1) = R(T_2 - T_1)$$

The total work for m in kg is

$$\begin{aligned} W &= mR(T_2 - T_1) \\ &= \frac{(0.2486\ \text{kg})\left(8314.5\ \frac{\text{J}}{\text{kmol·K}}\right)(38^\circ\text{C} - 82^\circ\text{C})}{29\ \frac{\text{g}}{\text{mol}}} \\ &= -3136.1\ \text{J} \quad (-3.1\ \text{kJ}) \end{aligned}$$

The answer is (A).

9.

Customary U.S. Solution

From appendixMERM24B (also *NCEES Handbook* table "Saturated Steam (U.S. Units)—Temperature Table"), for 300 psia, the enthalpy of saturated liquid, h_f, is 394.0 Btu/lbm. The heat of vaporization, h_{fg}, is 809.4 Btu/lbm. The enthalpy is given by equationMERM24040 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems).

$$\begin{aligned} h_1 &= h_f + x h_{fg} = 394.0\ \frac{\text{Btu}}{\text{lbm}} + (0.95)\left(809.4\ \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 1162.9\ \text{Btu/lbm} \end{aligned}$$

From the Mollier diagram (also *NCEES Handbook* diagram "Temperature-Entropy (T-S) Diagram (U.S. Customary Units)"), for an isentropic process from 300 psia to 50 psia, $h_2 = 1031$ Btu/lbm.

The change in enthalpy for the isentropic process is

$$\begin{aligned} h_1 - h_2 &= 1162.9\ \frac{\text{Btu}}{\text{lbm}} - 1031\ \frac{\text{Btu}}{\text{lbm}} \\ &= 131.9\ \text{Btu/lbm} \quad (130\ \text{Btu/lbm}) \end{aligned}$$

The answer is (B).

SI Solution

From appendixMERM24O (also *NCEES Handbook* table "Saturated Steam (SI Units)—Temperature Table"), for 2 MPa, the enthalpy of saturated liquid, h_f, is 908.50 kJ/kg. The heat of vaporization, h_{fg}, is 1889.8 kJ/kg. The enthalpy is given by equationMERM24040 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems).

$$\begin{aligned} h_1 &= h_f + x h_{fg} = 908.50\ \frac{\text{kJ}}{\text{kg}} + (0.95)\left(1889.8\ \frac{\text{kJ}}{\text{kg}}\right) \\ &= 2703.8\ \text{kJ/kg} \end{aligned}$$

From the Mollier diagram (also *NCEES Handbook* diagram "Temperature-Entropy (T-S) Diagram (U.S. Customary Units)," for an isentropic process from 2 MPa to 0.35 MPa, $h_2 = 2405$ kJ/kg.

The change in enthalpy for the isentropic process is

$$\begin{aligned} h_1 - h_2 &= 2703.8\ \frac{\text{kJ}}{\text{kg}} - 2405\ \frac{\text{kJ}}{\text{kg}} \\ &= 298.8\ \text{kJ/kg} \quad (300\ \text{kJ/kg}) \end{aligned}$$

The answer is (B).
10.

Customary U.S. Solution

The absolute temperature at the inlet of the air heater is

$$T_1 = 540^\circ\text{F} + 460^\circ = 1000^\circ\text{R}$$

The absolute temperature at the outlet of the air heater is

$$T_2 = 1540^\circ\text{F} + 460^\circ = 2000^\circ\text{R}$$

Using the first law of thermodynamics, the work is

$$W = (h_1 - h_2) + Q = (h_1 - h_2) + T_L(s_2 - s_1)$$

Substitute the change in enthalpy and the change in entropy with expressions from *NCEES Handbook:* Ideal Gas Law.

$$W = c_p\left(T_1 - T_2\right) + T_L\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{p_2}{p_1}\right)$$

As in *NCEES Handbook:* Temperature-Dependent Properties of Air (U.S. Customary Units), the heat capacity of air is $c_p = 0.24$ Btu/lbm°F. Since 1 degree Fahrenheit is equal to 1 degree Rankine, the heat capacity is the same when put in terms of Rankine. The work without the pressure term is

$$\begin{aligned} W_{\text{no } p \text{ change}} &= \left(0.24\ \tfrac{\text{Btu}}{\text{lbm-}^\circ\text{R}}\right)\left(1000^\circ\text{R} - 2000^\circ\text{R}\right) \\ &\quad + \left(560^\circ\text{R}\right)\left(0.24\ \tfrac{\text{Btu}}{\text{lbm-}^\circ\text{R}}\right)\left(\ln\tfrac{2000^\circ\text{R}}{1000^\circ\text{R}}\right) \\ &= -146.8\ \text{Btu/lbm} \end{aligned}$$

The work with the pressure term is

$$\begin{aligned} W_{p \text{ change}} &= -146.8\ \tfrac{\text{Btu}}{\text{lbm}} - \left(560^\circ\text{R}\right)\left(\frac{1545.35\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}}{29\ \frac{\text{lbm}}{\text{lbmol}}}\right) \\ &\quad \times\left(\ln\frac{80\ \frac{\text{lbf}}{\text{in}^2}}{100\ \frac{\text{lbf}}{\text{in}^2}}\right)\left(778.169\ \tfrac{\text{lbf-ft}}{\text{Btu}}\right) \\ &= -138.2\ \text{Btu/lbm} \end{aligned}$$

The percentage loss in available energy due to pressure drop is

$$\begin{aligned} \frac{W_{\max} - W_{\max,\text{p loss}}}{W_{\max}} \times 100\% &= \left(\frac{-146.8\ \frac{\text{Btu}}{\text{lbm}} - \left(-138.2\ \frac{\text{Btu}}{\text{lbm}}\right)}{-146.8\ \frac{\text{Btu}}{\text{lbm}}}\right) \\ &\quad \times 100\% \\ &= 5.8\% \quad (6\%) \end{aligned}$$

The answer is (A).

SI Solution

The absolute temperature at the inlet of the air heater is

$$T_1 = 280^\circ\text{C} + 273^\circ = 553\text{K}$$

The absolute temperature at the outlet of the air heater is

$$T_2 = 840^\circ\text{C} + 273^\circ = 1113\text{K}$$

From the first law of thermodynamics, the work is

$$W = \left(h_1 - h_2\right) + Q = \left(h_1 - h_2\right) + T_L\left(s_2 - s_1\right)$$

Substitute the change in enthalpy and the change in entropy with expressions from *NCEES Handbook:* Ideal Gas Law.

$$W = c_p\left(T_1 - T_2\right) + T_L\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{p_2}{p_1}\right)$$

As in *NCEES Handbook:* Temperature-Dependent Properties of Air (U.S. Customary Units), the heat capacity is $c_p = 1.01$ kJ/kg·K. The work without the pressure change is

$$\begin{aligned} W_{\text{no } p \text{ change}} &= \left(1.01\ \tfrac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)\left(550\text{K} - 1100\text{K}\right) \\ &\quad + \left(313\text{K}\right)\left(1.01\ \tfrac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)\left(\ln\tfrac{1100\text{K}}{550\text{K}}\right) \\ &= -336.4\ \text{kJ/kg} \end{aligned}$$

The work with the pressure change is

$$\begin{aligned} W_{p\text{ change}} &= -336.4\ \frac{\text{kJ}}{\text{kg}} - (313\text{K}) \\ &\quad \times \left(\frac{8.3145\ \frac{\text{kJ}}{\text{kmol}\cdot\text{K}}}{29\ \frac{\text{kg}}{\text{kmol}}}\right)\left(\ln \frac{700-150\ \text{kPa}}{700\ \text{kPa}}\right) \\ &= -314.75\ \text{kJ/kg} \end{aligned}$$

The percentage loss in available energy due to pressure drop is

$$\begin{aligned} \frac{W_{\text{max}} - W_{\text{max},\ p\text{ loss}}}{W_{\text{max}}} \times 100\% &= \left(\frac{-336.4\ \frac{\text{kJ}}{\text{kg}} - \left(-314.75\ \frac{\text{kJ}}{\text{kg}}\right)}{-336.4\ \frac{\text{kJ}}{\text{kg}}}\right) \\ &\quad \times 100\% \\ &= 6.43\% \quad (6\%) \end{aligned}$$

The answer is (A).
11.

Customary U.S. Solution

As in *NCEES Handbook* table "Conversion Table for Temperature Units," the absolute temperature is

$$T = 70^\circ\text{F} + 460^\circ = 530^\circ\text{R}$$

The mass is

$$\begin{aligned} m &= \frac{pV}{RT} = \frac{\left(20\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2\left(100\ \text{ft}^3\right)\left(44\ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545.35\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(530^\circ\text{R})} \\ &= 15.5\ \text{lbm} \end{aligned}$$

From *NCEES Handbook:* Physical Properties of Liquids and Gases—Temperature-Independent Properties, the critical temperature and pressure of carbon dioxide are

$$\begin{aligned} T_c &= 87.8^\circ\text{F} + 460^\circ = 547.8^\circ\text{R} \\ p_c &= 1070\ \text{lbf/in}^2 \end{aligned}$$

Using *NCEES Handbook:* Compressibility and the Theorem of Corresponding States, the reduced temperature and pressure of carbon dioxide are

$$T_r = \frac{T}{T_c} = \frac{530^\circ\text{R}}{547.8^\circ\text{R}} = 0.97$$

$$p_r = \frac{p}{p_c} = \frac{3800\ \frac{\text{lbf}}{\text{in}^2}}{1070\ \frac{\text{lbf}}{\text{in}^2}} = 3.55$$

From the compressibility chart, $Z = 0.45$.

The final mass is

$$\begin{aligned} m &= \frac{pV}{ZRT} = \frac{\left(3800\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2\left(100\ \text{ft}^3\right)\left(44\ \frac{\text{lbm}}{\text{lbmol}}\right)}{(0.45)\left(1545.35\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(530^\circ\text{R})} \\ &= 6532.5\ \text{lbm} \quad (6530\ \text{lbm}) \end{aligned}$$

The average mass flow rate of carbon dioxide is

$$\dot{m} = \frac{6530 \text{ lbm} - 15.5 \text{ lbm}}{1 \text{ hr}} = 6517 \text{ lbm/hr} \quad (6500 \text{ lbm/hr})$$

The answer is (A).

SI Solution

As in *NCEES Handbook* table "Conversion Table for Temperature Units," the absolute temperature is

$$T = 21^\circ\text{C} + 273^\circ = 294\text{K}$$

The mass is

$$\begin{aligned} m &= \frac{pV}{RT} = \frac{(150 \text{ kPa})(3 \text{ m}^3)\left(44 \frac{\text{g}}{\text{mol}}\right)\left(\frac{10^3 \text{ Pa/kPa}}{\text{kPa}}\right)}{\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(294\text{K})} \\ &= 8.1 \text{ kg} \end{aligned}$$

As in *NCEES Handbook:* Physical Properties of Liquids and Gases—Temperature-Independent Properties, the critical temperature and pressure of carbon dioxide are

$$T_c = 31^\circ\text{C} + 273^\circ = 304\text{K}$$

$$p_c = 7.38 \text{ MPa}$$

Using *NCEES Handbook:* Compressibility and the Theorem of Corresponding States, the reduced temperature and pressure of carbon dioxide are

$$T_r = \frac{T}{T_c} = \frac{294\text{K}}{304\text{K}} = 0.97$$

$$p_r = \frac{p}{p_c} = \frac{25 \text{ MPa}}{7.38 \text{ MPa}} = 3.39$$

From the compressibility chart, $Z = 0.45$.

The final mass is

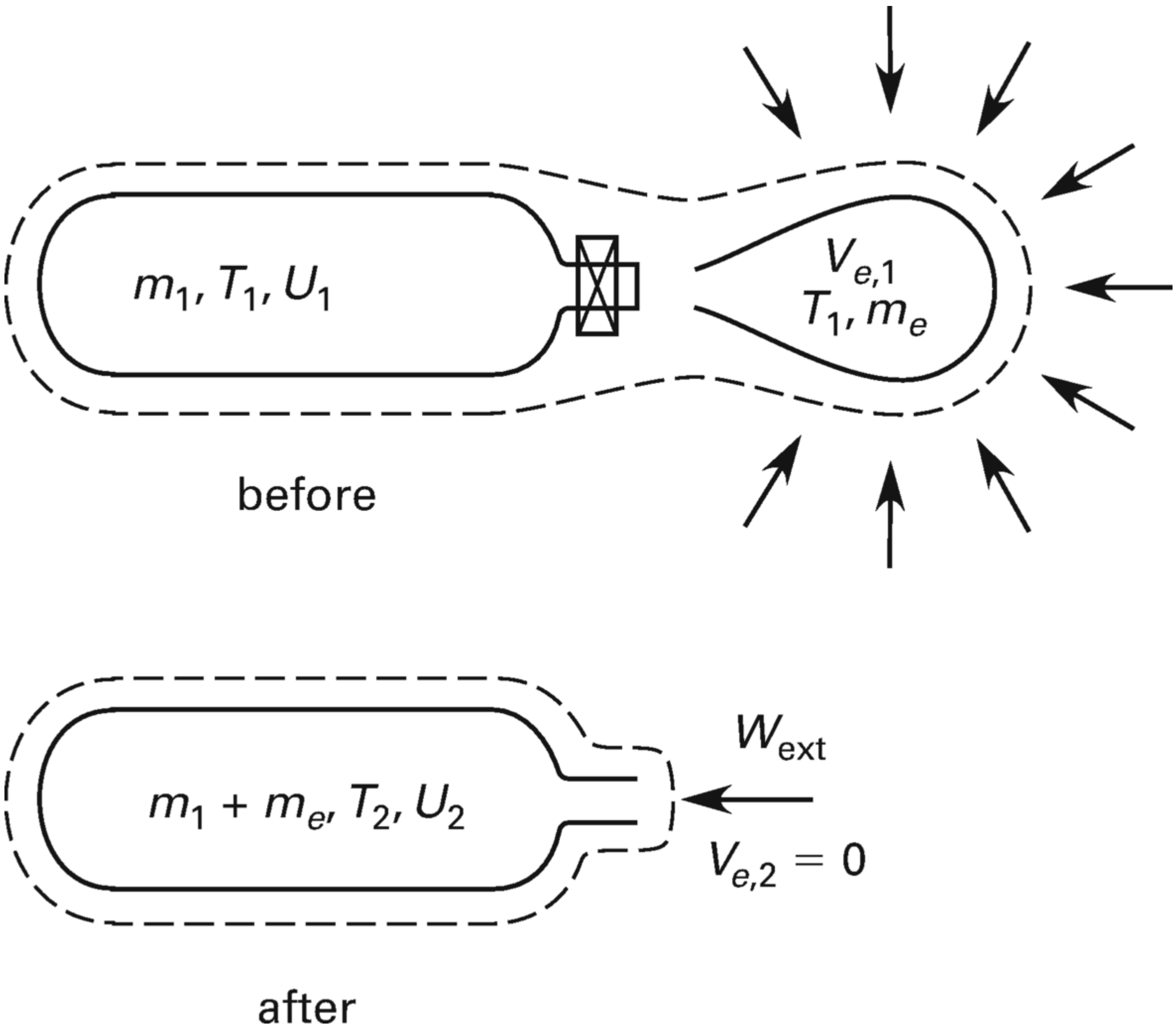
$$\begin{aligned} m &= \frac{pV}{ZRT} = \frac{(25 \text{ MPa})(3 \text{ m}^3)\left(44 \frac{\text{g}}{\text{mol}}\right)\left(10^6 \text{ Pa/kPa}\right)}{(0.45)\left(8314.5 \frac{\text{J}}{\text{kmol}\cdot\text{K}}\right)(294\text{K})} \\ &= 3000 \text{ kg} \end{aligned}$$

The average mass flow rate of carbon dioxide is

$$\dot{m} = \frac{3000 \frac{\text{kg}}{\text{hr}} - 8.1 \frac{\text{kg}}{\text{hr}}}{3600 \frac{\text{sec}}{\text{hr}}} = 0.8 \text{ kg/s}$$

The answer is (A).
12.

Choose the control volume to include the air outside the tank that is pushed into the tank (subscript "*e*" for "entering"), as well as the tank volume.



Customary U.S. Solution

As in the conversion table for temperature units, the absolute temperature of the air in the tank when evacuated is

$$T_1 = 70^\circ\text{F} + 460^\circ = 530^\circ\text{R}$$

Using ideal gas law, the mass, m_1, is

$$m_1 = \frac{P_1 V(\text{MW})}{RT_1} = \frac{\left(1\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2 (20\ \text{ft}^3)\left(29\ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(530^\circ\text{R})}$$

$$= 0.102\ \text{lbm}$$

The final system temperature, T_2, 300°F. The absolute temperature is

$$T_2 = 300^\circ\text{F} + 460^\circ = 760^\circ\text{R}$$

The final system mass of air, m_2, is

$$\begin{aligned} m_2 &= m_1 + m_e = \frac{P_2 V\,(\mathrm{MW})}{RT_2} \\ &= \frac{\left(14.7\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2 \left(20\ \mathrm{ft}^3\right)\left(29\ \frac{\mathrm{lbm}}{\mathrm{lbmol}}\right)}{\left(1545\ \frac{\mathrm{ft\text{-}lbf}}{\mathrm{lbmol\text{-}^\circ R}}\right)(760^\circ\mathrm{R})} \\ &= 1.046\ \mathrm{lbm} \\ m_1 + m_e &\approx 1.046\ \mathrm{lbm} \\ m_e &\approx 1.046\ \mathrm{lbm} - m_1 \\ &= 1.046\ \mathrm{lbm} - 0.102\ \mathrm{lbm} \\ &= 0.944\ \mathrm{lbm} \end{aligned}$$

Using the ideal gas law, the initial volume of external air entering the system, $V_{e,1}$, is

$$\begin{aligned} V_{e,1} &= \frac{m_2 RT_1}{MW P_{\mathrm{air}}} = \frac{(0.944\ \mathrm{lbm})\left(1545\ \frac{\mathrm{ft\text{-}lbf}}{\mathrm{lbmol\text{-}^\circ R}}\right)(530^\circ\mathrm{R})}{\left(29\ \frac{\mathrm{lbm}}{\mathrm{lbmol}}\right)\left(14.7\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2} \\ &= 12.59\ \mathrm{ft}^3 \end{aligned}$$

From *NCEES Handbook*: Closed System Changes, the isobaric (constant pressure), closed system total work is

$$\begin{aligned} W_{\mathrm{ext}} &= P\left(V_{e,2} - V_{e,1}\right) \\ &= \frac{\left(14.7\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2 \left(0\ \mathrm{ft} - 12.59\ \mathrm{ft}^3\right)}{778.21\ \frac{\mathrm{ft\text{-}lbf}}{\mathrm{Btu}}} \\ &= -34.25\ \mathrm{Btu} \quad (-34\ \mathrm{Btu}) \quad \left[\begin{array}{c}\text{surroundings do}\\ \text{work on the system}\end{array}\right] \end{aligned}$$

The answer is (B).

SI Solution

As in *NCEES Handbook:* Temperature, the absolute temperature of the air in the tank when evacuated is

$$T_1 = 21^\circ\mathrm{C} + 273^\circ = 294\mathrm{K}$$

As in *NCEES Handbook:* Ideal Gas Law,

$$\begin{aligned} m_1 &= \frac{P_1 V\,(\mathrm{MW})}{RT_1} = \frac{(7000\,\mathrm{Pa})\left(0.60\ \mathrm{m}^3\right)\left(29\ \frac{\mathrm{g}}{\mathrm{mol}}\right)}{\left(8.314\ \frac{\mathrm{m}^3\cdot\mathrm{Pa}}{\mathrm{mol}\cdot\mathrm{K}}\right)(294\ \mathrm{K})} \\ &= 49.8\ g \\ &= 0.0498\ \mathrm{kg} \end{aligned}$$

The final system temperature $T_2 = 149^\circ\mathrm{C}$. The absolute temperature is

$$T_2 = 149^\circ\mathrm{C} + 273^\circ = 422\ \mathrm{K}$$

The final system mass of air, m_2, is

$$
\begin{aligned}
m_2 &= m_1 + m_e = \frac{P_2 V\,(\mathrm{MW})}{RT_2} \\
&= \frac{(101.3\ \mathrm{kPa})\left(1000\ \dfrac{\mathrm{Pa}}{\mathrm{kPa}}\right)\left(0.60\ \mathrm{m}^3\right)\left(29\ \dfrac{\mathrm{g}}{\mathrm{mol}}\right)}{\left(8.314\ \dfrac{\mathrm{m}^3\cdot\mathrm{Pa}}{\mathrm{mol}\cdot\mathrm{K}}\right)(422\ \mathrm{K})} \\
&= 502.39\ \mathrm{g} \\
m_1 + m_e &\approx 0.5024\ \mathrm{kg} \\
m_e &\approx 0.5024\ \mathrm{kg} - m_1 \\
&= 0.5024\ \mathrm{kg} - 0.0498\ \mathrm{kg} \\
&= 0.4526\ \mathrm{kg}
\end{aligned}
$$

Using the ideal gas law, the initial volume of external air entering the system, $V_{e,1}$, is

$$
\begin{aligned}
V_{e,1} &= \frac{m_2 R T_1}{(\mathrm{MW})\,P_{\mathrm{air}}} = \frac{(0.4526\ \mathrm{kg})\left(1000\ \dfrac{\mathrm{g}}{\mathrm{kg}}\right)\left(8.314\ \dfrac{\mathrm{m}^3\cdot\mathrm{Pa}}{\mathrm{mol}\cdot\mathrm{K}}\right)(294\ \mathrm{K})}{\left(29\ \dfrac{\mathrm{g}}{\mathrm{mol}}\right)(101.3\ \mathrm{kPa})\left(1000\ \dfrac{\mathrm{Pa}}{\mathrm{kPa}}\right)} \\
&= 0.3766\ \mathrm{m}^3
\end{aligned}
$$

From *NCEES Handbook*: Closed System Changes, the isobaric (constant pressure), closed system total work is

$$
\begin{aligned}
W_{\mathrm{ext}} &= P\left(V_{e,2} - V_{e,1}\right) \\
&= (101.3\ \mathrm{kPa})\left(1000\ \frac{\mathrm{Pa}}{\mathrm{kPa}}\right)\left(0\ \mathrm{m}^3 - 0.3766\ \mathrm{m}^3\right) \\
&= -38\,150\ \mathrm{J} \quad (-38\,000\ \mathrm{J}) \quad \begin{bmatrix}\text{surroundings do} \\ \text{work on the system}\end{bmatrix}
\end{aligned}
$$

The answer is (B).