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Chapter 15. Gas Compression Cycles

Practice Problems

1.

The isentropic efficiency of a compressor that takes in air at 8 psia and −10°F (55 kPa and −20°C) and discharges it at 40 psia and 315°F (275 kPa and 160°C) is most nearly

(A)

61%

(B)

66%

(C)

74%

(D)

81%

2.

Air at 14.7 psia and 500°F (101.3 kPa and 260°C) is compressed in a centrifugal compressor to 6 atm. The isentropic efficiency of the compression process is 65%. The increase in entropy is most nearly

(A)

0.05 Btu/lbm-°R (0.20 kJ/kg·K)

(B)

0.099 Btu/lbm-°R (0.47 kJ/kg·K)

(C)

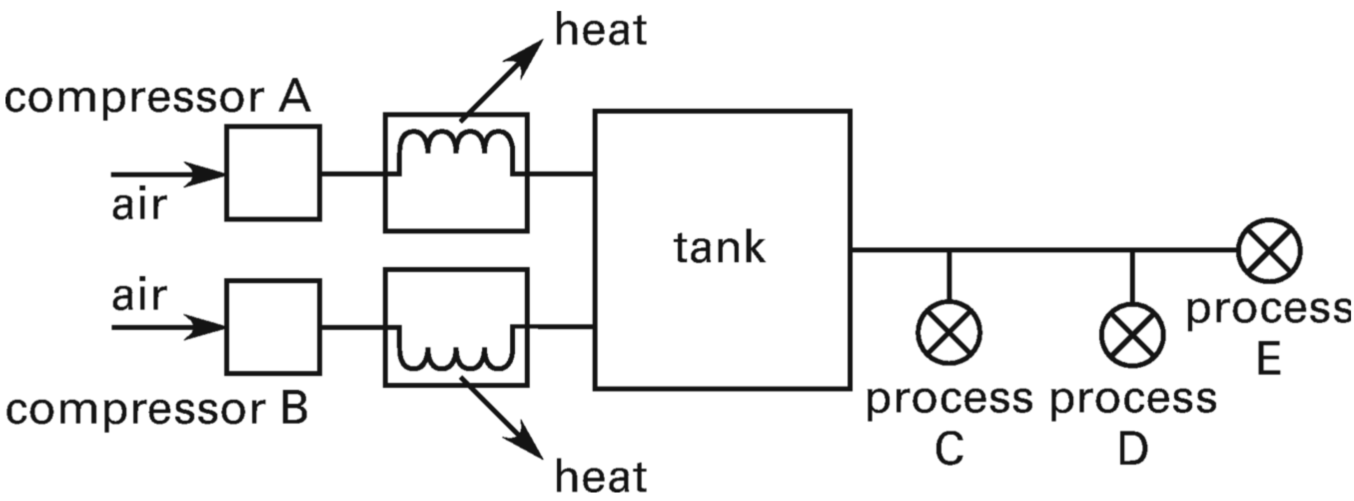
0.23 Btu/lbm-°R (1.0 kJ/kg·K)

(D)

0.44 Btu/lbm-°R (2.1 kJ/kg·K)

3.

Compressors A and B both discharge into a common tank. The storage tank contains 100 psia, 90°F air (700 kPa, 32°C). Both compressors receive air at 14.7 psia and 80°F (101.3 kPa and 27°C). The flow rate through compressor A is 600 cfm (300 L/s). Process C uses 100 cfm of 80 psia, 85°F (50 L/s of 550 kPa, 29°C) air. Process D uses 120 cfm of 85 psia, 80°F (60 L/s of 590 kPa, 27°C) air. Process E uses 8 lbm/min (0.06 kg/s) of 85°F (29°C) air. Air is an ideal gas, and compressibility effects are to be disregarded.



The volumetric flow rate through compressor B is most nearly

(A)

620 ft^3/min (320 L/s)

(B)

740 ft^3/min (370 L/s)

(C)

900 ft^3/min (450 L/s)

(D)

1100 ft^3/min (550 L/s)
4.

300 cfm (150 L/s) of air at 14.7 psia and 90°F (101.3 kPa and 32°C) enters a compressor. The compressor discharges air into a water-cooled heat exchanger. The compressed air is stored at 300 psig and 90°F (2.07 MPa and 32°C) in a 1000 ft^3 (27 m^3) tank. The tank feeds three air-driven tools with the flow rates and properties listed. The pressures to the air-driven tools are regulated and remain constant at the minimum required operating pressure as the tank pressure changes. Air is an ideal gas, and compressibility effects are to be disregarded.

	tool 1	tool 2	tool 3
flow rate			
(cfm)	40	15	unknown
(L/s)	19	7	unknown
flow rate			
(lbm/min)	unknown	unknown	6
(kg/s)	unknown	unknown	0.045
minimum pressure			
(psig)	90	50	80
(kPa)	620	350	550
temperature			
(°F)	90	85	80
(°C)	32	29	27

Approximately how long can the system run?

(A)

0.6 hr (1.2 h)

(B)

1.8 hr (3.6 h)

(C)

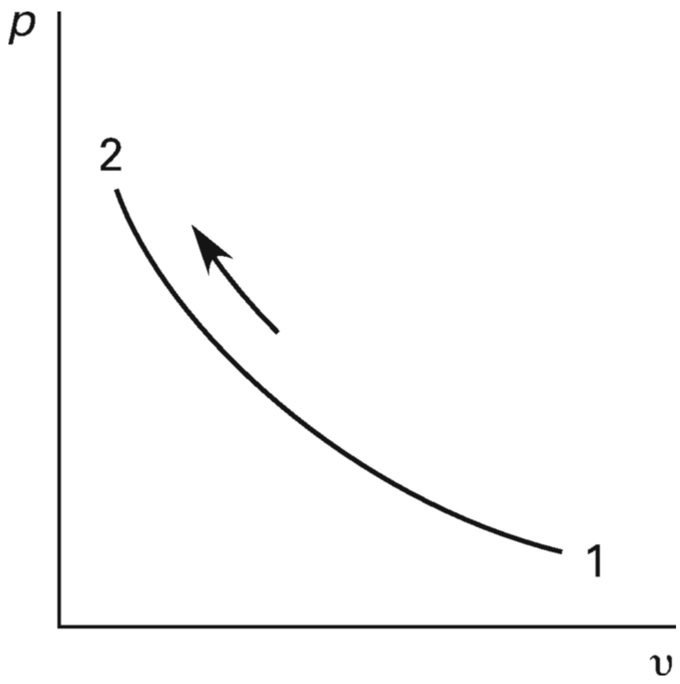
3.4 hr (6.8 h)

(D)

6.6 hr (13 h)

Solutions

1.



Customary U.S. Solution

Assume air is an ideal gas.

From equationMERM29018 (also *NCEES Handbook:* Closed Thermodynamic Systems), the isentropic temperature at point 2 is

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{(k-1)/k}$$

As in *NCEES Handbook* table "Conversion Table for Temperature Units," the absolute temperature at point 1 is

$$\begin{aligned} T_1 &= -10^\circ\text{F} + 460^\circ = 450^\circ\text{R} \\ T_2 &= (450^\circ\text{R}) \left(\frac{40 \text{ psia}}{8 \text{ psia}} \right)^{(1.4-1)/1.4} \\ &= 712.7^\circ\text{R} \\ T_2 &= 712.7^\circ\text{R} - 460^\circ = 252.7^\circ\text{F} \end{aligned}$$

The efficiency of the compressor is given by equationMERM29099 (also *NCEES Handbook:* Open Thermodynamic Systems).

$$\begin{aligned}\eta_{s,\text{compressor}} &= \frac{T_2 - T_1}{T_2' - T_1} \\ &= \frac{252.7^\circ\text{F} - (-10^\circ\text{F})}{315^\circ\text{F} - (-10^\circ\text{F})} \\ &= 0.808 \quad (81\%)\end{aligned}$$

The answer is (D).

SI Solution

Assume air is an ideal gas.

From equationMERM29018 (also *NCEES Handbook:* Closed Thermodynamic Systems), the isentropic temperature at point 2 is

$$T_2 = T_1\left(\frac{p_2}{p}\right)^{(k-1)/k}$$

As in *NCEES Handbook* table "Conversion Table for Temperature Units," the absolute temperature at point 1 is

$$\begin{aligned}T_1 &= -20^\circ\text{C} + 273^\circ = 253\text{K} \\ T_2 &= (253\text{K})\left(\frac{275 \text{ kPa}}{55 \text{ kPa}}\right)^{(1.4-1)/1.4} \\ &= 400.7\text{K} \\ T_2 &= 400.7\text{K} - 273^\circ = 127.7^\circ\text{C}\end{aligned}$$

The efficiency of the compressor is given by equationMERM29099 (also *NCEES Handbook:* Open Thermodynamic Systems).

$$\begin{aligned}\eta_{s,\text{compressor}} &= \frac{T_2 - T_1}{T_2' - T_1} \\ &= \frac{127.7^\circ\text{C} - (-20^\circ\text{C})}{160^\circ\text{C} - (-20^\circ\text{C})} \\ &= 0.821 \quad (81\%)\end{aligned}$$

The answer is (D).
2.

Customary U.S. Solution

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

$$T_1 = 500^\circ\text{F} + 460^\circ = 960^\circ\text{R}$$

From equationMERM29018 (also *NCEES Handbook:* Closed Thermodynamic Systems), the isentropic temperature after expansion is

$$\begin{aligned}T_2 &= T_1\left(\tfrac{p_2}{p_1}\right)^{(k-1)/k} \\ &= (960^\circ\text{R})\left(\tfrac{6 \text{ atm}}{1 \text{ atm}}\right)^{(1.4-1)/1.4} \\ &= 1602^\circ\text{R}\end{aligned}$$

As in *NCEES Handbook:* Open Thermodynamic Systems, the actual temperature, taking into account isentropic efficiency, is

$$
\begin{aligned}
T_2' &= T_1 - \frac{T_1 - T_2}{\eta_{\text{isen}}} \\
&= 960^\circ\text{R} - \frac{960^\circ\text{R} - 1602^\circ\text{R}}{0.65} \\
&= 1948^\circ\text{R}
\end{aligned}
$$

Using Eq. 10.39 (also the molecular weight as explained in *NCEES Handbook:* Combustion Reactions and *NCEES Handbook:* Ideal Gas Law), the increase in entropy is

$$
\begin{aligned}
\Delta s &= c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \\
&= \left(0.24\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)\left(\ln \frac{1948^\circ\text{R}}{960^\circ\text{R}}\right) \\
&\quad - \left(\frac{1545\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}}{\left(29\ \frac{\text{lbm}}{\text{lbmol}}\right)\left(778\ \frac{\text{ft-lbf}}{\text{Btu}}\right)}\right)\left(\ln \frac{6\ \text{atm}}{1\ \text{atm}}\right) \\
&= 0.047\ \text{Btu/lbm-}^\circ\text{R} \quad (0.05\ \text{Btu/lbm-}^\circ\text{R})
\end{aligned}
$$

The answer is (A).

SI Solution

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

$$
T_1 = 260^\circ\text{C} + 273^\circ = 533\text{K}
$$

From equationMERM29018 (also *NCEES Handbook:* Closed Thermodynamic Systems), the isentropic temperature after expansion is

$$
T_2 = T_1\left(\frac{p_2}{p_1}\right)^{(k-1)/k} = (533\text{K})\left(\frac{6\ \text{atm}}{1\ \text{atm}}\right)^{(1.4-1)/1.4} = 889\text{K}
$$

As in *NCEES Handbook:* Open Thermodynamic Systems, the actual temperature, taking into account isentropic efficiency, is

$$
\begin{aligned}
T_2' &= T_1 - \frac{(T_1 - T_2)}{\eta_{\text{isen}}} = 533\text{K} - \frac{533\text{K} - 889\text{K}}{0.65} \\
&= 1081\text{K}
\end{aligned}
$$

Using Eq. 10.39 (also the molecular weight as explained in *NCEES Handbook:* Combustion Reactions and *NCEES Handbook:* Ideal Gas Law), the increase in entropy is

$$
\begin{aligned}
\Delta s &= c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \\
&= \left(1.009\ \frac{\text{kJ}}{\text{kg·K}}\right)\left(\ln \frac{1081\text{K}}{533\text{K}}\right) \\
&\quad - \left(\frac{8.314\ \frac{\text{kJ}}{\text{kmol·K}}}{29\ \frac{\text{kg}}{\text{kmol}}}\right)\left(\ln \frac{6\ \text{atm}}{1\ \text{atm}}\right) \\
&= (0.1998\ \text{kJ/kg·K}) \quad (0.20\ \text{kJ/kg·K})
\end{aligned}
$$

The answer is (A).
3.

Customary U.S. Solution

For process C, the absolute temperature is 85°F + 460°= 545°R. Using ideal gas laws, the mass flow rate for process C is

$$
\begin{aligned}
\dot{m}_{\text{C}} &= \frac{p_{\text{C}}\dot{V}_{\text{C}}M}{RT_{\text{C}}} = \frac{\left(80\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2\left(100\ \frac{\text{ft}^3}{\text{min}}\right)\left(29\ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(545^\circ\text{R})} \\
&= 39.66\ \text{lbm/min}
\end{aligned}
$$

Similarly, the mass flow rate for process D with an absolute temperature of 80°F + 460° = 540°R is

$$\begin{aligned}\dot{m}_{\mathrm{D}} &= \frac{p_{\mathrm{D}}\dot{V}_{\mathrm{D}}M}{RT_{\mathrm{D}}} \\ &= \frac{\left(85\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2\left(120\ \frac{\mathrm{ft}^3}{\mathrm{min}}\right)\left(29\ \frac{\mathrm{lbm}}{\mathrm{lbmol}}\right)}{\left(1545\ \frac{\mathrm{ft\text{-}lbf}}{\mathrm{lbmol\text{-}^\circ R}}\right)(540^\circ\mathrm{R})} \\ &= 51.03\ \mathrm{lbm/min}\end{aligned}$$

For process E, the mass flow rate is given as $\dot{m}_{\mathrm{E}} = 8\ \mathrm{lbm/min}$.

The total mass flow rate for all three processes is

$$\begin{aligned}\dot{m}_{\mathrm{total}} &= \dot{m}_{\mathrm{C}} + \dot{m}_{\mathrm{D}} + \dot{m}_{\mathrm{E}} \\ &= 39.66\ \frac{\mathrm{lbm}}{\mathrm{min}} + 51.03\ \frac{\mathrm{lbm}}{\mathrm{min}} + 8\ \frac{\mathrm{lbm}}{\mathrm{min}} \\ &= 98.69\ \mathrm{lbm/min}\end{aligned}$$

The mass flow rate into compressor A is with an absolute temperature of 80°F + 460° = 540°R.

$$\begin{aligned}\dot{m}_{\mathrm{A}} &= \frac{p_{\mathrm{A}}\dot{V}_{\mathrm{A}}M}{RT_{\mathrm{A}}} \\ &= \frac{\left(14.7\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2\left(600\ \frac{\mathrm{ft}^3}{\mathrm{min}}\right)\left(29\ \frac{\mathrm{lbm}}{\mathrm{lbmol}}\right)}{\left(1545\ \frac{\mathrm{ft\text{-}lbf}}{\mathrm{lbmol\text{-}^\circ R}}\right)(540^\circ\mathrm{R})} \\ &= 44.13\ \mathrm{lbm/min}\end{aligned}$$

The required input for compressor B is

$$\begin{aligned}\dot{m}_{\mathrm{B}} &= \dot{m}_{\mathrm{total}} - \dot{m}_{\mathrm{A}} \\ &= 98.69\ \frac{\mathrm{lbm}}{\mathrm{min}} - 44.13\ \frac{\mathrm{lbm}}{\mathrm{min}} \\ &= 54.56\ \mathrm{lbm/min}\end{aligned}$$

The volumetric flow rate for compressor B is

$$\begin{aligned}\dot{V}_{\mathrm{B}} &= \frac{\dot{m}_{\mathrm{B}}RT_{\mathrm{B}}}{p_{\mathrm{A}}M} = \frac{\left(54.56\ \frac{\mathrm{lbm}}{\mathrm{min}}\right)\left(1545\ \frac{\mathrm{ft\text{-}lbf}}{\mathrm{lbmol\text{-}^\circ R}}\right)(540^\circ\mathrm{R})}{\left(14.7\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2\left(29\ \frac{\mathrm{lbm}}{\mathrm{lbmol}}\right)} \\ &= 742\ \mathrm{ft}^3/\mathrm{min}\quad \left(740\ \mathrm{ft}^3/\mathrm{min}\right)\end{aligned}$$

The answer is (B).

SI Solution

The absolute temperature for process C is 29°C + 273° = 302K. Using ideal gas laws, the mass flow rate for process C is

$$\begin{aligned}\dot{m}_{\mathrm{C}} &= \frac{p_{\mathrm{C}}\dot{V}_{\mathrm{C}}M}{RT_{\mathrm{C}}} = \frac{(550\ \mathrm{kPa})\left(50\ \frac{\mathrm{L}}{\mathrm{s}}\right)\left(29\ \frac{\mathrm{kg}}{\mathrm{kmol}}\right)}{\left(8.314\ \frac{\mathrm{kJ}}{\mathrm{kmol{\cdot}K}}\right)(302\mathrm{K})\left(1000\ \frac{\mathrm{L}}{\mathrm{m}^3}\right)} \\ &= 0.3173\ \mathrm{kg/s}\end{aligned}$$

The absolute temperature for process D is 27°C + 273° = 300K. Using ideal gas laws, the mass flow rate for process D is

$$\begin{aligned}\dot{m}_{\mathrm{D}} &= \frac{p_{\mathrm{D}}\dot{V}_{\mathrm{D}}M}{RT_{\mathrm{D}}} = \frac{(590\ \mathrm{kPa})\left(60\ \frac{\mathrm{L}}{\mathrm{s}}\right)\left(29\ \frac{\mathrm{kg}}{\mathrm{kmol}}\right)}{\left(8.314\ \frac{\mathrm{kJ}}{\mathrm{kmol{\cdot}K}}\right)(300\mathrm{K})\left(1000\ \frac{\mathrm{L}}{\mathrm{m}^3}\right)} \\ &= 0.4111\ \mathrm{kg/s}\end{aligned}$$

For process E, the mass flow rate is given as $\dot{m}_{\mathrm{E}} = 0.06\ \mathrm{kg/s}$.

The total mass flow rate for all three processes is

$$\begin{aligned}\dot{m}_{\text{total}} &= \dot{m}_{\text{C}} + \dot{m}_{\text{D}} + \dot{m}_{\text{E}} \\ &= 0.3173\ \frac{\text{kg}}{\text{s}} + 0.4111\ \frac{\text{kg}}{\text{s}} + 0.06\ \frac{\text{kg}}{\text{s}} \\ &= 0.7884\ \text{kg/s}\end{aligned}$$

The absolute temperature for air into compressors A and B is 27°C + 273° = 300K.

The mass flow rate into compressor A is

$$\begin{aligned}\dot{m}_{\text{A}} &= \frac{p_{\text{A}}\dot{V}_{\text{A}}M}{RT_{\text{A}}} = \frac{(101.3\ \text{kPa})\left(300\frac{\text{L}}{\text{s}}\right)\left(29\ \frac{\text{kg}}{\text{kmol}}\right)}{\left(8.314\ \frac{\text{kJ}}{\text{kmol·K}}\right)(300\text{K})\left(1000\ \frac{\text{L}}{\text{m}^3}\right)} \\ &= 0.3530\ \text{kg/s}\end{aligned}$$

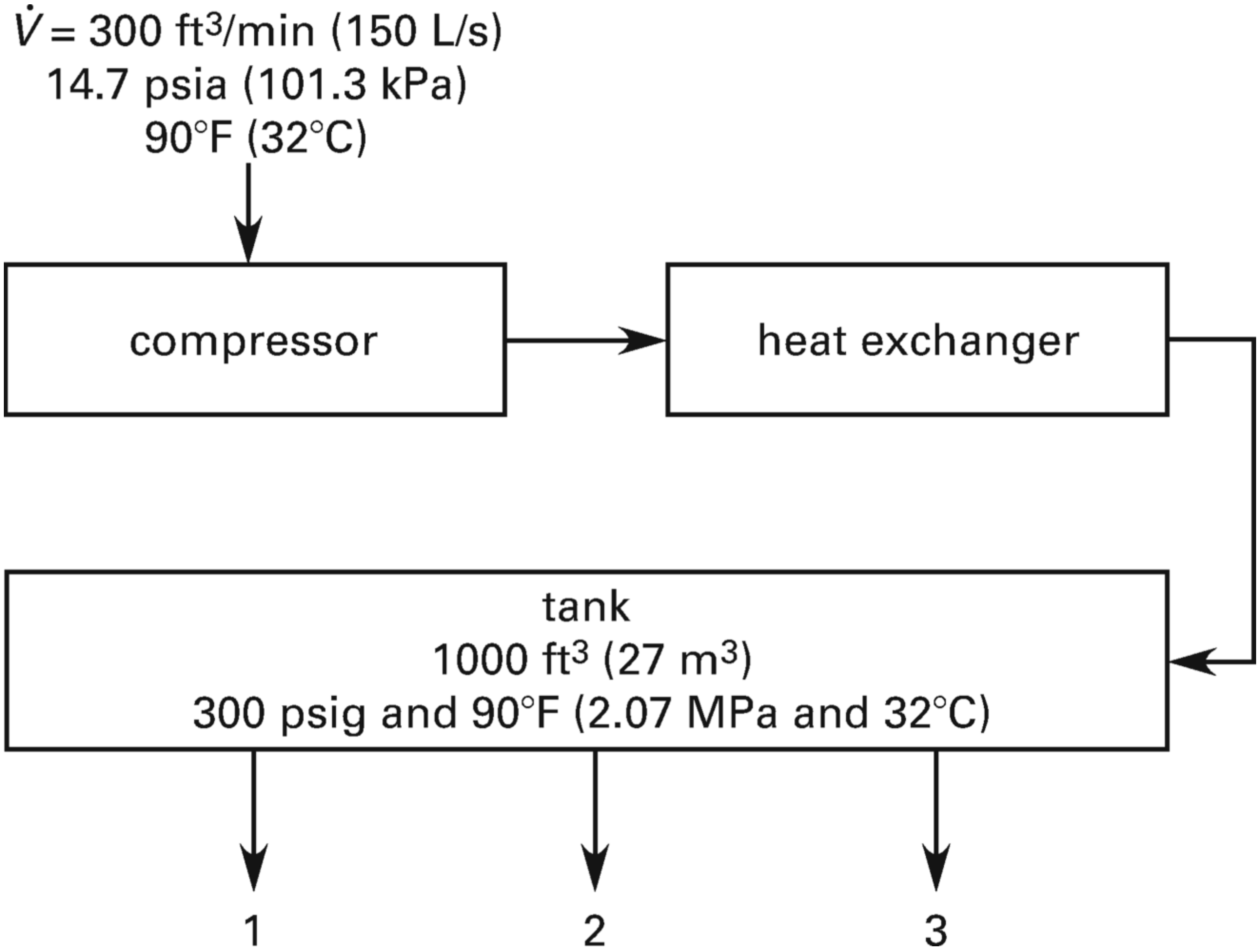
The required input for compressor B is

$$\begin{aligned}\dot{m}_{\text{B}} &= \dot{m}_{\text{total}} - \dot{m}_{\text{A}} \\ &= 0.7884\ \frac{\text{kg}}{\text{s}} - 0.3530\ \frac{\text{kg}}{\text{s}} \\ &= 0.4354\ \text{kg/s}\end{aligned}$$

The volumetric flow rate for compressor B is

$$\begin{aligned}\dot{V}_{\text{B}} &= \frac{\dot{m}_{\text{B}}RT_{\text{B}}}{p_{\text{A}}M} = \frac{\left(0.4354\ \frac{\text{kg}}{\text{s}}\right)\left(8.314\ \frac{\text{kJ}}{\text{kmol·K}}\right)(300\text{K})}{(101.3\ \text{kPa})\left(29\ \frac{\text{kg}}{\text{kmol}}\right)} \\ &= 370\ \text{L/s}\end{aligned}$$

The answer is (B).
4.



Customary U.S. Solution

Assume steady flow and constant properties.

As in *NCEES Handbook* table "Conversion Table for Temperature Units," the absolute temperature for compressor air is 90°F + 460° = 550°R. Using ideal gas laws, the mass flow rate of air into the compressor is

$$\begin{aligned}\dot{m} &= \frac{p\dot{V}M}{RT} \\ &= \frac{\left(14.7\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2\left(300\ \frac{\text{ft}^3}{\text{min}}\right)\left(29\ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(550^\circ\text{R})} \\ &= 21.7\ \text{lbm/min}\end{aligned}$$

As in *NCEES Handbook* table "Conversion Table for Temperature Units," the absolute temperature and absolute pressure of stored compressed air are

$$\begin{aligned}T &= 90^\circ\text{F} + 460^\circ \\ &= 550^\circ\text{R} \\ p &= 300\ \text{psig} + 14.7\ \text{psia} \\ &= 314.7\ \text{psia}\end{aligned}$$

The mass of stored compressed air in a 1000 ft^3 tank is

$$\begin{aligned}m &= \frac{pVM}{RT} \\ &= \frac{\left(314.7\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2\left(1000\ \text{ft}^3\right)\left(29\ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(550^\circ\text{R})} \\ &= 1545.9\ \text{lbm}\end{aligned}$$

Assuming that each tool operates at its minimum pressure, the mass leaving the system can be calculated as follows.

Tool 1:

The absolute pressure is

$$90 \text{ psig} + 14.7 \text{ psia} = 104.7 \text{ psia}$$

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

$$90^\circ\text{F} + 460^\circ = 550^\circ\text{R}$$

$$\begin{aligned} \dot{m}_{\text{tool 1}} &= \frac{p\dot{V}M}{RT} \\ &= \frac{\left(104.7 \ \frac{\text{lbf}}{\text{in}^2}\right)\left(12 \ \frac{\text{in}}{\text{ft}}\right)^2\left(40 \ \frac{\text{ft}^3}{\text{min}}\right)\left(29 \ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545 \ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(550^\circ\text{R})} \\ &= 20.57 \text{ lbm/min} \end{aligned}$$

Tool 2:

The absolute pressure is

$$50 \text{ psig} + 14.7 \text{ psia} = 64.7 \text{ psia}$$

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

$$85^\circ\text{F} + 460^\circ = 545^\circ\text{R}$$

$$\begin{aligned} \dot{m}_{\text{tool 2}} &= \frac{p\dot{V}M}{RT} \\ &= \frac{\left(64.7 \ \frac{\text{lbf}}{\text{in}^2}\right)\left(12 \ \frac{\text{in}}{\text{ft}}\right)^2\left(15 \ \frac{\text{ft}^3}{\text{min}}\right)\left(29 \ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545 \ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(545^\circ\text{R})} \\ &= 4.81 \text{ lbm/min} \end{aligned}$$

Tool 3:

$$\dot{m}_{\text{tool 3}} = 6 \text{ lbm/min} \quad \text{[given]}$$

The total mass flow leaving the system is

$$\begin{aligned} \dot{m}_{\text{total}} &= \dot{m}_{\text{tool 1}} + \dot{m}_{\text{tool 2}} + \dot{m}_{\text{tool 3}} \\ &= 20.57 \ \frac{\text{lbm}}{\text{min}} + 4.81 \ \frac{\text{lbm}}{\text{min}} + 6 \ \frac{\text{lbm}}{\text{min}} \\ &= 31.38 \text{ lbm/min} \end{aligned}$$

The critical pressure of 104.7 psia is required for tool 1 operation. The mass in the tank when critical pressure is achieved is

$$\begin{aligned} m_{\text{tank critical}} &= \frac{pVM}{RT} \\ &= \frac{\left(104.7 \ \frac{\text{lbf}}{\text{in}^2}\right)\left(12 \ \frac{\text{in}}{\text{ft}}\right)^2\left(1000 \text{ ft}^3\right)\left(29 \ \frac{\text{lbm}}{\text{lbmol}}\right)}{\left(1545 \ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}\right)(550^\circ\text{R})} \\ &= 514.3 \text{ lbm} \end{aligned}$$

The amount in the tank to be depleted is

$$\begin{aligned} m_{\text{depleted}} &= m_{\text{tank}} - m_{\text{tank,critical}} = 1545.9 \text{ lbm} - 514.3 \text{ lbm} \\ &= 1031.6 \text{ lbm} \end{aligned}$$

The net flow rate of air to the tank is

$$\begin{aligned}\dot{m}_{\text{net}} &= \dot{m}_{\text{in}} - \dot{m}_{\text{out}}\\ &= 21.7\ \frac{\text{lbm}}{\text{min}} - 31.38\ \frac{\text{lbm}}{\text{min}}\\ &= -9.68\ \text{lbm/min}\end{aligned}$$

The time the system can run is

$$\begin{aligned}\frac{m_{\text{depleted}}}{\dot{m}_{\text{net}}} &= \frac{1031.6\ \text{lbm}}{9.68\ \frac{\text{lbm}}{\text{min}}}\\ &= 106.6\ \text{min} \quad (1.8\ \text{hr})\end{aligned}$$

The answer is (B).

SI Solution

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

$$32^\circ\text{C} + 273^\circ = 305\text{K}$$

Using ideal gas laws, the mass flow rate of air into the compressor is

$$\begin{aligned}\dot{m} &= \frac{p\dot{V}M}{RT} = \frac{(101.3\ \text{kPa})\left(150\ \frac{\text{L}}{\text{s}}\right)\left(29\ \frac{\text{kg}}{\text{kmol}}\right)}{\left(8.314\ \frac{\text{kJ}}{\text{kmol·K}}\right)(305\text{K})\left(1000\ \frac{\text{L}}{\text{m}^3}\right)}\\ &= 0.1736\ \text{kg/s}\end{aligned}$$

As in *NCEES Handbook* table "Conversion Table for Temperature Units," the absolute temperature and pressure of stored compressed air are

$$\begin{aligned}T &= 32^\circ\text{C} + 273^\circ = 305\text{K}\\ p &= (2.07\ \text{MPa})\left(10^6\ \frac{\text{Pa}}{\text{MPa}}\right)\\ &= 2.07\times10^6\ \text{Pa}\end{aligned}$$

The mass of stored compressed air in a 1000 ft^3 tank is

$$\begin{aligned}m_{\text{tank}} &= \frac{pVM}{RT}\\ &= \frac{(2.07\times10^6\ \text{Pa})(27\ \text{m}^3)\left(29\ \frac{\text{kg}}{\text{kmol}}\right)}{\left(8.314\ \frac{\text{kJ}}{\text{kmol·K}}\right)(305\text{K})}\\ &= 639.1\ \text{kg}\end{aligned}$$

Assuming that each tool operates at its minimum pressure, the mass leaving the system can be calculated as follows.

Tool 1:

As in *NCEES Handbook* table "Conversion Table for Temperature Units," the absolute temperature is 32°C + 273° = 305K.

$$\begin{aligned}\dot{m}_{\text{tool 1}} &= \frac{p\dot{V}M}{RT}\\ &= \frac{(620\ \text{kPa})\left(19\ \frac{\text{L}}{\text{s}}\right)\left(29\ \frac{\text{kg}}{\text{kmol}}\right)}{\left(8.314\ \frac{\text{kJ}}{\text{kmol·K}}\right)(305\text{K})\left(1000\ \frac{\text{L}}{\text{m}^3}\right)}\\ &= 0.1346\ \text{kg/s}\end{aligned}$$

Tool 2:

As in *NCEES Handbook* table “Conversion Table for Temperature Units,” the absolute temperature is 29°C + 273° = 302K.

$$\begin{aligned}
\dot{m}_{\text{tool 2}} &= \frac{p\dot{V}}{RT} \\
&= \frac{(350\ \text{kPa})\left(1000\ \frac{\text{Pa}}{\text{kPa}}\right)\left(7\ \frac{\text{L}}{\text{s}}\right)}{\left(287\ \frac{\text{J}}{\text{kg·K}}\right)(302\text{K})\left(1000\ \frac{\text{L}}{\text{m}^3}\right)} \\
&= 0.02827\ \text{kg/s}
\end{aligned}$$

Tool 3:

$$\dot{m}_{\text{tool 3}} = 0.045\ \text{kg/s} \quad [\text{given}]$$

The total mass flow rate leaving the system is

$$\begin{aligned}
\dot{m}_{\text{total}} &= \dot{m}_{\text{tool 1}} + \dot{m}_{\text{tool 2}} + \dot{m}_{\text{tool 3}} \\
&= 0.1346\ \frac{\text{kg}}{\text{s}} + 0.02827\ \frac{\text{kg}}{\text{s}} + 0.045\ \frac{\text{kg}}{\text{s}} \\
&= 0.2079\ \text{kg/s}
\end{aligned}$$

The critical pressure of 620 kPa is required for tool 1 operation. The mass in the tank when critical pressure is achieved is

$$\begin{aligned}
m_{\text{tank critical}} &= \frac{pVM}{RT} = \frac{(620\ \text{kPa})(27\ \text{m}^3)\left(29\ \frac{\text{kg}}{\text{kmol}}\right)}{\left(8.314\ \frac{\text{kJ}}{\text{kmol·K}}\right)(305\text{K})} \\
&= 191.2\ \text{kg}
\end{aligned}$$

The amount in the tank to be depleted is

$$\begin{aligned}
m_{\text{depleted}} &= m_{\text{tank}} - m_{\text{tank,critical}} = 638.5\ \text{kg} - 191.2\ \text{kg} \\
&= 447.3\ \text{kg}
\end{aligned}$$

The net flow rate of air into the tank is

$$\begin{aligned}
\dot{m}_{\text{net}} &= \dot{m}_{\text{in}} - \dot{m}_{\text{out}} = 0.1736\ \frac{\text{kg}}{\text{s}} - 0.2079\ \frac{\text{kg}}{\text{s}} \\
&= -0.0343\ \text{kg/s}
\end{aligned}$$

The time the system can run is

$$\frac{m_{\text{depleted}}}{\dot{m}_{\text{net}}} = \frac{447.3\ \text{kg}}{0.0343\ \frac{\text{kg}}{\text{s}}} = 13\,041\ \text{s} \quad (3.6\ \text{h})$$

The answer is (B).