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Chapter 16. Refrigeration Cycles

Practice Problems

1.

A heat pump operates on the Carnot cycle between 40°F and 700°F (4°C and 370°C). The coefficient of performance is most nearly

(A)

1.5

(B)

1.8

(C)

2.2

(D)

2.7

2.

A refrigerator uses refrigerant R-12. The input power is 585 W. Heat absorbed from the cooled space is 450 Btu/hr (0.13 kW). The coefficient of performance is most nearly

(A)

0.2

(B)

0.4

(C)

0.7

(D)

0.9

3.

Ammonia is used in a reversed Carnot cycle refrigerator with reservoirs at 110°F (45°C) and 10°F (−10°C). 1000 Btu/hr (1000 kJ/h) are to be removed. The rejected heat is most nearly

(A)

1000 Btu/hr (1000 kJ/h)

(B)

1200 Btu/hr (1200 kJ/h)

(C)

1400 Btu/hr (1400 kJ/h)

(D)

1600 Btu/hr (1600 kJ/h)
4.

A refrigerator cools a continuous aqueous solution (c_p = 1 Btu/lbm-°F; 4.19 kJ/kg·°C) flow of 100 gal/min (0.4 m^3/min) from 80°F (25°C) to 20°F (−5°C) in an 80°F (25°C) environment. The minimum power requirement is most nearly

(A)

82 hp (63 kW)

(B)

100 hp (74 kW)

(C)

130 hp (90 kW)

(D)

150 hp (94 kW)
5.

An air refrigeration cycle compresses air from 70°F (20°C) and 14.7 psia (101 kPa) to 60 psia (400 kPa) in a 70% efficient compressor. The air is cooled to 25°F (−4.0°C) in a constant pressure process before entering a turbine with isentropic efficiency of 0.80. Assume air is an ideal gas. The coefficient of performance of the cycle is most nearly

(A)

0.7

(B)

0.8

(C)

0.9

(D)

1.1

Solutions

1.

Customary U.S. Solution

The coefficient of performance for a heat pump operating on the Carnot cycle is given by equationMERM33009 (also *NCEES Handbook:* Power Cycles).

$$\text{COP}_{\text{heat pump}} = \frac{T_{\text{high}}}{T_{\text{high}} - T_{\text{low}}}$$

The absolute temperatures (see also *NCEES Handbook:* Temperature) are

$$\begin{aligned} T_{\text{high}} &= 700^{\circ}\text{F} + 460^{\circ} = 1160^{\circ}\text{R} \\ T_{\text{low}} &= 40^{\circ}\text{F} + 460^{\circ} = 500^{\circ}\text{R} \\ \text{COP}_{\text{heat pump}} &= \frac{1160^{\circ}\text{R}}{1160^{\circ}\text{R} - 500^{\circ}\text{R}} \\ &= 1.76 \quad (1.8) \end{aligned}$$

The answer is (B).

SI Solution

The coefficient of performance for a heat pump operating on the Carnot cycle is given by equationMERM33009 (also *NCEES Handbook:* Power Cycles).

$$\text{COP}_{\text{heat pump}} = \frac{T_{\text{high}}}{T_{\text{high}} - T_{\text{low}}}$$

The absolute temperatures (see also *NCEES Handbook:* Temperature) are

$$\begin{aligned} T_{\text{high}} &= 370^{\circ}\text{C} + 273^{\circ} = 643\text{K} \\ T_{\text{low}} &= 4^{\circ}\text{C} + 273^{\circ} = 277\text{K} \\ \text{COP}_{\text{heat pump}} &= \frac{643\text{K}}{643\text{K} - 277\text{K}} \\ &= 1.76 \quad (1.8) \end{aligned}$$

The answer is (B).
2.

Customary U.S. Solution

The coefficient of performance for a refrigerator is given by equationMERM33001 (also *NCEES Handbook:* Power Cycles).

$$\begin{aligned} \text{COP}_{\text{refrigerator}} &= \frac{Q_{\text{in}}}{W_{\text{in}}} = \frac{450\ \frac{\text{Btu}}{\text{hr}}}{(585\ \text{W})\left(3.4121\ \frac{\frac{\text{Btu}}{\text{hr}}}{\text{W}}\right)} \\ &= 0.225 \quad (0.2) \end{aligned}$$

The answer is (A).

SI Solution

The coefficient of performance for a refrigerator is given by equationMERM33001 (also *NCEES Handbook:* Power Cycles).

$$\begin{aligned} \text{COP}_{\text{refrigerator}} &= \frac{Q_{\text{in}}}{W_{\text{in}}} = \frac{(0.13\ \text{kW})\left(1000\ \frac{\text{W}}{\text{kW}}\right)}{585\ \text{W}} \\ &= 0.222 \quad (0.2) \end{aligned}$$

The answer is (A).

3.

Customary U.S. Solution

Absolute temperature is

$$\begin{aligned} T_H &= 110\ ^{\circ}\mathrm{F} + 459.67 \\ &= 569.67\ ^{\circ}\mathrm{R} \\ T_C &= 10\ ^{\circ}\mathrm{F} + 459.67 \\ &= 469.67\ ^{\circ}\mathrm{R} \end{aligned}$$

As in the *NCEES* Handbook: section titled "Power Cycles - Refrigeration Cycles," the coefficient of performance is

$$\begin{aligned} COP_{\mathrm{R,\ Carnot}} &= \frac{1}{\left(T_H/T_C\right)-1} \\ &= \frac{1}{\left(569.67\ ^{\circ}\mathrm{R}/469.67\ ^{\circ}\mathrm{R}\right)-1} \\ &= 4.7 \end{aligned}$$

The work input is

$$\begin{aligned} W_{\mathrm{net,\ in}} &= \frac{Q_C}{\mathrm{COP}_R} = \frac{1000\ \frac{\mathrm{Btu}}{\mathrm{hr}}}{4.7} \\ &= 212.77\ \mathrm{Btu/hr} \end{aligned}$$

The rejected heat is

$$\begin{aligned} Q_{\mathrm{out}} &= Q_C + W_{\mathrm{net,\ in}} = 1000\ \frac{\mathrm{Btu}}{\mathrm{hr}} + 212.77\ \frac{\mathrm{Btu}}{\mathrm{hr}} \\ &= 1212.77\ \mathrm{Btu/hr} \quad (1200\ \mathrm{Btu/hr}) \end{aligned}$$

The answer is (B).

SI Solution

Absolute temperature is

$$\begin{aligned} T_H &= 45\ ^{\circ}\mathrm{C} + 273.15 \\ &= 318.15\ \mathrm{K} \\ T_C &= -10\ ^{\circ}\mathrm{C} + 273.15 \\ &= 263.15\ \mathrm{K} \end{aligned}$$

As in the *NCEES Handbook:* section titled "Power Cycles - Refrigeration Cycles," the coefficient of performance is

$$\begin{aligned} COP_{\mathrm{R,\ Carnot}} &= \frac{1}{\left(T_H/T_C\right)-1} \\ &= \frac{1}{\left(318.15\ \mathrm{K}/263.15\ \mathrm{K}\right)-1} \\ &= 4.785 \end{aligned}$$

The work input is

$$\begin{aligned} W_{\mathrm{net,\ in}} &= \frac{Q_C}{\mathrm{COP}_R} = \frac{1000\ \frac{\mathrm{kJ}}{\mathrm{h}}}{4.785} \\ &= 208.99\ \mathrm{kJ/h} \end{aligned}$$

The rejected heat is

$$\begin{aligned} Q_{\mathrm{out}} &= Q_C + W_{\mathrm{net,\ in}} = 1000\ \frac{\mathrm{kJ}}{\mathrm{h}} + 208.99\ \frac{\mathrm{kJ}}{\mathrm{h}} \\ &= 1208.99\ \mathrm{kJ/h} \quad (1200\ \mathrm{kJ/h}) \end{aligned}$$

The answer is (B).

4.

Customary U.S. Solution

The density of an aqueous solution is essentially the same as water.

$$\begin{aligned}\dot{m} &= \dot{V}\rho = \left(100\ \frac{\text{gal}}{\text{min}}\right)\left(0.1337\ \frac{\text{ft}^3}{\text{gal}}\right)\left(62.4\ \frac{\text{lbm}}{\text{ft}^3}\right)\\ &= 834.3\ \text{lbm/min}\end{aligned}$$

$$\begin{aligned}\dot{Q}_{\text{in}} &= \dot{m}c_p\Delta T\\ &= \left(834.3\ \frac{\text{lbm}}{\text{min}}\right)\left(1\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)(80^\circ\text{F} - 20^\circ\text{F})\\ &= 50{,}058\ \text{Btu/min}\end{aligned}$$

$$\begin{aligned}\dot{Q}_{\text{in, ton refrigeration}} &= \left(50{,}058\ \frac{\text{Btu}}{\text{min}}\right)\left(\frac{60\ \text{min}}{1\ \text{hr}}\right)\left(\frac{1\ \text{ton refrigeration}}{1.2\times 10^4\ \frac{\text{Btu}}{\text{hr}}}\right)\\ &= 250.29\ \text{ton refrigeration}\end{aligned}$$

As in the *NCEES Handbook* section titled “Power Cycles,” the coefficient of performance is

$$\text{COP} = \frac{T_{\text{low}}}{T_{\text{high}} - T_{\text{low}}} = \frac{20^\circ\text{F} + 460^\circ}{80^\circ\text{F} - 20^\circ\text{F}} = 8$$

$$\begin{aligned}W_{\text{in, hp}} &= \frac{\left(\frac{4.7141\ \text{hp}}{1\ \text{ton refrigeration}}\right)\dot{Q}_{\text{in, ton refrigeration}}}{COP}\\ &= \frac{\left(\frac{4.7141\ \text{hp}}{1\ \text{ton refrigeration}}\right)(250.29\ \text{ton refrigeration})}{8}\\ &= 147.5\ \text{hp}\quad (150\ \text{hp})\end{aligned}$$

The answer is (D).

SI Solution

The density of an aqueous solution is essentially the same as water.

$$\begin{aligned}\dot{m} &= \dot{V}\rho = \left(0.4\ \frac{\text{m}^3}{\text{min}}\right)\left(1000\ \frac{\text{kg}}{\text{m}^3}\right)\\ &= 400\ \text{kg/min}\\ \dot{Q}_{\text{in}} &= \dot{m}c_p\Delta T\\ &= \left(400\ \frac{\text{kg}}{\text{min}}\right)\left(4.19\ \frac{\text{kJ}}{\text{kg}\cdot{}^\circ\text{C}}\right)\big(25^\circ\text{C} - (-5^\circ\text{C})\big)\\ &= 50\,280\ \text{kJ/min}\end{aligned}$$

As in the *NCEES Handbook:* section titled “Power Cycles,” the coefficient of performance is

$$\begin{aligned}\text{COP} &= \frac{T_{\text{low}}}{T_{\text{high}} - T_{\text{low}}} = \frac{-5^\circ\text{C} + 273.15^\circ}{25^\circ\text{C} - (-5^\circ\text{C})}\\ &= 8.938\end{aligned}$$

$$\begin{aligned}\dot{W}_{\text{in}} &= \frac{\dot{Q}_{\text{in}}}{\text{COP}} = \frac{50\,280\ \frac{\text{kJ}}{\text{min}}}{(8.938)\left(60\ \frac{\text{s}}{\text{min}}\right)}\\ &= 93.76\ \text{kW}\quad (94\ \text{kW})\end{aligned}$$

The answer is (D).
5.

Customary U.S. Solution

Assuming ideal gas, from *NCEES Handbook:* Closed Thermodynamic Systems,

$$\frac{T_\mathrm{D}}{T_\mathrm{C}} = \left(\frac{p_\mathrm{high}}{p_\mathrm{low}}\right)^{(k-1)/k}$$

For air, $k = 1.4$.

$$\begin{aligned} T_\mathrm{D} &= T_\mathrm{C}\left(\frac{60\ \mathrm{psia}}{14.7\ \mathrm{psia}}\right)^{(1.4-1)/1.4} \\ &= (70^\circ\mathrm{F} + 460^\circ)(1.495) \\ &= 792.1^\circ\mathrm{R} \end{aligned}$$

As in *NCEES Handook*: Open Thermodynamic Systems, the temperature leaving the compressor if the process is not isentropic is

$$\begin{aligned} T'_\mathrm{D} &= T_\mathrm{C} + \frac{T_\mathrm{D} - T_\mathrm{C}}{\eta_\mathrm{compressor}} \\ &= 530^\circ\mathrm{R} + \frac{792.1^\circ\mathrm{R} - 530^\circ\mathrm{R}}{0.7} \\ &= 904.4^\circ\mathrm{R} \end{aligned}$$

From *NCEES Handbook:* Closed Thermodynamic Systems, find the temperature at B.

$$\frac{T_\mathrm{A}}{T_\mathrm{B}} = \left(\frac{p_\mathrm{high}}{p_\mathrm{low}}\right)^{(k-1)/k}$$

$$\begin{aligned} T_\mathrm{B} &= \frac{T_\mathrm{A}}{\left(\frac{p_\mathrm{high}}{p_\mathrm{low}}\right)^{(k-1)/k}} = \frac{25^\circ\mathrm{F} + 460^\circ}{\left(\frac{60\ \mathrm{psia}}{14.7\ \mathrm{psia}}\right)^{(1.4-1)/1.4}} \\ &= 324.5^\circ\mathrm{R} \end{aligned}$$

As in *NCEES Handbook:* Open Thermodynamic Systems, the temperature leaving the turbine if the process is not isentropic is

$$\begin{aligned} T'_\mathrm{B} &= T_\mathrm{A} - \eta_\mathrm{turbine}(T_\mathrm{A} - T_\mathrm{B}) \\ &= 485^\circ\mathrm{R} - (0.80)(485^\circ\mathrm{R} - 324.5^\circ\mathrm{R}) \\ &= 356.6^\circ\mathrm{R} \end{aligned}$$

As in *NCEES Handbook:* Power Cycles, the coefficient of performance of the cycle is

$$\begin{aligned} \mathrm{COP} &= \frac{T_\mathrm{C} - T'_\mathrm{B}}{(T'_\mathrm{D} - T_\mathrm{A}) - (T_\mathrm{C} - T'_\mathrm{B})} \\ &= \frac{530^\circ\mathrm{R} - 356.6^\circ\mathrm{R}}{(904.5^\circ\mathrm{R} - 485^\circ\mathrm{R}) - (530^\circ\mathrm{R} - 356.6^\circ\mathrm{R})} \\ &= 0.705 \quad (0.7) \end{aligned}$$

The answer is (A).

SI Solution

From *NCEES Handbook:* Closed Thermodynamic Systems, assuming air is an ideal gas with $k = 1.4$,

$$\frac{T_\mathrm{D}}{T_\mathrm{C}} = \left(\frac{p_\mathrm{high}}{p_\mathrm{low}}\right)^{(k-1)/k}$$

$$
\begin{aligned}
T_{\mathrm{C}} &= 20^{\circ}\mathrm{C} + 273.15^{\circ} = 293.15\mathrm{K} \\
T_{\mathrm{D}} &= T_{\mathrm{C}}\left(\frac{p_{\text{high}}}{p_{\text{low}}}\right)^{(k-1)/k} = (293.15\mathrm{K})\left(\frac{400\ \mathrm{kPa}}{101\ \mathrm{kPa}}\right)^{(1.4-1)/1.4} \\
&= 434.4\mathrm{K}
\end{aligned}
$$

As in *NCEES Handbook:* Open Thermodynamic Systems, the temperature leaving the compressor if the process is not isentropic is

$$
\begin{aligned}
T_{\mathrm{D}}^{'} &= T_{\mathrm{C}} + \frac{T_{\mathrm{D}} - T_{\mathrm{C}}}{\eta_{\text{compressor}}} \\
&= 293.15\mathrm{K} + \frac{434.4\mathrm{K} - 293.15\mathrm{K}}{0.7} \\
&= 494.9\mathrm{K}
\end{aligned}
$$

From *NCEES Handbook:* Closed Thermodynamic Systems, find the temperature at B.

$$
\begin{aligned}
T_{\mathrm{A}} &= -4^{\circ}\mathrm{C} + 273.15^{\circ} = 269.15\mathrm{K} \\
T_{\mathrm{B}} &= \frac{T_{\mathrm{A}}}{\left(\frac{p_{\text{high}}}{p_{\text{low}}}\right)^{(k-1)/k}} = \frac{269.15\mathrm{K}}{\left(\frac{400\ \mathrm{kPa}}{101\ \mathrm{kPa}}\right)^{(1.4-1)/1.4}} \\
&= 181.6\mathrm{K}
\end{aligned}
$$

As in *NCEES Handbook:* Open Thermodynamic Systems, the temperature leaving the turbine if the process is not isentropic is

$$
\begin{aligned}
T_{\mathrm{B}}^{'} &= T_{\mathrm{A}} - \eta_{\text{turbine}}\left(T_{\mathrm{A}} - T_{\mathrm{B}}\right) \\
&= 269.15\mathrm{K} - (0.80)(269.15\mathrm{K} - 181.6\mathrm{K}) \\
&= 199.1\mathrm{K}
\end{aligned}
$$

As in *NCEES Handbook:* Power Cycles, the coefficient of performance of the cycle is

$$
\begin{aligned}
\mathrm{COP} &= \frac{T_{\mathrm{C}} - T_{\mathrm{B}}^{'}}{(T_{\mathrm{D}}^{'} - T_{\mathrm{A}}) - (T_{\mathrm{C}} - T_{\mathrm{B}}^{'})} \\
&= \frac{293.15\mathrm{K} - 199.1\mathrm{K}}{(494.9\mathrm{K} - 269.15\mathrm{K}) - (293.15\mathrm{K} - 199.1\mathrm{K})} \\
&= 0.714 \quad (0.7)
\end{aligned}
$$

The answer is (A).