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Chapter 13. Vapor Power Cycles

Practice Problems

1.

An air combustion cycle operates between 650°F and 100°F (340°C and 38°C). The maximum possible thermal efficiency is most nearly

(A)

42%

(B)

49%

(C)

54%

(D)

58%

2.

A steam Carnot cycle operates between 650°F and 100°F (340°C and 38°C). The turbine and compressor (pump) isentropic efficiencies are 90% and 80%, respectively. The thermal efficiency is most nearly

(A)

32%

(B)

37%

(C)

42%

(D)

48%

3.

A steam turbine cycle produces 600 MWe (mega-watts of electrical power). The condenser load is 3.07×10^9 Btu/hr (900 MW). The thermal efficiency is most nearly

(A)

32%

(B)

37%

(C)

40%

(D)

44%
4.

A steam Rankine cycle operates with 100 psia (700 kPa) saturated steam that is reduced to 1 atm through expansion in a turbine with an isentropic efficiency of 80%. There is significant subcooling, and water is at 80°F (27°C) and 1 atm when it enters the boilerfeed pump. The pump's isentropic efficiency is 60%. The cycle's thermal efficiency is most nearly

(A)

10%

(B)

14%

(C)

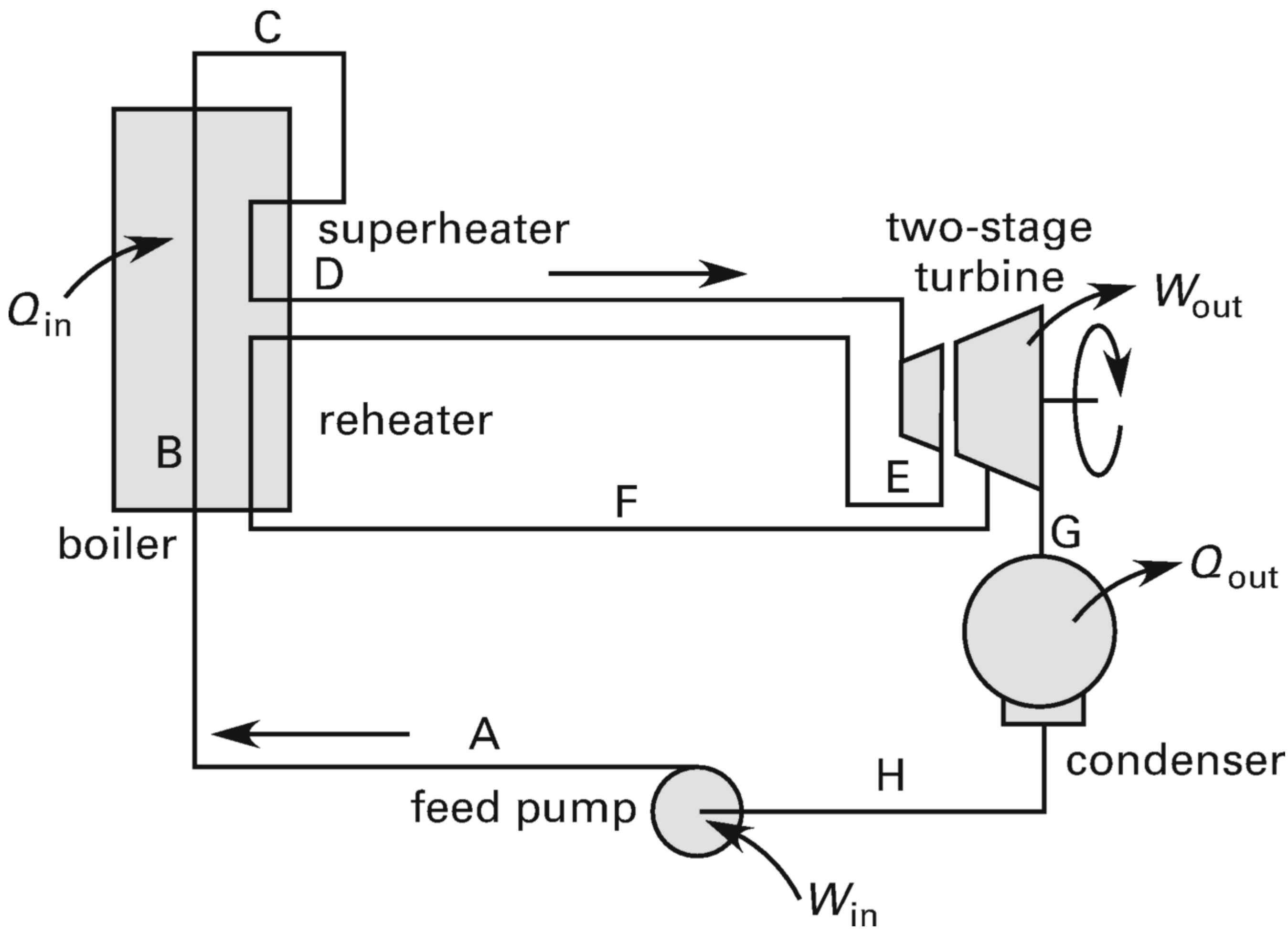
21%

(D)

26%

5.

A turbine and the boilerfeed pumps in a reheat cycle have isentropic efficiencies of 88% and 96%, respectively. The cycle starts with water at 60°F (16°C) at the entrance to the boilerfeed pump and produces 600°F (300°C), 600 psia (4 MPa) steam. The steam is reheated when its pressure drops during the first expansion to 20 psia (150 kPa).



The thermal efficiency of the cycle is most nearly

(A)

28%

(B)

34%

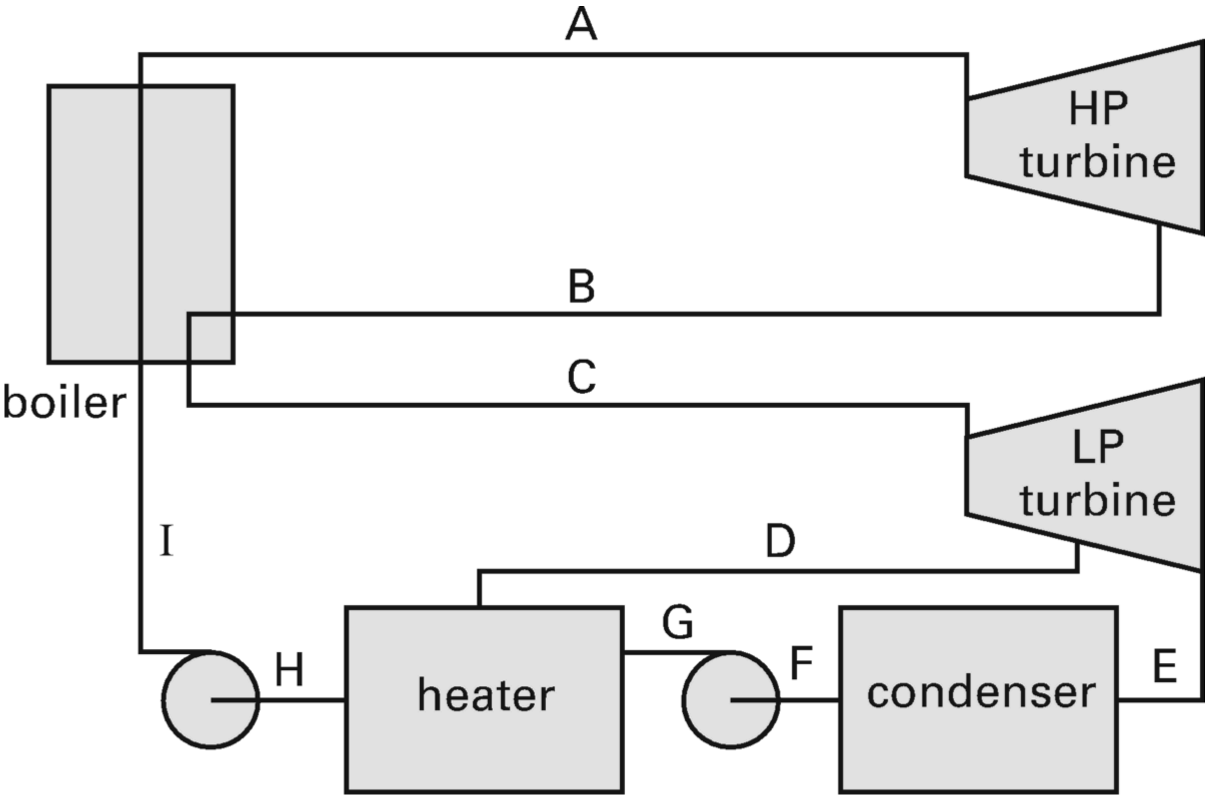
(C)

39%

(D)

42%
6.

A reheat steam cycle operates as shown. The pump work between points F and G is 0.15 Btu/lbm (0.3 kJ/kg).



At A:	900 psia (6.2 MPa)800°F (420°C)
At B:	200 psia (1.5 MPa)1270 Btu/lbm (2960 kJ/kg)
At C:	190 psia (1.4 MPa)800°F (420°C)
At D:	50 psia (350 kPa)1280 Btu/lbm (2980 kJ/kg)
At E:	2 in Hg absolute (6.8 kPa)1075 Btu/lbm (2500 kJ/kg)
At F:	69.73 Btu/lbm (162.5 kJ/kg)
At H:	250.2 Btu/lbm (583.0 kJ/kg)0.0173 ft^3/lbm (0.0011 m^3/kg)
At I:	253.1 Btu/lbm (589.7 kJ/kg)

The thermal efficiency of the cycle is most nearly

(A)

22%

(B)

29%

(C)

34%

(D)

41%

Solutions

1.

Customary U.S. Solution

As in the *NCEES Handbook:* section titled “Temperature,” the absolute temperatures are

$$\begin{aligned} T_{\text{high}} &= 650^\circ\text{F} + 460^\circ = 1110^\circ\text{R} \\ T_{\text{low}} &= 100^\circ\text{F} + 460^\circ = 560^\circ\text{R} \end{aligned}$$

The maximum possible thermal efficiency is given by the Carnot cycle. From equationMERM28008 (also the *NCEES Handbook:* section titled “Gas Power Cycles”),

$$\begin{aligned} \eta_{\text{th}} &= \frac{T_{\text{high}} - T_{\text{low}}}{T_{\text{high}}} \\ &= \frac{1110^\circ\text{R} - 560^\circ\text{R}}{1110^\circ\text{R}} \\ &= 0.495 \quad (49\%) \end{aligned}$$

The answer is (B).

SI Solution

As in the *NCEES Handbook:* section titled “Temperature”), the absolute temperatures are

$$\begin{aligned} T_{\text{high}} &= 340^\circ\text{C} + 273^\circ = 613\text{K} \\ T_{\text{low}} &= 38^\circ\text{C} + 273^\circ = 311\text{K} \end{aligned}$$

The maximum possible thermal efficiency is given by the Carnot cycle. From equationMERM28008 (also the *NCEES Handbook*: section titled “Gas Power Cycles”),

$$\begin{aligned} \eta_{\text{th}} &= \frac{T_{\text{high}} - T_{\text{low}}}{T_{\text{high}}} = \frac{613\text{K} - 311\text{K}}{613\text{K}} \\ &= 0.493 \quad (49\%) \end{aligned}$$

The answer is (B).
2.

Customary U.S. Solution

Refer to the Carnot cycle (see figureMERM28002 and *NCEES Handbook:* Power Cycles).

At point A, from appendixMERM24A (also *NCEES Handbook* table “Saturated Steam (U.S. Units)—Temperature Table”), for saturated liquid at T_A = 650°F,

$$\begin{aligned} h_{\text{A}} &= 696.0 \text{ Btu/lbm} \\ s_{\text{A}} &= 0.8833 \text{ Btu/lbm-}^\circ\text{F} \end{aligned}$$

At point B, from appendixMERM24A, for saturated vapor at T_B = 650°F,

$$\begin{aligned} h_{\text{B}} &= 1119.7 \text{ Btu/lbm} \\ s_{\text{B}} &= 1.2651 \text{ Btu/lbm-}^\circ\text{F} \end{aligned}$$

At point C,

$$\begin{aligned} T_{\text{C}} &= 100^\circ\text{F} \\ s_{\text{C}} &= s_{\text{B}} \\ &= 1.2651 \text{ Btu/lbm-}^\circ\text{F} \end{aligned}$$

From appendixMERM24A,

$$\begin{aligned} s_f &= 0.1296 \text{ Btu/lbm-}^\circ\text{F} \\ s_g &= 1.9819 \text{ Btu/lbm-}^\circ\text{F} \\ h_f &= 68.03 \text{ Btu/lbm} \\ h_{fg} &= 1036.7 \text{ Btu/lbm} \end{aligned}$$

As in *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems, the quality of the system at point C is

$$
\begin{aligned}
x_{\mathrm{C}} &= \frac{s_{\mathrm{C}} - s_f}{s_g - s_f} = \frac{1.2651\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{F}} - 0.1296\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{F}}}{1.9819\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{F}} - 0.1296\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{F}}} \\
&= 0.613
\end{aligned}
$$

The specific enthalpy of the system at point C is

$$
\begin{aligned}
h_{\mathrm{C}} &= h_f + x_{\mathrm{C}} h_{fg} \\
&= 68.03\ \frac{\mathrm{Btu}}{\mathrm{lbm}} + (0.613)\left(1036.7\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\
&= 703.5\ \mathrm{Btu/lbm}
\end{aligned}
$$

At point D,

$$
\begin{aligned}
T_{\mathrm{D}} &= 100^\circ\mathrm{F} \\
s_{\mathrm{D}} &= s_{\mathrm{A}} = 0.8833\ \mathrm{Btu/lbm\text{-}^\circ F}
\end{aligned}
$$

As in *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems, the quality of the system at point D is

$$
\begin{aligned}
x_{\mathrm{D}} &= \frac{s_{\mathrm{D}} - s_f}{s_g - s_f} = \frac{0.8833\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{F}} - 0.1296\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{F}}}{1.9819\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{F}} - 0.1296\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{F}}} \\
&= 0.407
\end{aligned}
$$

The specific enthalpy of the system at point D is

$$
\begin{aligned}
h_{\mathrm{D}} &= h_f + x_{\mathrm{D}} h_{fg} \\
&= 68.03\ \frac{\mathrm{Btu}}{\mathrm{lbm}} + (0.407)\left(1036.7\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\
&= 489.8\ \mathrm{Btu/lbm}
\end{aligned}
$$

From equationMERM28009 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the turbine,

$$
\begin{aligned}
h_{\mathrm{C}}' &= h_{\mathrm{B}} - \eta_{s,\mathrm{turbine}}\left(h_{\mathrm{B}} - h_{\mathrm{C}}\right) \\
&= 1119.7\ \frac{\mathrm{Btu}}{\mathrm{lbm}} \\
&\qquad - (0.9)\left(1119.7\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 703.5\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\
&= 745.1\ \mathrm{Btu/lbm}
\end{aligned}
$$

From equationMERM28010 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the pump,

$$
\begin{aligned}
h_{\mathrm{A}}' &= h_{\mathrm{D}} + \frac{h_{\mathrm{A}} - h_{\mathrm{D}}}{\eta_{s,\mathrm{pump}}} \\
&= 489.8\ \frac{\mathrm{Btu}}{\mathrm{lbm}} \\
&\qquad + \frac{696.0\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}} - 489.8\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}}}{0.8} \\
&= 747.6\ \mathrm{Btu/lbm}
\end{aligned}
$$

From equationMERM28008 (also *NCEES Handbook:* Power Cycles), the thermal efficiency of the entire cycle is

$$
\begin{aligned}
\eta_{\mathrm{th}} &= \frac{(h_{\mathrm{B}}-h_{\mathrm{C}}^{'})-(h_{\mathrm{A}}^{'}-h_{\mathrm{D}})}{h_{\mathrm{B}}-h_{\mathrm{A}}^{'}} \\
&= \frac{\begin{array}{c}\left(1119.7\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}}-745.1\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}}\right)\\ -\left(747.6\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}}-489.8\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}}\right)\end{array}}{1119.7\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}}-747.6\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}}} \\
&= 0.314 \quad (32\%)
\end{aligned}
$$

The answer is (A).

SI Solution

At point A, $T_{\mathrm{A}} = 340°\mathrm{C}$.

From appendixMERM24N (also *NCEES Handbook* table “Saturated Steam (U.S. Units)—Temperature Table”), for saturated liquid,

$$
\begin{aligned}
h_{\mathrm{A}} &= 1594.5\ \mathrm{kJ/kg} \\
s_{\mathrm{A}} &= 3.6601\ \mathrm{kJ/kg\cdot K}
\end{aligned}
$$

At point B, $T_{\mathrm{B}} = 340°\mathrm{C}$.

From appendixMERM24N, for saturated vapor,

$$
\begin{aligned}
h_{\mathrm{B}} &= 2621.9\ \mathrm{kJ/kg} \\
s_{\mathrm{B}} &= 5.3356\ \mathrm{kJ/kg\cdot K}
\end{aligned}
$$

At point C,

$$
\begin{aligned}
T_{\mathrm{C}} &= 38^{\circ}\mathrm{C} \\
s_{\mathrm{C}} &= s_{\mathrm{B}} \\
&= 5.3356\ \mathrm{kJ/kg\cdot K}
\end{aligned}
$$

From appendixMERM24N,

$$
\begin{aligned}
s_f &= 0.5456\ \mathrm{kJ/kg\cdot K} \\
s_g &= 8.2935\ \mathrm{kJ/kg\cdot K} \\
h_f &= 159.17\ \mathrm{kJ/kg} \\
h_{fg} &= 2410.7\ \mathrm{kJ/kg}
\end{aligned}
$$

As in *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems, the quality of the system at point C is

$$
\begin{aligned}
x_{\mathrm{C}} &= \frac{s_{\mathrm{C}}-s_f}{s_g-s_f} = \frac{5.3356\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}-0.5456\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}}{8.2935\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}-0.5456\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}} \\
&= 0.618
\end{aligned}
$$

The specific enthalpy of the system at point C is

$$
\begin{aligned}
h_{\mathrm{C}} &= h_f + x_{\mathrm{C}} h_{fg} = 159.17\ \frac{\mathrm{kJ}}{\mathrm{kg}} + (0.618)\left(2410.7\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\
&= 1649.0\ \mathrm{kJ/kg}
\end{aligned}
$$

At point D,

$$
\begin{aligned}
T_{\mathrm{D}} &= 38^{\circ}\mathrm{C} \\
s_{\mathrm{D}} &= s_{\mathrm{A}} = 3.6601\ \mathrm{kJ/kg\cdot K}
\end{aligned}
$$

As in *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems, the quality of the system at point D is

$$x_\mathrm{D} = \frac{s_\mathrm{D} - s_f}{s_g - s_f} = \frac{3.6601\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}} - 0.5456\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}}{8.2935\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}} - 0.5456\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}}$$
$$= 0.402$$

The specific enthalpy of the system at point D is

$$\begin{aligned} h_\mathrm{D} &= h_f + x_\mathrm{D} h_{fg} \\ &= 159.17\ \frac{\mathrm{kJ}}{\mathrm{kg}} + (0.402)\left(2410.7\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\ &= 1128.3\ \mathrm{kJ/kg} \end{aligned}$$

From equationMERM28009 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the turbine,

$$\begin{aligned} h_\mathrm{C}^{'} &= h_\mathrm{B} - \eta_{s,\mathrm{turbine}}\,(h_\mathrm{B} - h_\mathrm{C}) \\ &= 2621.9\ \frac{\mathrm{kJ}}{\mathrm{kg}} - (0.9)\left(2621.9\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 1649.0\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\ &= 1746.3\ \mathrm{kJ/kg} \end{aligned}$$

From equationMERM28010 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the pump,

$$\begin{aligned} h_\mathrm{A}^{'} &= h_\mathrm{D} + \frac{h_\mathrm{A} - h_\mathrm{D}}{\eta_{s,\mathrm{pump}}} \\ &= 1128.3\ \frac{\mathrm{kJ}}{\mathrm{kg}} + \frac{1594.5\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 1128.3\ \frac{\mathrm{kJ}}{\mathrm{kg}}}{0.8} \\ &= 1711.1\ \mathrm{kJ/kg} \end{aligned}$$

From equationMERM28008 (also *NCEES Handbook:* Power Cycles), the thermal efficiency of the entire cycle is

$$\begin{aligned} \eta_\mathrm{th} &= \frac{(h_\mathrm{B} - h_\mathrm{C}^{'}) - (h_\mathrm{A}^{'} - h_\mathrm{D})}{h_\mathrm{B} - h_\mathrm{A}^{'}} \\ &= \frac{\left(2621.9\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 1746.3\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) - \left(1711.1\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 1128.3\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right)}{2621.9\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 1711.1\ \frac{\mathrm{kJ}}{\mathrm{kg}}} \\ &= 0.321 \quad (32\%) \end{aligned}$$

The answer is (A).
3.

Customary U.S. Solution

The condenser load is $Q_\mathrm{out} = 3.07 \times 10^9$ Btu/hr.

The net work is

$$W_\mathrm{net} = Q_\mathrm{in} - Q_\mathrm{out}$$

The boiler load is

$$
\begin{aligned}
Q_{\text{in}} &= W_{\text{net}} + Q_{\text{out}} \\
&= (600\ \text{MW})\left(1000\ \frac{\text{kW}}{\text{MW}}\right)\left(3412\ \frac{\text{Btu}}{\text{kW-hr}}\right) \\
&\qquad +3.07\times 10^9\ \frac{\text{Btu}}{\text{hr}} \\
&= 5.12\times 10^9\ \text{Btu/hr}
\end{aligned}
$$

From equationMERM28001 (also *NCEES Handbook:* Power Cycles), the thermal efficiency is

$$
\begin{aligned}
\eta_{\text{th}} &= \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = \frac{5.12\times 10^9\ \frac{\text{Btu}}{\text{hr}} - 3.07\times 10^9\ \frac{\text{Btu}}{\text{hr}}}{5.12\times 10^9\ \frac{\text{Btu}}{\text{hr}}} \\
&= 0.400 \quad (40\%)
\end{aligned}
$$

The answer is (C).

SI Solution

The condenser load is $Q_{\text{out}} = 900$ MW.

The boiler load is

$$
\begin{aligned}
Q_{\text{in}} &= W_{\text{net}} + Q_{\text{out}} = 600\ \text{MW} + 900\ \text{MW} \\
&= 1500\ \text{MW}
\end{aligned}
$$

From equationMERM28001 (also *NCEES Handbook:* Power Cycles), the thermal efficiency is

$$
\begin{aligned}
\eta_{\text{th}} &= \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = \frac{1500\ \text{MW} - 900\ \text{MW}}{1500\ \text{MW}} \\
&= 0.400 \quad (40\%)
\end{aligned}
$$

The answer is (C).
4.

Customary U.S. Solution

At point A, $p_{\text{A}} = 100$ psia.

From appendixMERM24B (also *NCEES Handbook* table “Saturated Steam (U.S. Units)—Temperature Table”), the enthalpy of saturated liquid is $h_{\text{A}} = 298.5$ Btu/lbm.

From appendixMERM24B, the enthalpy and entropy of saturated vapor are

$$
\begin{aligned}
h_{\text{B}} &= 1187.5\ \text{Btu/lbm} \\
s_{\text{B}} &= 1.6032\ \text{Btu/lbm-}^\circ\text{R}
\end{aligned}
$$

At point C,

$$
\begin{aligned}
p_{\text{C}} &= 1\ \text{atm} \\
s_{\text{C}} &= s_{\text{B}} = 1.6032\ \text{Btu/lbm-}^\circ\text{R}
\end{aligned}
$$

From appendixMERM24B, the entropy and enthalpy of saturated liquid and entropy and enthalpy of vaporization are

$$
\begin{aligned}
s_f &= 0.3122\ \text{Btu/lbm-}^\circ\text{R} \\
h_f &= 180.2\ \text{Btu/lbm} \\
s_{fg} &= 1.4445\ \text{Btu/lbm-}^\circ\text{R} \\
h_{fg} &= 970.1\ \text{Btu/lbm}
\end{aligned}
$$

As in *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems, the quality of the system at point C is

$$\begin{aligned} x_C &= \frac{s_C - s_f}{s_{fg}} \\ &= \frac{1.6032\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{R}} - 0.3122\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{R}}}{1.4445\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{R}}} \\ &= 0.894 \end{aligned}$$

The specific enthalpy of the system at point C is

$$\begin{aligned} h_C &= h_f + x_C h_{fg} = 180.2\ \frac{\text{Btu}}{\text{lbm}} + (0.894)\left(970.1\ \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 1047.5\ \text{Btu/lbm} \end{aligned}$$

At point D, $T = 80°\text{F}$ and $p_D = 1$ atm (subcooled). h and v are essentially independent of pressure.

From appendixMERM24A, the enthalpy and specific volume of saturated liquid are

$$\begin{aligned} h_D &= 48.07\ \text{Btu/lbm} \\ v_D &= 0.01607\ \text{ft}^3/\text{lbm} \end{aligned}$$

At point E, $p_E = p_A = 100$ psia.

From equationMERM28014 (also *NCEES Handbook:* Open Thermodynamic Systems),

$$\begin{aligned} h_E &\approx h_D + v_D (p_E - p_D) \\ &= 48.07\ \frac{\text{Btu}}{\text{lbm}} + \left(0.01607\ \frac{\text{ft}^3}{\text{lbm}}\right) \\ &\quad \times \frac{\left(100\ \frac{\text{lbf}}{\text{in}^2} - 14.7\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2}{778\ \frac{\text{ft-lbf}}{\text{Btu}}} \\ &= 48.32\ \text{Btu/lbm} \end{aligned}$$

From equationMERM28018 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the turbine,

$$\begin{aligned} h'_C &= h_B - \eta_{s,\text{turbine}} (h_B - h_C) \\ &= 1187.5\ \frac{\text{Btu}}{\text{lbm}} - (0.80)\left(1187.5\ \frac{\text{Btu}}{\text{lbm}} - 1047.5\ \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 1075.5\ \text{Btu/lbm} \end{aligned}$$

From equationMERM28019 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the pump,

$$\begin{aligned} h'_E &= h_D + \frac{h_E - h_D}{\eta_{s,\text{pump}}} \\ &= 48.07\ \frac{\text{Btu}}{\text{lbm}} + \frac{48.32\ \frac{\text{Btu}}{\text{lbm}} - 48.07\ \frac{\text{Btu}}{\text{lbm}}}{0.6} \\ &= 48.49\ \text{Btu/lbm} \end{aligned}$$

From equationMERM28017 (also *NCEES Handbook:* Power Cycles), the thermal efficiency of the cycle is

$$\begin{aligned}\eta_{\text{th}} &= \frac{(h_{\text{B}} - h_{\text{C}}^{'}) - (h_{\text{E}}^{'} - h_{\text{D}})}{h_{\text{B}} - h_{\text{E}}^{'}} \\ &= \frac{\left(1187.5\ \frac{\text{Btu}}{\text{lbm}} - 1075.5\ \frac{\text{Btu}}{\text{lbm}}\right) - \left(48.49\ \frac{\text{Btu}}{\text{lbm}} - 48.07\ \frac{\text{Btu}}{\text{lbm}}\right)}{1187.5\ \frac{\text{Btu}}{\text{lbm}} - 48.49\ \frac{\text{Btu}}{\text{lbm}}} \\ &= 0.098 \quad (10\%)\end{aligned}$$

The answer is (A).

SI Solution

At point A, $p_{\text{A}} = 700$ kPa (7 bars).

From appendixMERM24O (also *NCEES Handbook* table “Saturated Steam (SI Units)—Temperature Table”), the enthalpy of saturated liquid is $h_{\text{A}} = 697.00$ kJ/kg.

From appendixMERM24O, the enthalpy and entropy of saturated vapor are

$$\begin{aligned}h_{\text{B}} &= 2762.8\ \text{kJ/kg} \\ s_{\text{B}} &= 6.7071\ \text{kJ/kg·K}\end{aligned}$$

At point C,

$$\begin{aligned}p_{\text{C}} &= 1\ \text{atm} \\ s_{\text{C}} &= s_{\text{B}} = 6.7071\ \text{kJ/kg·K}\end{aligned}$$

From appendixMERM24O, the entropy and enthalpy of saturated liquid, the entropy of saturated vapor, and the enthalpy of vaporization are

$$\begin{aligned}s_f &= 1.3062\ \text{kJ/kg·K} \\ h_f &= 418.79\ \text{kJ/kg} \\ s_g &= 7.3553\ \text{kJ/kg·K} \\ h_{fg} &= 2256.6\ \text{kJ/kg}\end{aligned}$$

As in *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems,

$$\begin{aligned}x_{\text{C}} &= \frac{s_{\text{C}} - s_f}{s_g - s_f} = \frac{6.7071\ \frac{\text{kJ}}{\text{kg·K}} - 1.3062\ \frac{\text{kJ}}{\text{kg·K}}}{7.3553\ \frac{\text{kJ}}{\text{kg·K}} - 1.3062\ \frac{\text{kJ}}{\text{kg·K}}} \\ &= 0.893 \\ h_{\text{C}} &= h_f + x_{\text{C}} h_{fg} = 418.79\ \frac{\text{kJ}}{\text{kg}} + (0.893)\left(2256.6\ \frac{\text{kJ}}{\text{kg}}\right) \\ &= 2433.9\ \text{kJ/kg}\end{aligned}$$

At point D, $T = 27°\text{C}$ and $p_{\text{D}} = 1$ atm (subcooled). h and υ are essentially independent of pressure.

From appendixMERM24N, the enthalpy and specific volume of saturated liquid are

$$\begin{aligned}h_{\text{D}} &= 113.19\ \text{kJ/kg} \\ \upsilon_{\text{D}} &= 1.0035\ \text{cm}^3/\text{g}\end{aligned}$$

At point E, $p_{\text{E}} = p_{\text{A}} = 700$ kPa.

From equationMERM28014,

$$
\begin{aligned}
h_{\mathrm{E}} &\approx h_{\mathrm{D}} + \upsilon_{\mathrm{D}}\left(p_{\mathrm{E}} - p_{\mathrm{D}}\right) \\
&= 113.19\ \frac{\mathrm{kJ}}{\mathrm{kg}} + \frac{\begin{array}{c}\left(1.0035\ \frac{\mathrm{cm}^3}{\mathrm{g}}\right)\left(1000\ \frac{\mathrm{g}}{\mathrm{kg}}\right) \\ \times\left(700\ \mathrm{kPa} - 101\ \mathrm{kPa}\right)\end{array}}{10^6\ \frac{\mathrm{cm}^3}{\mathrm{m}^3}} \\
&= 113.79\ \mathrm{kJ/kg}
\end{aligned}
$$

From equationMERM28018 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the turbine,

$$
\begin{aligned}
h_{\mathrm{C}}^{'} &= h_{\mathrm{B}} - \eta_{s,\mathrm{turbine}}\left(h_{\mathrm{B}} - h_{\mathrm{C}}\right) \\
&= 2762.8\ \frac{\mathrm{kJ}}{\mathrm{kg}} - (0.80)\left(2762.8\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 2433.9\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\
&= 2499.7\ \mathrm{kJ/kg}
\end{aligned}
$$

From equationMERM28019 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the pump,

$$
\begin{aligned}
h_{\mathrm{E}}^{'} &= h_{\mathrm{D}} + \frac{h_{\mathrm{E}} - h_{\mathrm{D}}}{\eta_{s,\mathrm{pump}}} \\
&= 113.19\ \frac{\mathrm{kJ}}{\mathrm{kg}} + \frac{113.79\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 113.19\ \frac{\mathrm{kJ}}{\mathrm{kg}}}{0.6} \\
&= 114.19\ \mathrm{kJ/kg}
\end{aligned}
$$

From equationMERM28017 (also *NCEES Handbook:* Power Cycles), the thermal efficiency of the cycle is

$$
\begin{aligned}
\eta_{\mathrm{th}} &= \frac{\left(h_{\mathrm{B}} - h_{\mathrm{C}}^{'}\right) - \left(h_{\mathrm{E}}^{'} - h_{\mathrm{D}}\right)}{h_{\mathrm{B}} - h_{\mathrm{E}}^{'}} \\
&= \frac{\begin{array}{c}\left(2762.8\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 2499.7\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\ -\left(114.19\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 113.19\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right)\end{array}}{2762.8\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 114.19\ \frac{\mathrm{kJ}}{\mathrm{kg}}} \\
&= 0.10 \quad (10\%)
\end{aligned}
$$

The answer is (A).
5.

Customary U.S. Solution

At point B, $p_{\mathrm{B}} = 600$ psia.

From appendixMERM24B (also *NCEES Handbook* table “Saturated Steam (U.S. Units)—Temperature Table”), the enthalpy of the saturated liquid is $h_{\mathrm{B}} = 471.7$ Btu/lbm.

At point C, $p_{\mathrm{C}} = 600$ psia.

From appendixMERM24B, the enthalpy of the saturated vapor is $h_{\mathrm{C}} = 1203.8$ Btu/lbm.

At point D,

$$
\begin{aligned}
T_{\mathrm{D}} &= 600^{\circ}\mathrm{F} \\
p_{\mathrm{D}} &= 600\ \mathrm{psia}
\end{aligned}
$$

From appendixMERM24C (also *NCEES Handbook:* Superheated Steam (U.S. Customary Units)), the enthalpy and entropy of superheated vapor are

$$\begin{aligned} h_{\mathrm{D}} &= 1289.9\ \mathrm{Btu/lbm} \\ s_{\mathrm{D}} &= 1.5326\ \mathrm{Btu/lbm\text{-}^\circ R} \end{aligned}$$

At point E,

$$\begin{aligned} p_{\mathrm{E}} &= 20\ \mathrm{psia} \\ s_{\mathrm{E}} &= s_{\mathrm{D}} = 1.5326\ \mathrm{Btu/lbm\text{-}^\circ R} \end{aligned}$$

From appendixMERM24B (also *NCEES Handbook* table "Saturated Steam (U.S. Units)—Temperature Table"), the various saturation properties are

$$\begin{aligned} s_f &= 0.3358\ \mathrm{Btu/lbm\text{-}^\circ R} \\ s_{fg} &= 1.3961\ \mathrm{Btu/lbm\text{-}^\circ R} \\ h_f &= 196.3\ \mathrm{Btu/lbm} \\ h_{fg} &= 959.9\ \mathrm{Btu/lbm} \end{aligned}$$

As in *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems,

$$\begin{aligned} x_{\mathrm{E}} &= \frac{s_{\mathrm{E}} - s_f}{s_g - s_f} = \frac{1.3961\ \frac{\mathrm{Btu}}{\mathrm{lbm\text{-}^\circ R}} - 0.3358\ \frac{\mathrm{Btu}}{\mathrm{lbm\text{-}^\circ R}}}{1.5236\ \frac{\mathrm{Btu}}{\mathrm{lbm\text{-}^\circ R}}} \\ &= 0.89 \\ h_{\mathrm{E}} &= h_f + x_{\mathrm{E}} h_{fg} \\ &= 196.3\ \frac{\mathrm{Btu}}{\mathrm{lbm}} + (0.89)\left(959.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ &= 1050.6\ \mathrm{Btu/lbm} \end{aligned}$$

From equationMERM28038 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the turbine,

$$\begin{aligned} h_{\mathrm{E}}' &= h_{\mathrm{D}} - \eta_{s,\mathrm{turbine}}\left(h_{\mathrm{D}} - h_{\mathrm{E}}\right) \\ &= 1289.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - (0.88) \\ &\quad \times \left(1289.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 1050.6\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ &= 1079.3\ \mathrm{Btu/lbm} \end{aligned}$$

At point F, the temperature has been returned to 600°F, but the pressure stays at the expansion pressure, p_{E}.

$$\begin{aligned} p_{\mathrm{F}} &= 20\ \mathrm{psia} \\ T_{\mathrm{F}} &= 600^\circ\mathrm{F} \end{aligned}$$

From appendixMERM24C (also *NCEES Handbook:* Superheated Steam (U.S. Customary Units)), the enthalpy and entropy of the superheated vapor are

$$\begin{aligned} h_{\mathrm{F}} &= 1334.9\ \mathrm{Btu/lbm} \\ s_{\mathrm{F}} &= 1.9399\ \mathrm{Btu/lbm\text{-}^\circ R} \end{aligned}$$

At point G,

$$\begin{aligned} T_{\mathrm{G}} &= 60^\circ\mathrm{F} \\ s_{\mathrm{G}} &= s_{\mathrm{F}} \\ &= 1.9399\ \mathrm{Btu/lbm\text{-}^\circ R} \end{aligned}$$

From appendixMERM24A (also *NCEES Handbook* "Saturated Steam (U.S. Units)—Temperature Table"), the various saturation properties are

$$
\begin{aligned}
s_f &= 0.05554 \text{ Btu/lbm-}^\circ\text{R} \\
s_g &= 2.0940 \text{ Btu/lbm-}^\circ\text{R} \\
h_f &= 28.08 \text{ Btu/lbm} \\
h_{fg} &= 1059.3 \text{ Btu/lbm}
\end{aligned}
$$

From *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems,

$$
\begin{aligned}
x_\text{G} &= \frac{s_\text{G} - s_f}{s_g - s_f} \\
&= \frac{1.9399 \ \frac{\text{Btu}}{\text{lbm-}^\circ\text{R}} - 0.05554 \ \frac{\text{Btu}}{\text{lbm-}^\circ\text{R}}}{2.0940 \ \frac{\text{Btu}}{\text{lbm-}^\circ\text{R}} - 0.05554 \ \frac{\text{Btu}}{\text{lbm-}^\circ\text{R}}} \\
&= 0.924 \\
h_\text{G} &= h_f + x_\text{G} h_{fg} \\
&= 28.08 \ \frac{\text{Btu}}{\text{lbm}} + (0.924)\left(1059.3 \ \frac{\text{Btu}}{\text{lbm}}\right) \\
&= 1006.9 \text{ Btu/lbm}
\end{aligned}
$$

From equationMERM28039 (also *NCEES Handbook:* Open Thermodynamic Systems, due to the inefficiency of the turbine,

$$
\begin{aligned}
h_\text{G}^{'} &= h_\text{F} - \eta_{s,\text{turbine}}\left(h_\text{F} - h_\text{G}\right) \\
&= 1334.9 \ \frac{\text{Btu}}{\text{lbm}} - \left(0.88\right)\left(1334.9 \ \tfrac{\text{Btu}}{\text{lbm}} - 1006.9 \ \tfrac{\text{Btu}}{\text{lbm}}\right) \\
&= 1046.3 \text{ Btu/lbm}
\end{aligned}
$$

At point H, $T_\text{H} = 60°\text{F}$.

From appendixMERM24A (also *NCEES Handbook* table “Saturated Steam (U.S. Units)—Temperature Table”), the saturation pressure, enthalpy, and specific volume of the saturated liquid are

$$
\begin{aligned}
p_\text{H} &= 0.2564 \text{ psia} \\
h_\text{H} &= 28.08 \text{ Btu/lbm} \\
\upsilon_\text{H} &= 0.01604 \text{ ft}^3\text{/lbm}
\end{aligned}
$$

At point A, $p_\text{A} = 600$ psia.

From equationMERM28014 (also *NCEES Handbook:* Open Thermodynamic Systems),

$$
\begin{aligned}
h_\text{A} &\approx h_\text{H} + \upsilon_\text{H}\left(p_\text{A} - p_\text{H}\right) \\
&= 28.08 \ \frac{\text{Btu}}{\text{lbm}} \\
&\quad + \frac{\begin{array}{c}\left(0.01604 \ \frac{\text{ft}^3}{\text{lbm}}\right) \\ \times\left(600 \ \frac{\text{lbf}}{\text{in}^2} - 0.2564 \ \frac{\text{lbf}}{\text{in}^2}\right)\left(12 \ \frac{\text{in}}{\text{ft}}\right)^2\end{array}}{778 \ \frac{\text{ft-lbf}}{\text{Btu}}} \\
&= 29.86 \text{ Btu/lbm}
\end{aligned}
$$

From equationMERM28040 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the pump,

$$
\begin{aligned}
h'_{\mathrm{A}} &= h_{\mathrm{H}} + \frac{h_{\mathrm{A}} - h_{\mathrm{H}}}{\eta_{s,\mathrm{pump}}} \\
&= 28.08\ \frac{\mathrm{Btu}}{\mathrm{lbm}} + \frac{29.86\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 28.08\ \frac{\mathrm{Btu}}{\mathrm{lbm}}}{0.96} \\
&= 29.93\ \mathrm{Btu/lbm}
\end{aligned}
$$

From equationMERM28037 (also *NCEES Handbook:* Power Cycles), the thermal efficiency of the cycle for a non-isentropic process for the turbine and the pump is

$$
\begin{aligned}
\eta_{\mathrm{th}} &= \frac{(h_{\mathrm{D}} - h'_{\mathrm{A}}) + (h_{\mathrm{F}} - h'_{\mathrm{E}}) - (h'_{\mathrm{G}} - h_{\mathrm{H}})}{(h_{\mathrm{D}} - h'_{\mathrm{A}}) + (h_{\mathrm{F}} - h'_{\mathrm{E}})} \\
&= \frac{\begin{array}{l} \left(1289.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 29.93\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ \quad + \left(1334.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 1079.3\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ \quad - \left(1046.3\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 28.08\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \end{array}}{\begin{array}{l} \left(1289.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 29.93\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ \quad + \left(1334.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 1051.4\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \end{array}} \\
&= 0.33 \quad (33\%)
\end{aligned}
$$

The answer is (B).

SI Solution

At point B, $p_{\mathrm{B}} = 4$ MPa.

From appendixMERM24O (also *NCEES Handbook* “Saturated Steam (SI Units)—Temperature Table”), the enthalpy of saturated liquid is $h_{\mathrm{B}} = 1082.5$ kJ/kg.

At point C, $p_{\mathrm{C}} = 4$ MPa.

From appendixMERM24O, the enthalpy of saturated vapor is $h_{\mathrm{C}} = 2800.8$ kJ/kg.

At point D, $p_{\mathrm{D}} = 4$ MPa and $T_{\mathrm{D}} = 300°\mathrm{C}$.

As in *NCEES Handbook* figure “Temperature-Entropy (T-S) Diagram (SI Units),” the enthalpy of superheated vapor is $h_{\mathrm{D}} = 2980$ kJ/kg.

At point E, in the diagram, assuming isentropic expansion, $h_{\mathrm{E}} = 2395$ kJ/kg.

From equationMERM28038 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the turbine,

$$
\begin{aligned}
h'_{\mathrm{E}} &= h_{\mathrm{D}} - \eta_{s,\mathrm{turbine}}\,(h_{\mathrm{D}} - h_{\mathrm{E}}) \\
&= 2980\ \frac{\mathrm{kJ}}{\mathrm{kg}} - (0.88)\left(2980\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 2395\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\
&= 2465.2\ \mathrm{kJ/kg}
\end{aligned}
$$

At point F,

$$
\begin{aligned}
p_{\mathrm{F}} &= 150\ \mathrm{kPa} \\
T_{\mathrm{F}} &= 300^\circ\mathrm{C}
\end{aligned}
$$

From appendixMERM24P (also *NCEES Handbook* table “Saturated Steam (SI Units)—Temperature Table”), the enthalpy and entropy of the superheated vapor are

$$\begin{aligned} h_\text{F} &= 3073.3 \text{ kJ/kg} \\ s_\text{F} &= 8.0284 \text{ kJ/kg·K} \end{aligned}$$

At point G,

$$\begin{aligned} T_\text{G} &= 16^\circ\text{C} \\ s_\text{G} &= s_\text{F} = 8.0284 \text{ kJ/kg·K} \end{aligned}$$

From appendixMERM24N (also *NCEES Handbook* table “Saturated Steam (SI Units)—Temperature Table”), the various saturation properties are

$$\begin{aligned} s_f &= 0.2390 \text{ kJ/kg·K} \\ s_g &= 8.7570 \text{ kJ/kg·K} \\ h_f &= 67.17 \text{ kJ/kg} \\ h_{fg} &= 2463.0 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} x_\text{G} &= \frac{s_\text{G} - s_f}{s_g - s_f} \\ &= \frac{8.0284 \ \frac{\text{kJ}}{\text{kg·K}} - 0.2390 \ \frac{\text{kJ}}{\text{kg·K}}}{8.7570 \ \frac{\text{kJ}}{\text{kg·K}} - 0.2390 \ \frac{\text{kJ}}{\text{kg·K}}} \\ &= 0.914 \end{aligned}$$

$$\begin{aligned} h_\text{G} &= h_f + x_\text{G} h_{fg} \\ &= 67.17 \ \frac{\text{kJ}}{\text{kg}} + (0.914)\left(2463.0 \ \frac{\text{kJ}}{\text{kg}}\right) \\ &= 2318.4 \text{ kJ/kg} \end{aligned}$$

From equationMERM28039, due to the inefficiency of the turbine,

$$\begin{aligned} h'_\text{G} &= h_\text{F} - \eta_{s,\text{turbine}}\left(h_\text{F} - h_\text{G}\right) \\ &= 3073.3 \ \frac{\text{kJ}}{\text{kg}} - (0.88)\left(3073.3 \ \frac{\text{kJ}}{\text{kg}} - 2318.4 \ \frac{\text{kJ}}{\text{kg}}\right) \\ &= 2409.0 \text{ kJ/kg} \end{aligned}$$

At point H, $T_\text{H} = 16°\text{C}$.

From appendixMERM24N (also *NCEES Handbook* “Saturated Steam (SI Units)—Temperature Table”), the saturation pressure, enthalpy, and specific volume of the saturated liquid are

$$\begin{aligned} p_\text{H} &= (0.01819 \text{ bar})\left(100 \ \frac{\text{kPa}}{\text{bar}}\right) = 1.819 \text{ kPa} \\ h_\text{H} &= 67.17 \text{ kJ/kg} \\ \upsilon_\text{H} &= \frac{\left(1.0011 \ \frac{\text{cm}^3}{\text{g}}\right)\left(1000 \ \frac{\text{g}}{\text{kg}}\right)}{\left(100 \ \frac{\text{cm}}{\text{m}}\right)^3} \\ &= 1.0011 \times 10^{-3} \text{ m}^3/\text{kg} \end{aligned}$$

At point A,

$$p_\text{A} = (4 \text{ MPa})\left(1000 \ \frac{\text{kPa}}{\text{MPa}}\right) = 4000 \text{ kPa}$$

From equationMERM28014 (also *NCEES Handbook:* Open Thermodynamic Systems),

$$\begin{aligned} h_\text{A} &\approx h_\text{H} + \upsilon_\text{H}\,(p_\text{A} - p_\text{H}) \\ &= 67.17\ \frac{\text{kJ}}{\text{kg}} + \left(1.0011 \times 10^{-3}\ \frac{\text{m}^3}{\text{kg}}\right) \\ &\qquad \times (4000\ \text{kPa} - 1.819\ \text{kPa}) \\ &= 71.17\ \text{kJ/kg} \end{aligned}$$

From equationMERM28040 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the pump,

$$\begin{aligned} h_\text{A}^{'} &= h_\text{H} + \frac{h_\text{A} - h_\text{H}}{\eta_{s,\text{pump}}} \\ &= 67.17\ \frac{\text{kJ}}{\text{kg}} + \frac{71.17\ \frac{\text{kJ}}{\text{kg}} - 67.17\ \frac{\text{kJ}}{\text{kg}}}{0.96} \\ &= 71.34\ \text{kJ/kg} \end{aligned}$$

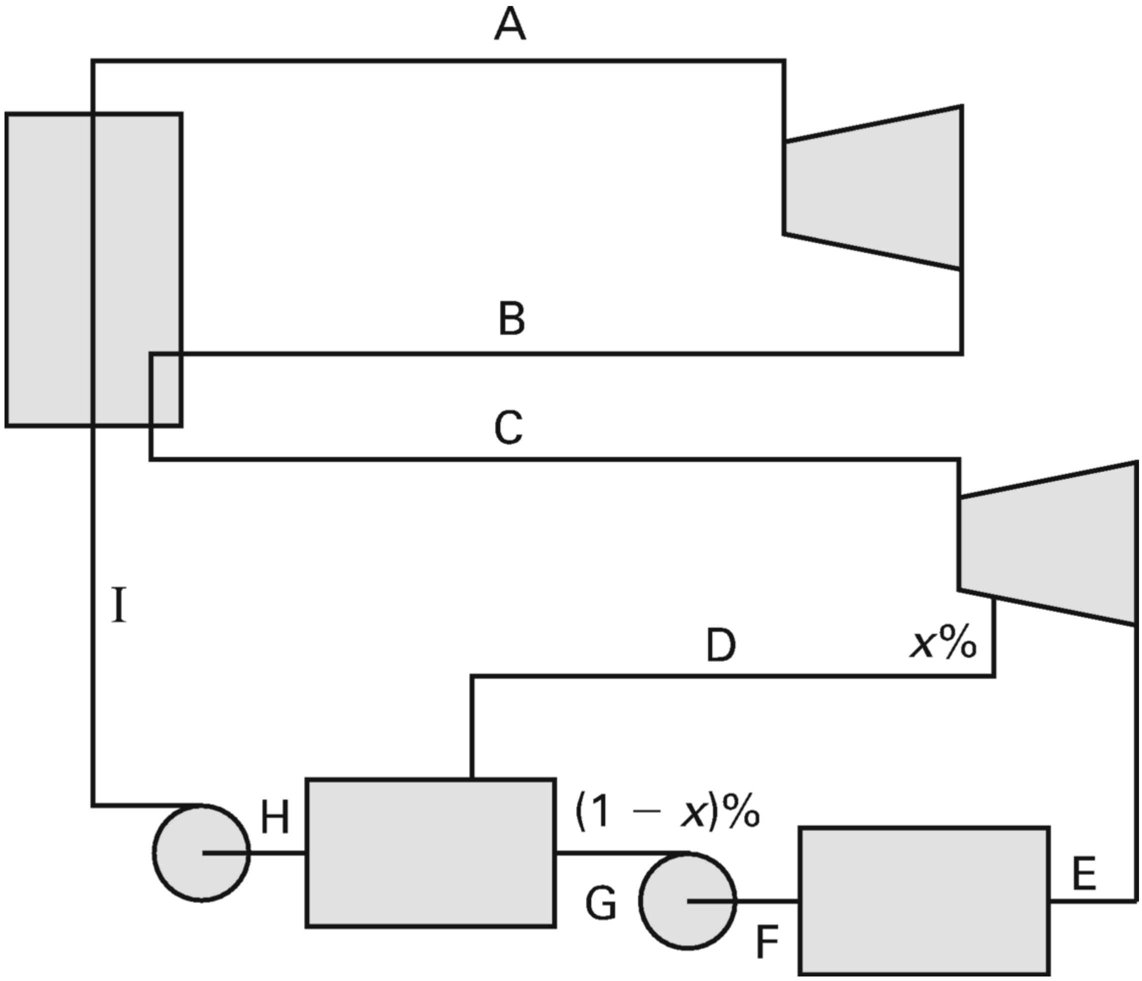
From equationMERM28037 (also *NCEES Handbook:* Power Cycles), the thermal efficiency of the cycle for a non-isentropic process for the turbine and the pump is

$$\begin{aligned} \eta_\text{th} &= \frac{(h_\text{D} - h_\text{A}^{'}) + (h_\text{F} - h_\text{E}^{'}) - (h_\text{G}^{'} - h_\text{H})}{(h_\text{D} - h_\text{A}^{'}) + (h_\text{F} - h_\text{E}^{'})} \\ &= \frac{\begin{array}{l} \left(2980\ \frac{\text{kJ}}{\text{kg}} - 71.34\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad + \left(3073.3\ \frac{\text{kJ}}{\text{kg}} - 2465.2\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad - \left(2409.0\ \frac{\text{kJ}}{\text{kg}} - 67.17\ \frac{\text{kJ}}{\text{kg}}\right) \end{array}}{\begin{array}{l} \left(2980\ \frac{\text{kJ}}{\text{kg}} - 71.34\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad + \left(3073.3\ \frac{\text{kJ}}{\text{kg}} - 2465.2\ \frac{\text{kJ}}{\text{kg}}\right) \end{array}} \\ &= 0.334 \quad (34\%) \end{aligned}$$

The answer is (B).
6.

Customary U.S. Solution

Refer to the given illustration in the problem statement and to the following diagram.



At point A,

$$\begin{aligned} p_{\mathrm{A}} &= 900 \text{ psia} \\ T_{\mathrm{A}} &= 800^\circ\mathrm{F} \end{aligned}$$

Using *NCEES Handbook* table "Superheated Steam (U.S. Units),"

$$\begin{aligned} h_{\mathrm{A}} &= 1393.9 \text{ Btu/lbm} \\ s_{\mathrm{A}} &= 1.5816 \text{ Btu/lbm-}^\circ\mathrm{R} \end{aligned}$$

From the Mollier diagram, assuming isentropic expansion to 200 psia, h_{B} = 1230 Btu/lbm.

As in *NCEES Handbook:* Open Thermodynamic Systems, isentropic efficiency of the high pressure turbine is

$$\begin{aligned} \eta_{s,\text{turbine}} &= \frac{h_{\mathrm{A}} - h'_{\mathrm{B}}}{h_{\mathrm{A}} - h_{\mathrm{B}}} \\ &= \left(\frac{1393.9 \ \frac{\text{Btu}}{\text{lbm}} - 1270 \ \frac{\text{Btu}}{\text{lbm}}}{1393.9 \ \frac{\text{Btu}}{\text{lbm}} - 1230 \ \frac{\text{Btu}}{\text{lbm}}} \right) \times 100\% \\ &= 75.59\% \end{aligned}$$

At point C,

$$\begin{aligned} p_{\mathrm{C}} &= 190 \text{ psia} \\ T_{\mathrm{C}} &= 800^\circ\mathrm{F} \end{aligned}$$

Using appendixMERM24C (also *NCEES Handbook* table "Superheated Steam (U.S. Units)"), h_{C} = 1426.0 Btu/lbm.

$$
\begin{aligned}
&\text{At D:} & h'_{\mathrm{D}} &= 1280\ \mathrm{Btu/lbm} \\
&\text{At E:} & h'_{\mathrm{E}} &= 1075\ \mathrm{Btu/lbm} \\
&\text{At F:} & h_{\mathrm{F}} &= 69.73\ \mathrm{Btu/lbm} \\
&\text{At G:} & W_{\mathrm{pump}} &= 0.15\ \mathrm{Btu/lbm} \\
& & W_{\mathrm{pump}} &= h'_{\mathrm{G}} - h_{\mathrm{F}} \\
& & h'_{\mathrm{G}} &= W_{\mathrm{pump}} + h_{\mathrm{F}} \\
& & &= 0.15\ \frac{\mathrm{Btu}}{\mathrm{lbm}} + 69.73\ \frac{\mathrm{Btu}}{\mathrm{lbm}} \\
& & &= 69.88\ \mathrm{Btu/lbm} \\
&\text{At H:} & h_{\mathrm{H}} &= 250.2\ \mathrm{Btu/lbm} \\
&\text{At I:} & h'_{\mathrm{I}} &= 253.1\ \mathrm{Btu/lbm}
\end{aligned}
$$

From an energy balance in the heater,

$$
\begin{aligned}
x h'_{\mathrm{D}} + (1-x)\, h'_{\mathrm{G}} &= h_{\mathrm{H}} \\
x\left(h'_{\mathrm{D}} - h'_{\mathrm{G}}\right) &= h_{\mathrm{H}} - h'_{\mathrm{G}} \\
x = \frac{h_{\mathrm{H}} - h'_{\mathrm{G}}}{h'_{\mathrm{D}} - h'_{\mathrm{G}}} &= \frac{250.2\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 69.88\ \frac{\mathrm{Btu}}{\mathrm{lbm}}}{1280\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 69.88\ \frac{\mathrm{Btu}}{\mathrm{lbm}}} \\
&= 0.149
\end{aligned}
$$

From equationMERM28008 (also *NCEES Handbook:* Power Cycles), the thermal efficiency of the cycle is

$$
\begin{aligned}
\eta_{\mathrm{th}} &= \frac{W_{\mathrm{out}} - W_{\mathrm{in}}}{Q_{\mathrm{in}}} \\
&= \frac{\begin{array}{c}\left(h_{\mathrm{A}} - h'_{\mathrm{B}}\right) + \left(h_{\mathrm{C}} - h'_{\mathrm{D}}\right) + (1-x)\left(h'_{\mathrm{D}} - h'_{\mathrm{E}}\right) \\ -\left(h'_{\mathrm{I}} - h_{\mathrm{H}}\right) - (1-x)\left(h'_{\mathrm{G}} - h_{\mathrm{F}}\right)\end{array}}{\left(h_{\mathrm{A}} - h'_{\mathrm{I}}\right) + \left(h_{\mathrm{C}} - h'_{\mathrm{B}}\right)} \\
&= \frac{\begin{array}{l}\left(1393.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 1270\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ \quad + \left(1426.0\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 1280\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ \quad + (1-0.149)\left(1280\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 1075\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ \quad - \left(253.1\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 250.2\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ \quad - (1-0.149)\left(69.88\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 69.73\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right)\end{array}}{\begin{array}{l}\left(1393.9\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 253.1\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right) \\ \quad + \left(1426.0\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 1270\ \frac{\mathrm{Btu}}{\mathrm{lbm}}\right)\end{array}} \\
&= 0.340 \quad (34\%)
\end{aligned}
$$

The answer is (C).

SI Solution

Refer to the illustration in the problem statement and to the diagram in the customary U.S. solution.

At point A,

$$
\begin{aligned}
p_{\mathrm{A}} &= 6.2\ \mathrm{MPa} \\
T_{\mathrm{A}} &= 420^\circ\mathrm{C}
\end{aligned}
$$

From (also *NCEES Handbook* figure “Temperature-Entropy (T-S) Diagram (SI Units)”),

$$h_A = 3235.0 \text{ kJ/kg}$$
$$s_A = 6.65 \text{ kJ/kg·K}$$

Use *NCEES Handbook* table "Pressure-Enthalpy (p-H) Diagram (SI Units)." Assuming isentropic expansion to 1.5 MPa, $h_B = 2860$ kJ/kg.

As in *NCEES Handbook:* Open Thermodynamic Systems, isentropic efficiency of the high pressure turbine is

$$\eta_{s,\text{turbine}} = \frac{h_A - h_B'}{h_A - h_B} = \frac{3235.0 \ \frac{\text{kJ}}{\text{kg}} - 2960 \ \frac{\text{kJ}}{\text{kg}}}{3235.0 \ \frac{\text{kJ}}{\text{kg}} - 2860 \ \frac{\text{kJ}}{\text{kg}}}$$
$$= 0.733 \quad (73\%)$$

At point C,

$$p_C = 1.4 \text{ MPa}$$
$$T_C = 420^\circ\text{C}$$

Using appendixMERM24P (also *NCEES Handbook* table "Superheated Steam (SI Units)"), $h_C = 3301.3$ kJ/kg.

At point D, $h_D' = 2980 \text{ kJ/kg}$.

At point E, $h_E' = 2500 \text{ kJ/kg}$.

At point F, $h_F' = 162.5 \text{ kJ/kg}$.

At point G,

$$W_{\text{pump}} = 0.3 \text{ kJ/kg}$$
$$= h_G' - h_F$$
$$h_G' = W_{\text{pump}} + h_F$$
$$= 0.3 \ \frac{\text{kJ}}{\text{kg}} + 162.5 \ \frac{\text{kJ}}{\text{kg}}$$
$$= 162.8 \text{ kJ/kg}$$

At point H, $h_H = 583.0$ kJ/kg.

At point I, $h_I' = 589.7 \text{ kJ/kg}$.

From an energy balance in the heater,

$$x h_D' + (1 - x) h_G' = h_H$$
$$x (h_D' - h_G') = h_H - h_G'$$
$$x = \frac{h_H - h_G}{h_D' - h_G'}$$
$$= \frac{583.0 \ \frac{\text{kJ}}{\text{kg}} - 162.8 \ \frac{\text{kJ}}{\text{kg}}}{2980 \ \frac{\text{kJ}}{\text{kg}} - 162.8 \ \frac{\text{kJ}}{\text{kg}}}$$
$$= 0.149$$

From equationMERM28008 (also *NCEES Handbook:* Power Cycles), the thermal efficiency of the cycle is

$$
\begin{aligned}
\eta_{\text{th}} &= \frac{W_{\text{out}} - W_{\text{in}}}{Q_{\text{in}}} \\
&= \frac{\begin{array}{c}(h_{\text{A}} - h_{\text{B}}^{'}) + (h_{\text{C}} - h_{\text{D}}^{'}) + (1-x)\,(h_{\text{D}}^{'} - h_{\text{E}}^{'}) \\ -\,(h_{\text{I}}^{'} - h_{\text{H}}) - (1-x)\,(h_{\text{G}}^{'} - h_{\text{F}})\end{array}}{(h_{\text{A}} - h_{\text{I}}^{'}) + (h_{\text{C}} - h_{\text{B}}^{'})} \\
&= \frac{\begin{array}{l}\left(3235.0\ \frac{\text{kJ}}{\text{kg}} - 2960\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad + \left(3301.3\ \frac{\text{kJ}}{\text{kg}} - 2980\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad + (1-0.149)\left(2980\ \frac{\text{kJ}}{\text{kg}} - 2500\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad - \left(598.7\ \frac{\text{kJ}}{\text{kg}} - 583.0\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad - (1-0.149)\left(162.8\ \frac{\text{kJ}}{\text{kg}} - 162.5\ \frac{\text{kJ}}{\text{kg}}\right)\end{array}}{\begin{array}{l}\left(3235.0\ \frac{\text{kJ}}{\text{kg}} - 598.7\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad + \left(3301.3\ \frac{\text{kJ}}{\text{kg}} - 2960\ \frac{\text{kJ}}{\text{kg}}\right)\end{array}} \\
&= 0.332 \quad (34\%)
\end{aligned}
$$

The answer is (C).