Chapter 14. Combustion Power Cycles

Practice Problems

1.

Air expands isentropically at the rate of 10 ft^3/sec (280 L/s) from 200 psia and 1500°F (1.4 MPa and 820°C) to 50 psia (350 kPa). Using air tables, the air's enthalpy change is most nearly

(A)

−350 Btu/lbm (−770 kJ/kg)

(B)

−230 Btu/lbm (−530 kJ/kg)

(C)

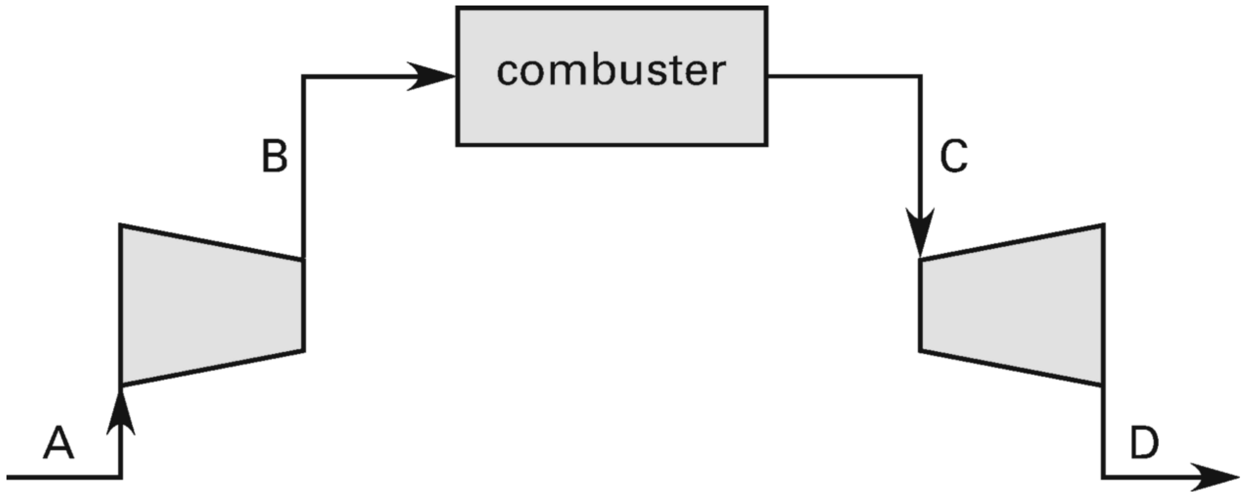
−160 Btu/lbm (−380 kJ/kg)

(D)

−110 Btu/lbm (−250 kJ/kg)

2.

In an air-standard gas turbine, air at 14.7 psia and 60°F (101.3 kPa and 16°C) enters a compressor and is compressed through a volume ratio of 5:1. The compressor efficiency is 83%. Air enters the turbine at 1500°F (820°C) and expands to 14.7 psia (101.3 kPa). The turbine efficiency is 92%.



The thermal efficiency of the cycle is most nearly

(A)

33%

(B)

39%

(C)

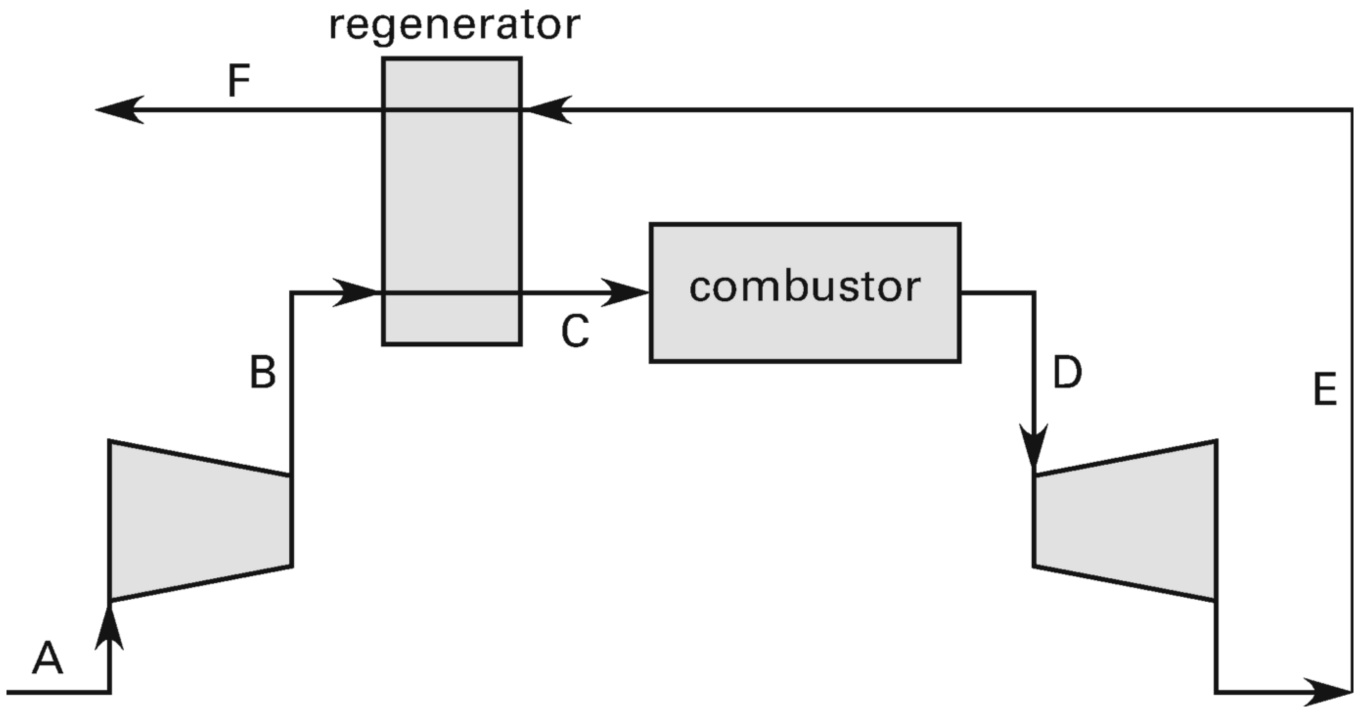
44%

(D)

51%

3.

In an air-standard gas turbine, air at 14.7 psia and 60°F (101.3 kPa and 16°C) enters a compressor and is compressed through a volume ratio of 5:1. The compressor efficiency is 83%. Air enters the turbine at 1500°F (820°C) and expands to 14.7 psia (101.3 kPa). The turbine efficiency is 92%. A 65% efficient regenerator is added to the gas turbine.



Assume the specific heat remains constant. The new thermal efficiency is most nearly

(A)

24%

(B)

28%

(C)

34%

(D)

41%

4.

A gas turbine operating on the Brayton cycle with an 8:1 pressure ratio is located at 7000 ft (2100 m) altitude. The conditions at that altitude are 12 psia and 35°F (82 kPa and 2°C). While consuming 0.609 lbm/hp-hr (100 kg/GJ) of fuel and 50,000 cfm (23 500 L/s) of air, the turbine develops 6000 bhp (4.5 MW). The turbine efficiency is 80%, and the compressor efficiency is 85%. The fuel has a lower heating value of 19,000 Btu/lbm (44 MJ/kg). The fuel mass is small compared to the air mass. There is no pressure loss in the combustor. The turbine receives combustor gases at 1800°F (980°C). The air inlet filter area is 254 ft^2 (22.9 m^2). The combustion efficiency and combustor temperature remain the same. At 7000 ft, the ideal fuel rate is most nearly

(A)

3000 lbm/hr (0.37 kg/s)
(B)

3200 lbm/hr (0.40 kg/s)

(C)

3400 lbm/hr (0.42 kg/s)

(D)

3600 lbm/hr (0.44 kg/s)
5.

A precision air turbine is used to drive a small dentist's drill. 140°F (60°C) air enters the turbine at the rate of 15 lbm/hr (1.9 g/s). The output of the turbine is 0.25 hp (0.19 kW). The turbine exhausts to 15 psia (103.5 kPa). The flow is steady. The isentropic efficiency of the expansion process is 60%. The change in entropy through the turbine is most nearly

(A)

0.08 Btu/lbm-°R (0.33 kJ/kg·K)

(B)

0.10 Btu/lbm-°R (0.46 kJ/kg·K)

(C)

0.18 Btu/lbm-°R (0.82 kJ/kg·K)

(D)

0.32 Btu/lbm-°R (1.5 kJ/kg·K)

Solutions

1.

Customary U.S. Solution

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

$$T_1 = 1500^\circ\text{F} + 460^\circ = 1960^\circ\text{R}$$

From *NCEES Handbook:* Closed Thermodynamic Systems, the new temperature after isentropic expansion is

$$\begin{aligned} T_2 &= T_1\left(\frac{p_2}{p_1}\right)^{(k-1)/k} = (1960^\circ\text{R})\left(\frac{50\ \frac{\text{lbf}}{\text{in}^2}}{200\ \frac{\text{lbf}}{\text{in}^2}}\right)^{(1.4-1)/1.4} \\ &= 1319^\circ\text{R} \end{aligned}$$

As in *NCEES Handbook:* Temperature-Dependent Properties of Air (U.S. Customary Units), the heat capacity is $c_p = 0.2567$ Btu/lbm-°F. From *NCEES Handbook:* Ideal Gas Law, the air's enthalpy change is

$$\begin{aligned} \Delta h &= c_p \Delta T = \left(0.2567\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)\ (1319^\circ\text{R} - 1960^\circ\text{R}) \\ &= -164.5\ \text{Btu/lbm} \quad (-160\ \text{Btu/lbm}) \end{aligned}$$

The answer is (C).

SI Solution

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

$$\begin{aligned} T_1 &= 820^\circ\mathrm{C} + 273^\circ \\ &= 1093\mathrm{K} \end{aligned}$$

As in *NCEES Handbook:* Closed Thermodynamic Systems, the new temperature after isentropic expansion is

$$\begin{aligned} T_2 &= T_1\left(\tfrac{p_2}{p_1}\right)^{(k-1)/k} = (1093\mathrm{K})\left(\tfrac{350\ \mathrm{kPa}}{1400\ \mathrm{kPa}}\right)^{(1.4-1)/1.4} \\ &= 736\mathrm{K} \end{aligned}$$

From *NCEES Handbook:* Temperature-Dependent Properties of Air (SI Units), the heat capacity is $c_p =$ 1.068 kJ/kg·K. From *NCEES Handbook:* Ideal Gas Law, the air’s enthalpy change is

$$\begin{aligned} \Delta h &= c_p \Delta T \\ &= \left(1.068\ \tfrac{\mathrm{kJ}}{\mathrm{kg\cdot K}}\right)\ (736\mathrm{K} - 1093\mathrm{K}) \\ &= -381.3\ \mathrm{kJ/kg} \quad (-380\ \mathrm{kJ/kg}) \end{aligned}$$

The answer is (C).
2.

Customary U.S. Solution

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

$$T_\mathrm{A} = 60^\circ\mathrm{F} + 460^\circ = 520^\circ\mathrm{R}$$

As in *NCEES Handbook:* Closed Thermodynamic Systems, the temperature at point B after an isentropic compression with a volume ratio of 5 is

$$T_\mathrm{B} = T_\mathrm{A}\left(\frac{V_\mathrm{A}}{V_\mathrm{B}}\right)^{k-1} = (520^\circ\mathrm{R})\,(5)^{1.4-1} = 990^\circ\mathrm{R}$$

The pressure at point B is

$$p_\mathrm{B} = p_\mathrm{A}\left(\frac{V_\mathrm{A}}{V_\mathrm{B}}\right)^{k} = \left(14.7\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)(5)^{1.4} = 139.9\ \mathrm{lbf/in^2}$$

At point C,

$$\begin{aligned} T_\mathrm{C} &= 1500^\circ\mathrm{F} + 460^\circ = 1960^\circ\mathrm{R} \\ p_\mathrm{C} &= p_\mathrm{B} = 139.9\ \mathrm{lbf/in^2} \end{aligned}$$

At point D, the pressure is 14.7 psi. Since C-D is an isentropic process, the temperature at point D is

$$\begin{aligned} T_\mathrm{D} &= T_\mathrm{C}\left(\tfrac{p_\mathrm{D}}{p_\mathrm{C}}\right)^{(k-1)/k} \\ &= (1960^\circ\mathrm{R})\left(\frac{14.7\ \frac{\mathrm{lbf}}{\mathrm{in}^2}}{139.9\ \frac{\mathrm{lbf}}{\mathrm{in}^2}}\right)^{(1.4-1)/1.4} \\ &= 1030^\circ\mathrm{R} \end{aligned}$$

From *NCEES Handbook:* Temperature-Dependent Properties of Air (U.S. Customary Units), $c_p =$ 0.24 Btu/lbm-°F for both compressor and turbine. Using *NCEES Handbook:* Open Thermodynamic Systems, the actual work for the compressor is

$$\begin{aligned} W_\mathrm{actual} &= \frac{W_\mathrm{rev}}{\eta_\mathrm{isen}} = \frac{c_p(T_\mathrm{A}-T_\mathrm{B})}{\eta_\mathrm{isen}} \\ &= \frac{\left(0.24\ \frac{\mathrm{Btu}}{\mathrm{lbm\text{-}^\circ F}}\right)(520^\circ\mathrm{R}-990^\circ\mathrm{R})}{0.83} \\ &= -135.9\ \mathrm{Btu/lbm} \end{aligned}$$

The actual work for the turbine is

$$
\begin{aligned}
W_{\text{actual}} &= \eta_{\text{isen}} W_{\text{rev}} = \eta_{\text{isen}} c_p \left(T_{\text{C}} - T_{\text{D}}\right) \\
&= (0.92)\left(0.24\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)\left(1960^\circ\text{R} - 1030^\circ\text{R}\right) \\
&= 205.3\ \text{Btu/lbm}
\end{aligned}
$$

Rearrange the above equation to find the actual T_B.

$$
\begin{aligned}
c_p\left(T_{\text{A}} - T'_{\text{B}}\right) &= \frac{c_p\left(T_{\text{A}} - T_{\text{B}}\right)}{\eta_{\text{isen}}} \\
T'_{\text{B}} &= T_{\text{A}} - \frac{\left(T_{\text{A}} - T_{\text{B}}\right)}{\eta_{\text{isen}}} \\
&= 520^\circ\text{R} - \frac{520^\circ\text{R} - 990^\circ\text{R}}{0.83} \\
&= 1086^\circ\text{R}
\end{aligned}
$$

As in *NCEES Handbook:* Power Cycles, the cycle efficiency is

$$
\begin{aligned}
\eta_{cycle} &= \frac{W_{\text{AB}} + W_{\text{CD}}}{q_{\text{BC}}} = \frac{W_{\text{AB}} + W_{\text{CD}}}{c_p\left(T_{\text{C}} - T_{\text{B}}\right)} \\
&= \frac{-135.9\ \dfrac{\text{Btu}}{\text{lbm}} + 205.3\ \dfrac{\text{Btu}}{\text{lbm}}}{0.24\ \dfrac{\text{Btu}}{\text{lbm}^\circ\text{F}}(1960 - 1086)\ ^\circ\text{F}} \\
&= 0.33 \quad (33\%)
\end{aligned}
$$

The answer is (A).

SI Solution

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

$$
T_{\text{A}} = 16^\circ\text{C} + 273^\circ = 289\text{K}
$$

As in *NCEES Handbook:* Closed Thermodynamic Systems, the temperature at point B after an isentropic compression with a volume ratio of 5 is

$$
\begin{aligned}
T_{\text{B}} &= T_{\text{A}}\left(\frac{V_{\text{A}}}{V_{\text{B}}}\right)^{k-1} \\
&= (289\text{K})\,(5)^{1.4-1} \\
&= 550.2\text{K}
\end{aligned}
$$

The pressure at point B is

$$
\begin{aligned}
p_{\text{B}} &= p_{\text{A}}\left(\frac{V_{\text{A}}}{V_{\text{B}}}\right)^{k} \\
&= (101.3\ \text{kPa})\,(5)^{1.4} \\
&= 964.2\ \text{kPa}
\end{aligned}
$$

At point C,

$$
T_{\text{A}} = 820^\circ\text{C} + 273^\circ = 1093\text{K}
$$

$$
p_{\text{c}} = p_{\text{a}} = 964.2\ \text{kPa}
$$

At point D, the pressure is 101.3 kPa. Since C-D is an isentropic process, the temperature at point D is

$$
\begin{aligned}
T_{\text{D}} &= T_{\text{C}}\left(\frac{p_{\text{D}}}{p_{\text{C}}}\right)^{(k-1)/k} = (1093\text{K})\left(\frac{101.3\ \text{kPa}}{964.2\ \text{kPa}}\right)^{(1.4-1)/1.4} \\
&= 574\text{K}
\end{aligned}
$$

From *NCEES Handbook:* Temperature-Dependent Properties of Air (SI Units), $c_p = 1.009\ \text{kJ/kg}\cdot\text{K}$ for both compressor and turbine. Using *NCEES Handbook:* Open Thermodynamic Systems, the actual work for the compressor is

$$
\begin{aligned}
W_{\text{actual}} &= \frac{W_{\text{rev}}}{\eta_{\text{isen}}} = \frac{c_p(T_\text{A}-T_\text{B})}{\eta_{\text{isen}}} \\
&= \frac{\left(1.009\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)(289\text{K}-550.2\text{K})}{0.83} \\
&= -317.59\ \text{kJ}/\text{kg}
\end{aligned}
$$

The actual work for the turbine is

$$
\begin{aligned}
W_{\text{actual}} &= \eta_{\text{isen}} W_{\text{rev}} = \eta_{\text{isen}} c_p\left(T_\text{C}-T_\text{D}\right) \\
&= (0.92)\left(1.009\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)(1093\text{K}-574\text{K}) \\
&= 481.8\ \text{kJ}/\text{kg}
\end{aligned}
$$

Rearrange the expression to find the actual T_B'.

$$
\begin{aligned}
c_p\left(T_\text{A}-T_\text{B}'\right) &= \frac{c_p(T_\text{A}-T_\text{B})}{\eta_{\text{isen}}} \\
T_\text{B}' &= T_\text{A} - \frac{T_\text{A}-T_\text{B}}{\eta_{\text{isen}}} \\
&= 289\text{K} - \frac{289\text{K}-550.2\text{K}}{0.83} \\
&= 603.7\text{K}
\end{aligned}
$$

As in *NCEES Handbook:* Power Cycles, the cycle efficiency is

$$
\begin{aligned}
\eta_{cycle} &= \frac{W_{\text{AB}}+W_{\text{CD}}}{q_{\text{BC}}} = \frac{W_{\text{AB}}+W_{\text{CD}}}{c_p\left(T_\text{C}-T_\text{B}\right)} \\
&= \frac{-317.59\ \frac{\text{kJ}}{\text{kg}} + 481.8\ \frac{\text{kJ}}{\text{kg}}}{1.009\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}}(1093-603.7)\ \text{K}} \\
&= 0.33 \quad (33\%)
\end{aligned}
$$

The answer is (A).
3.

Customary U.S. Solution

Since specific heats are constant, use ideal gas equations rather than air tables. To convert temperatures, use *NCEES Handbook* table "Conversion Table for Temperature Units."

At A:

$$
\begin{aligned}
T_\text{A} &= 60^\circ\text{F} + 460^\circ = 520^\circ\text{R} \quad [\text{given}] \\
p_\text{A} &= 14.7\ \text{psia} \quad [\text{given}]
\end{aligned}
$$

From *NCEES Handbook:* Closed Thermodynamic Systems, at B:

$$
\begin{aligned}
T_\text{B} &= T_\text{A}\left(\frac{\upsilon_\text{A}}{\upsilon_\text{B}}\right)^{k-1} = (520^\circ\text{R})\,(5)^{1.4-1} = 989.9^\circ\text{R} \\
p_\text{B} &= p_\text{A}\left(\frac{\upsilon_\text{A}}{\upsilon_\text{B}}\right)^{k} = (14.7\ \text{psia})\,(5)^{1.4} \\
&= 139.9\ \text{psia}
\end{aligned}
$$

To convert temperatures, use *NCEES Handbook* table "Conversion Table for Temperature Units" for isentropic processes, at D:

$$
\begin{aligned}
T_\text{D} &= 1500^\circ\text{F} + 460^\circ = 1960^\circ\text{R} \quad [\text{given}] \\
p_\text{D} &= p_\text{B} = 139.9\ \text{psia}
\end{aligned}
$$

To convert temperatures, use *NCEES Handbook* table "Conversion Table for Temperature Units" for isentropic processes, at E:

$$\begin{aligned}p_{\mathrm{E}} &= 14.7\ \text{psia} \quad [\text{given}]\\ T_{\mathrm{E}} &= T_{\mathrm{D}}\left(\frac{p_{\mathrm{E}}}{p_{\mathrm{D}}}\right)^{(k-1)/k} = (1960^\circ\mathrm{R})\left(\frac{14.7\ \text{psia}}{139.9\ \text{psia}}\right)^{(1.4-1)/1.4}\\ &= 1029.6^\circ\mathrm{R}\end{aligned}$$

From equationMERM29099 (also *NCEES Handbook:* Open Thermodynamic Systems),

$$\begin{aligned}T_{\mathrm{B}}^{'} &= T_{\mathrm{A}} + \frac{T_{\mathrm{B}} - T_{\mathrm{A}}}{\eta_{s,\text{compressor}}}\\ &= 520^\circ\mathrm{R} + \frac{989.9^\circ\mathrm{R} - 520^\circ\mathrm{R}}{0.83}\\ &= 1086.1^\circ\mathrm{R}\end{aligned}$$

From equationMERM29101 (also *NCEES Handbook:* Open Thermodynamic Systems),

$$\begin{aligned}T_{\mathrm{E}}^{'} &= T_{\mathrm{D}} - \eta_{s,\text{turbine}}\left(T_{\mathrm{D}} - T_{\mathrm{E}}\right)\\ &= 1960^\circ\mathrm{R} - (0.92)\left(1960^\circ\mathrm{R} - 1029.6^\circ\mathrm{R}\right)\\ &= 1104.0^\circ\mathrm{R}\end{aligned}$$

From the problem statement,

$$\eta_{\text{regenerator}} = \frac{h_{\mathrm{C}} - h_{\mathrm{B}}^{'}}{h_{\mathrm{E}}^{'} - h_{\mathrm{B}}^{'}}$$

For constant c_p,

$$\begin{aligned}\eta_{\text{regenerator}} &= \frac{T_{\mathrm{C}} - T_{\mathrm{B}}^{'}}{T_{\mathrm{E}}^{'} - T_{\mathrm{B}}^{'}}\\ 0.65 &= \frac{T_{\mathrm{C}} - 1086.1^\circ\mathrm{R}}{1104.0^\circ\mathrm{R} - 1086.1^\circ\mathrm{R}}\\ T_{\mathrm{C}} &= 1097.7^\circ\mathrm{R}\end{aligned}$$

From equationMERM29103 (also *NCEES Handbook:* Power Cycles), with constant specific heats,

$$\begin{aligned}\eta_{\text{th}} &= \frac{\left(T_{\mathrm{D}} - T_{\mathrm{E}}^{'}\right) - \left(T_{\mathrm{B}}^{'} - T_{\mathrm{A}}\right)}{T_{\mathrm{D}} - T_{\mathrm{C}}}\\ &= \frac{\left(1960^\circ\mathrm{R} - 1104.0^\circ\mathrm{R}\right) - \left(1086.1^\circ\mathrm{R} - 520^\circ\mathrm{R}\right)}{1960^\circ\mathrm{R} - 1097.7^\circ\mathrm{R}}\\ &= 0.336 \quad (34\%)\end{aligned}$$

The answer is (C).

SI Solution

From Prob. 2,

$$\begin{aligned}T_{\mathrm{A}} &= 289\mathrm{K}\\ T_{\mathrm{B}}^{'} &= 603.7\mathrm{K}\\ T_{\mathrm{D}} &= 1093\mathrm{K}\\ T_{\mathrm{E}}^{'} &= T_{\mathrm{D}}^{'} = 615.7\mathrm{K}\end{aligned}$$

For constant specific heats,

$$\begin{aligned}\eta_{\text{regenerator}} &= \frac{T_{\mathrm{C}} - T_{\mathrm{B}}^{'}}{T_{\mathrm{E}}^{'} - T_{\mathrm{B}}^{'}}\\ 0.65 &= \frac{T_{\mathrm{C}} - 603.7\mathrm{K}}{615.7\mathrm{K} - 603.7\mathrm{K}}\\ T_{\mathrm{C}} &= 611.5\mathrm{K}\end{aligned}$$

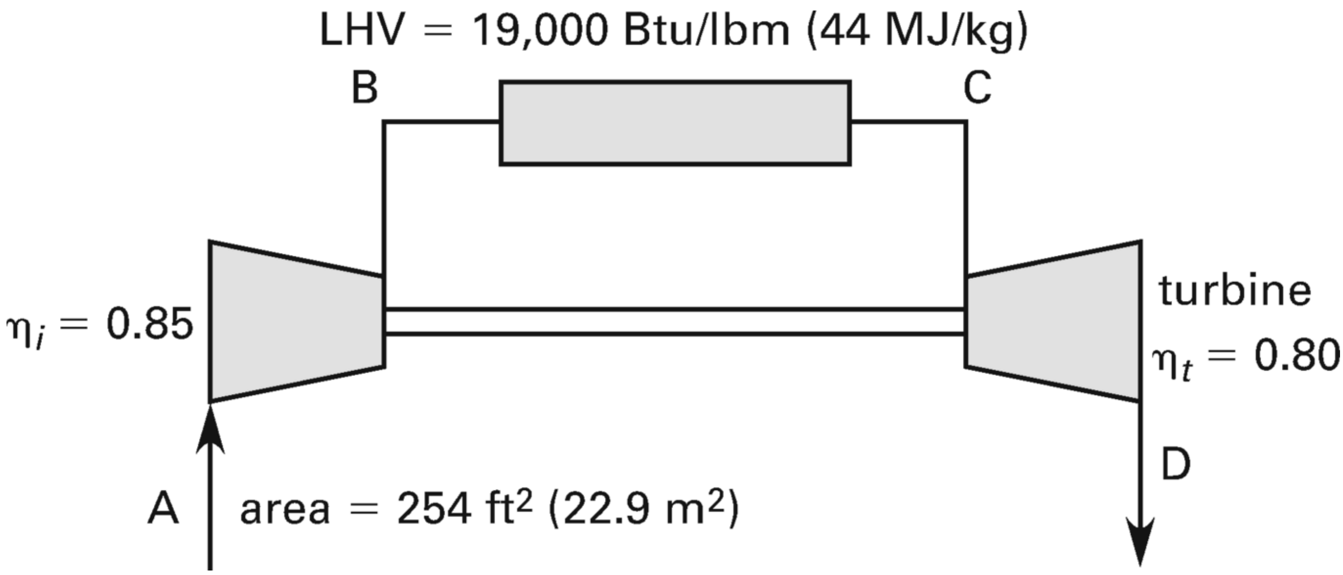
From equationMERM29103 (also *NCEES Handbook:* Power Cycles with constant specific heats),

$$\begin{aligned}\eta_{th} &= \frac{(T_D - T_E') - (T_B' - T_A)}{T_D - T_C}\\ &= \frac{(1093\text{K} - 615.7\text{K}) - (603.7\text{K} - 289\text{K})}{1093\text{K} - 611.5\text{K}}\\ &= 0.338 \quad (34\%)\end{aligned}$$

The answer is (C).

4.

Use the illustration shown for both the customary U.S. and SI solutions.



Customary U.S. Solution

At 7000 ft altitude:

$$\begin{aligned}\dot{V}_{a1} &= 50{,}000\ \text{ft}^3/\text{min}\\ \text{BHP}_1 &= 6000\ \text{hp}\\ \text{BSCF}_1 &= 0.609\ \text{lbm/hp-hr}\end{aligned}$$

At A:

$$\begin{aligned}p_A &= 12\ \text{psia}\\ T_A &= 35^\circ\text{F}\end{aligned}$$

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

$$T_A = 35^\circ\text{F} + 460^\circ = 495^\circ\text{R}$$

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

$$\begin{aligned}\rho_{a1} &= \frac{p_A}{RT_A} = \frac{\left(12\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2}{\left(53.35\ \frac{\text{ft-lbf}}{\text{lbm-}^\circ\text{R}}\right)(495^\circ\text{R})}\\ &= 0.0654\ \text{lbm/ft}^3 \quad (0.065\ \text{lbm/ft}^3)\end{aligned}$$

From equationMERM29076, the air mass flow rate is

$$\begin{aligned}\dot{m}_{a1} &= \dot{V}_{a1}\rho_{a1}\\ &= \left(50{,}000\ \frac{\text{ft}^3}{\text{min}}\right)\left(0.0654\ \frac{\text{lbm}}{\text{ft}^3}\right)\\ &= 3270\ \text{lbm/min}\end{aligned}$$

At B:

$$
\begin{aligned}
T_{\mathrm{B}} &= T_{\mathrm{A}}\left(\frac{p_{\mathrm{B}}}{p_{\mathrm{A}}}\right)^{(k-1)/k} \\
&= (495^{\circ}\mathrm{R})\,(8)^{(1.4-1)/1.4} \\
&= 896.7^{\circ}\mathrm{R}
\end{aligned}
$$

From equationMERM29099 (also *NCEES Handbook:* Open Thermodynamic Systems), due to the inefficiency of the compressor,

$$
\begin{aligned}
T'_{\mathrm{B}} &= T_{\mathrm{A}} - \frac{T_{\mathrm{A}}-T_{\mathrm{B}}}{\eta_{\mathrm{isen}}} \\
&= 495^{\circ}\mathrm{R} - \frac{495^{\circ}\mathrm{R}-896.7^{\circ}\mathrm{R}}{0.85} \\
&= 967.6^{\circ}\mathrm{R}
\end{aligned}
$$

The work of the compressor is

$$
\begin{aligned}
W_{\mathrm{compression}} &= c_p\left(T_{\mathrm{A}} - T'_{\mathrm{B}}\right) \\
&= \left(0.24\ \frac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^{\circ}\mathrm{F}}\right)(495^{\circ}\mathrm{R} - 967.6^{\circ}\mathrm{R}) \\
&= -113.4\ \mathrm{Btu/lbm}
\end{aligned}
$$

At C:

The absolute temperature is

$$
T_{\mathrm{C}} = 1800^{\circ}\mathrm{F} + 460^{\circ} = 2260^{\circ}\mathrm{R} \quad [\text{no change if moved}]
$$

Since there is no pressure drop across the combustor, $p_{\mathrm{C}} = 96$ psia.

The energy requirement from the fuel is

$$
\begin{aligned}
\dot{m}\Delta h &= \dot{m}_{a1}\left(h_{\mathrm{C}} - h'_{\mathrm{B}}\right) = \dot{m}_{a1} c_p \left(T_{\mathrm{C}} - T'_{\mathrm{B}}\right) \\
&= \left(3270\ \frac{\mathrm{lbm}}{\mathrm{min}}\right)\left(0.24\ \frac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^{\circ}\mathrm{F}}\right)(2260^{\circ}\mathrm{R} - 967.6^{\circ}\mathrm{R}) \\
&= 1.014 \times 10^{6}\ \mathrm{Btu/min}
\end{aligned}
$$

The ideal fuel rate is

$$
\begin{aligned}
\frac{\dot{m}\Delta h}{\mathrm{LHV}} &= \frac{\left(1.014 \times 10^{6}\ \dfrac{\mathrm{Btu}}{\mathrm{min}}\right)\left(60\ \dfrac{\mathrm{min}}{\mathrm{hr}}\right)}{19{,}000\ \dfrac{\mathrm{Btu}}{\mathrm{lbm}}} \\
&= 3202\ \mathrm{lbm/hr} \quad (3200\ \mathrm{lbm/hr})
\end{aligned}
$$

The answer is (B).

SI Solution

At 2100 m altitude:

At A:

$$
p_{\mathrm{A}} = 82\ \mathrm{kPa} \quad [\text{given}]
$$

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

$$
T_{\mathrm{A}} = 2^{\circ}\mathrm{C} + 273^{\circ} = 275\mathrm{K} \quad [\text{given}]
$$

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

$$\rho_{a1} = \frac{p_{\mathrm{A}}}{RT_{\mathrm{A}}} = \frac{(82\ \mathrm{kPa})\left(1000\ \dfrac{\mathrm{Pa}}{\mathrm{kPa}}\right)}{\left(287.03\ \dfrac{\mathrm{J}}{\mathrm{kg{\cdot}K}}\right)(275\mathrm{K})}$$
$$= 1.0389\ \mathrm{kg/m^3} \quad (1.0\ \mathrm{kg/m^3})$$

From equationMERM29076, the air mass flow rate is

$$\dot{m}_{a1} = \dot{V}_{a1}\rho_{a1} = \frac{\left(23\,500\ \dfrac{\mathrm{L}}{\mathrm{s}}\right)\left(1.0389\ \dfrac{\mathrm{kg}}{\mathrm{m^3}}\right)}{1000\ \dfrac{\mathrm{L}}{\mathrm{m^3}}}$$
$$= 24.41\ \mathrm{kg/s} \quad (24\ \mathrm{kg/s})$$

At B:

$$p_{\mathrm{C}} = 8p_{\mathrm{A}} = (8)(82\ \mathrm{kPa}) = 656\ \mathrm{kPa}$$

Assuming isentropic compression,

$$T_{\mathrm{B}} = T_{\mathrm{A}}\left(\frac{p_{\mathrm{B}}}{p_{\mathrm{A}}}\right)^{(k-1)/\mathrm{k}} = (275\mathrm{K})(8)^{(1.4-1)/1.4} = 498.1\mathrm{K}$$

Due to the inefficiency of the compressor, from equationMERM29099 (also *NCEES Handbook:* Open Thermodynamic Systems),

$$T'_{\mathrm{B}} = T_{\mathrm{A}} - \frac{(T_{\mathrm{A}} - T_{\mathrm{B}})}{\eta_{\mathrm{isen}}} = 275\mathrm{K} - \frac{275\mathrm{K} - 498.1\mathrm{K}}{0.85}$$
$$= 537.5\mathrm{K}$$

The work of the compressor is

$$W_{\mathrm{compression}} = c_p\left(T_{\mathrm{A}} - T'_{\mathrm{B}}\right) = \left(1.009\ \tfrac{\mathrm{kJ}}{\mathrm{kg{\cdot}K}}\right)(275\mathrm{K} - 537.5\mathrm{K})$$
$$= -264.9\ \mathrm{kJ/kg}$$

At C:

The absolute temperature is

$$T_{\mathrm{C}} = 980^\circ\mathrm{C} + 273^\circ = 1253\mathrm{K}$$

Since there is no pressure drop across the combustor, $p_{\mathrm{C}} = 656$ kPa.

The power provided by the fuel is

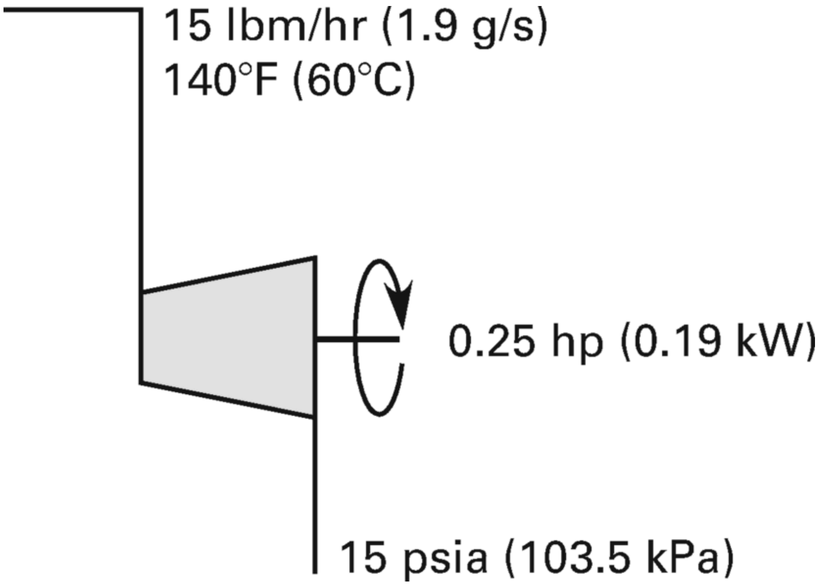
$$\dot{m}\Delta h = \dot{m}_{a1}\left(h_{\mathrm{C}} - h'_{\mathrm{B}}\right) = \dot{m}_{a1}c_p\left(T_{\mathrm{C}} - T'_{\mathrm{B}}\right)$$
$$= \left(24.41\ \tfrac{\mathrm{kg}}{\mathrm{s}}\right)\left(1.009\ \tfrac{\mathrm{kJ}}{\mathrm{kg{\cdot}K}}\right)(1253\mathrm{K} - 537.5\mathrm{K})$$
$$= 17\,622\ \mathrm{kJ/s}$$

The ideal fuel rate is

$$\frac{\dot{m}\Delta h}{\mathrm{LHV}} = \frac{17\,622\ \dfrac{\mathrm{kJ}}{\mathrm{s}}}{\left(44\ \dfrac{\mathrm{MJ}}{\mathrm{kg}}\right)\left(1000\ \dfrac{\mathrm{kJ}}{\mathrm{MJ}}\right)}$$
$$= 0.40\ \mathrm{kg/s}$$

The answer is (B).
5.

Use the illustration shown for both the customary U.S. and SI solutions.



Customary U.S. Solution

The drill power is

$$\begin{aligned} P &= 0.25\ \text{hp} \quad [\text{given}] \\ &= (0.25\ \text{hp})\left(2545\ \frac{\text{Btu}}{\text{hp-hr}}\right) \\ &= 636.25\ \text{Btu/hr} \end{aligned}$$

The absolute inlet temperature is

$$T_1 = 140^\circ\text{F} + 460^\circ = 600^\circ\text{R}$$

From equationMERM27018,

$$P = \dot{m}\left(h_1 - h_2^{'}\right)$$

$$\eta_{s,\text{turbine}} = \frac{h_1 - h_2'}{h_1 - h_2} = \frac{c_p\left(T_1 - T_2'\right)}{c_p\left(T_1 - T_2\right)}$$

Combining equations and rearranging,

$$\begin{aligned} P &= \dot{m}\eta_{s,\text{turbine}}\left(h_1 - h_2\right) \\ &= \dot{m}\eta_{s,\text{turbine}} c_p\left(T_1 - T_2\right) \\ T_2 &= T_1 - \frac{P}{\dot{m}\eta_{s,\text{turbine}} c_p} \\ &= 600^\circ\text{R} - \frac{636.25\ \frac{\text{Btu}}{\text{hr}}}{\left(15\ \frac{\text{lbm}}{\text{hr}}\right)(0.6)\left(0.24\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)} \\ &= 305.4^\circ\text{R} \end{aligned}$$

The actual temperature is

$$\begin{aligned} T_2' &= T_1 - \eta_{s,\text{turbine}}\left(T_1 - T_2\right) \\ &= 600^\circ\text{R} - (0.6)\left(600^\circ\text{R} - 305.4^\circ\text{R}\right) \\ &= 423.2^\circ\text{R} \end{aligned}$$

Using an equation for isentropic processes from *NCEES Handbook:* Closed Thermodynamic Systems, the exit pressure is

$$
\begin{aligned}
P_1 &= P_2\left(\frac{T_1}{T_2}\right)^{k/(k-1)} \\
&= \left(15\ \frac{\text{lbf}}{\text{in}^2}\right)\left(\frac{600^\circ\text{R}}{305.4^\circ\text{R}}\right)^{1.4/(1.4-1)} \\
&= 159.4\ \text{psi}
\end{aligned}
$$

Using the molecular weight from *NCEES Handbook:* Combustion Reactions and *NCEES Handbook:* Ideal Gas Law, the change in entropy is

$$
\begin{aligned}
\Delta s &= c_p \ln\frac{T_2}{T_1} - \frac{R\ln\left(\frac{p_2}{p_1}\right)}{MW} \\
&= \left(0.24\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)\left(\ln\frac{423.2^\circ\text{R}}{600^\circ\text{R}}\right) \\
&\quad - \left(\frac{1545\ \frac{\text{ft-lbf}}{\text{lbmol-}^\circ\text{R}}}{\left(29\ \frac{\text{lbm}}{\text{lbmol}}\right)\left(778\ \frac{\text{ft-lbf}}{\text{Btu}}\right)}\right)\left(\ln\frac{15\ \frac{\text{lbf}}{\text{in}^2}}{159.4\ \frac{\text{lbf}}{\text{in}^2}}\right) \\
&= 0.0773\ \text{Btu/lbm-}^\circ\text{R} \quad (0.08\ \text{Btu/lbm-}^\circ\text{R})
\end{aligned}
$$

The answer is (A).

SI Solution

The absolute inlet temperature is

$$
T_1 = 60^\circ\text{C} + 273^\circ = 333\text{K}
$$

From equationMERM27018,

$$
P = \dot{m}\left(h_1 - h_2^{'}\right)
$$

$$
\eta_{s,\text{turbine}} = \frac{h_1 - h_2'}{h_1 - h_2} = \frac{c_p\left(T_1 - T_2'\right)}{c_p\left(T_1 - T_2\right)}
$$

Combining equations and rearranging,

$$
\begin{aligned}
P &= \dot{m}\eta_{s,\text{turbine}}\left(h_1 - h_2\right) = \dot{m}\eta_{s,\text{turbine}}c_p\left(T_1 - T_2\right) \\
T_2 &= T_1 - \frac{P}{\dot{m}\eta_{s,\text{turbine}}c_p} \\
&= 333\text{K} - \frac{\left(0.19\ \text{kW}\right)\left(1000\frac{\text{g}}{\text{kg}}\right)}{\left(1.9\ \frac{\text{g}}{\text{s}}\right)(0.6)\left(1.009\ \frac{\text{kJ}}{\text{kg·K}}\right)} \\
&= 167.8\text{K}
\end{aligned}
$$

The actual temperature is

$$
\begin{aligned}
T_2' &= T_1 - \eta_{s,\text{turbine}}\left(T_1 - T_2\right) \\
&= 333\text{K} - (0.6)\left(333\text{K} - 167.8\text{K}\right) \\
&= 233.9\text{K}
\end{aligned}
$$

Using an equation for isentropic processes from *NCEES Handbook:* Closed Thermodynamic Systems, the exit pressure is

$$
\begin{aligned}
P_1 &= P_2\left(\frac{T_1}{T_2}\right)^{k/(k-1)} \\
&= (103.5\ \text{kPa})\left(\frac{333\text{K}}{167.8\text{K}}\right)^{1.4/(1.4-1)} \\
&= 1140\ \text{kPa}
\end{aligned}
$$

Using the molecular weight from *NCEES Handbook:* Combustion Reactions and *NCEES Handbook:* Ideal Gas Law, the change in entropy is

$$
\begin{aligned}
\Delta s &= c_p \ln \frac{T_2}{T_1} - \frac{R \ln\left(\frac{p_2}{p_1}\right)}{MW} \\
&= \left(1.009\ \frac{\text{kJ}}{\text{kg·K}}\right)\left(\ln \frac{233.9\text{K}}{333\text{K}}\right) \\
&\quad - \left(\frac{8.314\ \frac{\text{kJ}}{\text{kmol·K}}}{29\ \frac{\text{kg}}{\text{kmol}}}\right)\left(\ln \frac{103.5\ \text{kPa}}{1140\ \text{kPa}}\right) \\
&= 0.3314\ \text{kJ/kg·K} \qquad (0.33\ \text{kJ/kg·K})
\end{aligned}
$$

The answer is (A).