PROBLEM 9.32

KNOWN: Air enters a cold air-standard ideal Brayton cycle with a given flow rate and at a specified state. The compressor pressure ratio and maximum cycle temperature are known.

FIND: Determine (a) the thermal efficiency, (b) the back work ratio, and (c) the net power.

SCHEMATIC & GIVEN DATA:

```
\[ T_3 = 1400K \]
\[ P_1/P_3 = 10 \]
\[ P_1 = 100 \text{ kPa} \]
\[ T_1 = 300K \]
\[ P_2/P_1 = 10 \]
\[ P_2 = 100 \text{ kPa} \]
\[ T_2 = 300K \]
\[ P_3 = 100 \text{ kPa} \]
\[ V_n = 6 \text{ kg/s} \]
```

ENGINEERING MODEL: See Example 9.4

Also, assume \( k = 1.4 \) and \( c_p = 1.005 \text{ kJ/kg K} \).

ANALYSIS: First, determine \( T_2 \) and \( T_4 \), as follows:

\[ (\text{Eq. 9.23}) \quad T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} = 300 \left( \frac{10}{10} \right)^{\frac{1.4-1}{1.4}} = 579.2 \text{ K} \]

\[ (\text{Eq. 9.24}) \quad T_4 = T_3 \left( \frac{P_2}{P_3} \right)^{\frac{k-1}{k}} = 1400 \left( \frac{10}{10} \right)^{\frac{1.4-1}{1.4}} = 725.13 \text{ K} \]

(a) To evaluate thermal efficiency, use

\[ \eta = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} \]

\[ Q_{\text{in}} = m(h_3-h_2) = m c_p(T_3-T_2) \]

\[ = (6 \text{ kg/s})(1.005 \text{ kJ/kg K})(1400-579.2)\text{ K} = 4949.4 \text{ kJ/s} \]

\[ Q_{\text{out}} = m(h_4-h_1) = m c_p(T_4-T_1) = (6)(1.005)(725.13-300) = 2563.5 \text{ kJ/s} \]

Thus

\[ \eta = 1 - \frac{2563.5}{4949.4} = 0.482 \text{ (48.2\%)} \]

(b) The back work ratio is \( b_{\text{wr}} = W_{\text{c}}/W_{\text{t}} \)

\[ W_{\text{c}} = m(h_2-h_1) = m c_p(T_2-T_1) = (6)(1.005)(579.2-300) = 1683.6 \text{ kJ/s} \]

\[ W_{\text{t}} = m(h_3-h_4) = m c_p(T_3-T_4) = (6)(1.005)(1400-725.13) = 4069.5 \text{ kJ/s} \]

and

\[ b_{\text{wr}} = \frac{W_{\text{c}}}{W_{\text{t}}} = \frac{1683.6}{4069.5} = 0.4137 \]

(c) The net power developed is

\[ W_{\text{cycle}} = W_{\text{t}} - W_{\text{c}} = (4069.5-1683.6) \text{ kJ/s} = 2385.9 \text{ kW} \]

1. Using the result of Problem 9.31(a)

\[ b_{\text{wr}} = \frac{T_1}{T_4} = \frac{300K}{725.13K} = 0.4137 \]

which agrees with the value determined, as expected.
The rate of heat addition to an ideal air-standard Brayton cycle is $5.2 \times 10^6$ Btu/h. The pressure ratio for the cycle is 12 and the minimum and maximum temperatures are 520°F and 2800°F, respectively. Determine

(a) the thermal efficiency of the cycle.
(b) the mass flow rate of air, in lb/h.
(c) the net power developed by the cycle, in hp.

KNOWN: The net power developed and the pressure ratio are known for an ideal air-standard Brayton cycle. The minimum and maximum temperatures are also known.

FIND: Determine (a) the thermal efficiency, (b) the mass flow rate of air, (c) the net power developed.

Schematic & Given Data:

![Schematic of the Brayton cycle]

Engr. Model: See Example 9.4

Analysis: First, fix each of the principal states (Table A-22E).

State 1 $T_1 = 520°F \Rightarrow h_1 = 124.27$ Btu/lb, $P_1 = 1.2147$

State 2 For the isentropic compression, $P_2 = \frac{P_1}{R}P_T = 14.5764$

Thus, $T_2 = 1047.6°F$ and $h_2 = 252.84$ Btu/lb

State 3 $T_3 = 2800°F \Rightarrow h_3 = 732.33$ Btu/lb, $P_3 = 702.0$

State 4 For the isentropic expansion, $P_4 = \frac{P_3}{R}P_T = 58.5$

Thus, $T_4 = 1518°F$ and $h_4 = 373.95$ Btu/lb

(a) The thermal efficiency is evaluated using Eq.9.19 in the form

$$\eta = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{(h_3 - h_1)}{(h_4 - h_2)} = 1 - \frac{(373.95 - 124.27)}{(732.33 - 252.84)} = 0.479 \ (47.9\%)$$

(b) To determine the mass flow rate of air, start with the rate of heat addition

$$m = \frac{\dot{Q}_{in}}{(h_3 - h_1)} = \frac{(5.2 \times 10^6 \text{ Btu/h})}{(732.33 - 252.84) \text{ Btu/lb}}$$

$$= 1.084 \times 10^4 \text{ lb/h}$$

(c) The net power is

$$W_{cycle} = m \left[ (h_2 - h_4) - (h_3 - h_1) \right]$$

$$= (1.084 \times 10^4 \left[(732.33 - 373.95) - (252.84 - 124.27) \right]$$

$$= 2.49 \times 10^6 \text{ Btu/h} \left( \frac{1 \text{ hp}}{1550 \text{ Btu/h}} \right) = 998 \text{ hp}$$
9.42 An ideal air-standard regenerative Brayton cycle produces 10 MW of power. Operating data at principal states in the cycle are given in the table below. The states are numbered as in Fig. 9.14. Sketch the T-s diagram and determine
(a) the mass flow rate of air, in kg/s.
(b) the rate of heat transfer, in kW, to the working fluid passing through the combustor.
(c) the thermal efficiency.

<table>
<thead>
<tr>
<th>State</th>
<th>$p$ (kPa)</th>
<th>$T$ (K)</th>
<th>$h$ (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>300</td>
<td>300.19</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>603.5</td>
<td>610.65</td>
</tr>
<tr>
<td>x</td>
<td>1200</td>
<td>780.7</td>
<td>800.78</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>1450</td>
<td>1575.57</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>780.7</td>
<td>800.78</td>
</tr>
<tr>
<td>y</td>
<td>100</td>
<td>603.5</td>
<td>610.65</td>
</tr>
</tbody>
</table>

**KNOWN:** An ideal air-standard regenerative Brayton cycle operates with property data given at principal states. The net power output of the cycle is given.

**FIND:** Determine the mass flow rate of air, the rate of heat transfer to the working fluid passing through the combustor, and the thermal efficiency.

**SCHEMATIC AND GIVEN DATA:**

- $T_i = 300\,\text{K}$, $p_i = 100\,\text{kPa}$
- $T_f = 603.5\,\text{K}$, $p_f = 100\,\text{kPa}$
- $T_2 = 603.5\,\text{K}$, $p_2 = 1200\,\text{kPa}$
- $T_x = 780.7\,\text{K}$, $p_x = 1200\,\text{kPa}$
- $T_3 = 1450\,\text{K}$, $p_3 = 1200\,\text{kPa}$
- $T_4 = 780.7\,\text{K}$, $p_4 = 100\,\text{kPa}$

$\dot{W}_{\text{cycle}} = 10\,\text{MW}$
Problem 9.42 (Continued) – Page 2

ENGINEERING MODEL:
1. Each component is analyzed as a control volume at steady state. The control volumes are shown on the accompanying sketch by dashed lines.
2. All processes of the working fluid are internally reversible.
3. The turbine and compressor operate adiabatically.
4. There are no pressure drops for flow through the regenerator and combustor.
5. Kinetic and potential energy effects are negligible.
6. The working fluid is air modeled as an ideal gas.

ANALYSIS: The T-s diagram for the cycle is shown below.

(a) The mass flow rate of air is found as follows. Mass and energy rate balances for control volumes enclosing the turbine and compressor give

\[ \dot{W}_t = \dot{m}(h_3 - h_4) \quad \text{and} \quad \dot{W}_c = \dot{m}(h_2 - h_1) \]

The net power of the cycle is

\[ \dot{W}_{\text{cycle}} = \dot{W}_t - \dot{W}_c = \dot{m}[(h_3 - h_4) - (h_2 - h_1)] \]

Solving for \( \dot{m} \)

\[ \dot{m} = \frac{\dot{W}_{\text{cycle}}}{[(h_3 - h_4) - (h_2 - h_1)]} \]

Inserting values

\[ \dot{m} = \frac{10,000 \, \text{kW}}{\left( \frac{1575.57 \, \text{kJ}}{\text{kg}} - \frac{800.78 \, \text{kJ}}{\text{kg}} \right) - \left( \frac{610.65 \, \text{kJ}}{\text{kg}} - \frac{300.19 \, \text{kJ}}{\text{kg}} \right)} = 21.54 \, \text{kg/s} \]

(b) The rate of heat transfer to the working fluid passing through the combustor can be determined by applying mass and energy balances to a control volume around the combustor to give

\[ \dot{Q}_{in} = \dot{m}(h_3 - h_4) = \left( \frac{21.54 \, \text{kg}}{\text{s}} \right) \left( 1575.57 \, \frac{\text{kJ}}{\text{kg}} - 800.78 \, \frac{\text{kJ}}{\text{kg}} \right) = 16.689 \, \text{kW} \]

(c) The thermal efficiency is

\[ \eta = \frac{\dot{W}_{\text{cycle}}}{\dot{Q}_{in}} = \frac{10,000 \, \text{kW}}{16,689 \, \text{kW}} = 0.599 \, (59.9\%) \]
PROBLEM 9.46

KNOWN: Steady-state operating data are provided for a regenerative air-standard Brayton cycle.

FIND: Plot (a) the thermal efficiency and (b) the percent decrease in heat addition, each versus regenerator effectiveness ranging from 0 to 1.

SCHEMATIC & GIVEN DATA:

![Schematic of a regenerative Brayton cycle]

T

\( T_J = 2500 \, ^\circ R \)

COMMENTS:

ENGINEERING MODEL: See Example 9.7. \( T_J = 5200 \, ^\circ R \)

ANALYSIS: Consider the sample case of \( \eta_{reg} = 0.78 \). Using data from Table A-22E together with Eqs. 6.48 and 6.46 for the compressor and turbine isentropic efficiencies, respectively, we get:

\( h_1 = 124.27 \, \text{Btu/lb} \), \( h_2 = 292.76 \), \( h_3 = 645.78 \), \( h_4 = 356.57 \)

The specific enthalpy \( h_x \) is found using the regenerator effectiveness;

\[ h_x = \eta_{reg} (h_4 - h_2) + h_2 = 342.53 \, \text{Btu/lb} \]

From an energy balance on the regenerator:

\[ h_y = (h_2 - h_x) + h_4 = 306.8 \, \text{Btu/lb} \]

(a) The thermal efficiency is:

\[ \eta = 1 - \frac{h_y - h_1}{h_3 - h_x} = 0.398 \, (39.8\%) \]

(b) The percent decrease in heat addition is:

\[ \%\text{decrease} = \frac{(h_3 - h_x) - (h_3 - h_2)}{(h_3 - h_2)} \times 100 = 14.1\% \]

The data for the required plots are obtained using IT, as follows:

<table>
<thead>
<tr>
<th>IT Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1 = 14</td>
<td>( \text{lbm/in}^2 )</td>
</tr>
<tr>
<td>T1 = 520</td>
<td>(^\circ R)</td>
</tr>
<tr>
<td>p2 / p1 = 14</td>
<td></td>
</tr>
<tr>
<td>T2 = 2500</td>
<td>(^\circ R)</td>
</tr>
<tr>
<td>p4 = p1</td>
<td></td>
</tr>
<tr>
<td>( \eta_c ) = 0.83</td>
<td></td>
</tr>
<tr>
<td>( \eta_t ) = 0.87</td>
<td></td>
</tr>
<tr>
<td>( \eta_{reg} ) = 0.78</td>
<td></td>
</tr>
<tr>
<td>h1 = h_T(Air, T1)</td>
<td></td>
</tr>
<tr>
<td>s1 = s_TP(Air, T1, p1)</td>
<td></td>
</tr>
<tr>
<td>s2s = s_HP(Air, h2s, p2)</td>
<td></td>
</tr>
<tr>
<td>s2s = s1</td>
<td></td>
</tr>
<tr>
<td>h2 = h1 + (h2s - h1) / ( \eta_c )</td>
<td></td>
</tr>
<tr>
<td>h3 = h_T(Air, T3)</td>
<td></td>
</tr>
<tr>
<td>s3 = s_TP(Air, T3, p3)</td>
<td></td>
</tr>
<tr>
<td>s4s = s_HP(Air, h4s, p4)</td>
<td></td>
</tr>
<tr>
<td>s4s = s3</td>
<td></td>
</tr>
<tr>
<td>h4 = h3 - (h3 - h4s) / ( \eta_t )</td>
<td></td>
</tr>
<tr>
<td>hx = ( \eta_{reg} ) (h4 - h2) + h2</td>
<td></td>
</tr>
<tr>
<td>hy = h2 - hx + h4</td>
<td></td>
</tr>
<tr>
<td>eta = (h4 - h1) / (h3 - hx)</td>
<td></td>
</tr>
<tr>
<td>pct = (((h3 - h2) - (h3 - hx)) / (h3 - h2)) * 100</td>
<td></td>
</tr>
</tbody>
</table>
The heat input to the cycle decreases by about 18% with an ideal regenerator. Since the power is constant (5 x 10^6 Btu/hr), the thermal efficiency increases by a comparable amount.
**PROBLEM 9.49**

**KNOWN:** Air expands in two stages through a turbine with reheating between the stages. The states are specified at the inlet and exit of each component.

**FIND:** Determine the work developed by each stage, (b) the heat transfer for reheating, and (c) the increase in net work compared to a single stage of expansion with no reheating.

**SCHEMATIC & GIVEN DATA:**

![Diagram of air expansion through a turbine with reheating]

- $P_1 = 1200$ kPa
- $T_1 = 1200$ K
- $P_2 = P_3 = 350$ kPa
- $T_3 = 1200$ K
- $P_4 = 100$ kPa

**ENGINEERING:**

**MODEL:** (1) Each control volume is at steady state. (2) The turbines operate isentropically. (3) Kinetic and potential energy effects are negligible. (4) The working fluid is air modeled as an ideal gas.

**ANALYSIS:** First, fix each of the principal states (Table A-22).

- **State 1** $T_1 = 1200$ K $\Rightarrow$ $h_1 = 1277.79$ kJ/kg, $P_1 = 238.0$ kPa
- **State 2** $P_2 = (P_1/P_1) P_1 = 69.87 \Rightarrow t_2 = 912.11$ kJ/kg
- **State 3** $T_3 = 1200$ K $\Rightarrow$ $h_3 = h_1 = 1277.79$, $P_3 = P_1 = 238.0$ kPa
- **State 4** $P_4 = (P_3/P_3) P_3 = 68 \Rightarrow h_4 = 906.85$ kJ/kg

(a) The work developed by each stage is

$$W_{21}/m = h_1 - h_2 = 365.68 \text{ kJ/kg}$$

(b) For the reheater

$$\frac{Q_{in}}{m} = h_3 - h_2 = (1277.79 - 912.11) = 365.7 \text{ kJ/kg}$$

(c) To determine the work for a single stage of expansion, determine $h_a$, as follows.

$$P_{ra} = (P_2/P_1) P_1 = 19.83 \Rightarrow h_a = 638.58 \text{ kJ/kg}$$

Thus

$$W/m = (h_1 - h_a) = 639.21 \text{ kJ/kg}$$

and

$$\% \text{ increase} = \frac{(365.68 + 370.94) - 639.21}{639.21} \times 100 = 15.2\%$$
PROBLEM 9.53

Air enters a two-stage compressor operating at steady state at 520°F, 14 lbm/in.². The overall pressure ratio across the stages is 12, and each stage operates isentropically. Intercooling occurs at constant pressure at the value that minimizes compressor work input as determined in Example 9.10, with air exiting the intercooler at 520°F. Assuming ideal gas behavior, with \( k = 1.4 \), determine the work per unit mass of air flowing for the two-stage compressor. Kinetic and potential energies can be ignored.

KNOWN: Air enters a two-stage compressor operating at steady state with known temperature and pressure. Each stage operates isentropically, and ideal intercooling occurs between the stages at the pressure that minimizes compressor work input. The overall pressure ratio and the temperature of the air exiting the intercooler are given.

FIND: Determine the work per unit mass of air flowing for the two-stage compressor.

SCHEMATIC AND GIVEN DATA:

![Diagram showing two-stage compressor with intercooler]

ENGINEERING MODEL:
1. The compressor stages and intercooler are analyzed as control volumes at steady state.
2. The compression processes are isentropic.
3. There is no pressure drop for flow through the intercooler.
4. Kinetic and potential energy effect are ignored.
5. The air is modeled as an ideal gas with \( k = 1.4 \).

ANALYSIS:
From Example 9.10, the intercooler pressure that corresponds to the minimum compressor work input is found from \( p_2/p_1 = p_2/p_n \), with \( p_2 = 12 p_1 \)

\[
p_1/p_1 = \sqrt{12} = 3.464
\]

From Example 9.10, the work input per unit mass is

\[
w_m = c_p T_1 \left( \frac{p_1}{p_n} \right)^{\frac{k-1}{k}} + \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 2 = 2 c_p T_1 \left( \frac{p_1}{p_n} \right)^{\frac{k-1}{k}} - 1
\]

For \( k = 1.4 \), \( c_p = kR/(k-1) = 0.24 \text{ Btu/lb} \cdot ^{\circ}R \). Thus

\[
w_m = 2(0.24 \text{ Btu/lb} \cdot ^{\circ}R (520^{\circ}R) \left( 3.464 \right)^{\frac{1.4-1}{1.4}} - 1) = 106.4 \text{ Btu/lb}
\]
PROBLEM 9.58

KNOWN: A turbojet engine is analyzed on an air-standard basis. Data are known at various locations and the mass flow rate is specified.

FIND: Determine (a) the pressures and temperatures at each principal state, (b) the rate of heat addition, and (c) the velocity at the nozzle exit.

SCHEMATIC & GIVEN DATA:

ENGINEERING MODEL: Same as in Example 9.13, except $\eta_t = 0.85$ and $\eta_f = 0.90$.

ANALYSIS: (a) Fix each of the principal states.

State 1: $T_1 = 2300 \text{ K}$, $P_1 = 26 \text{ kPa}$

State 2: From an energy balance for the diffuser:

$h_2 = h_1 + \frac{V_a^2}{2} = 230.02 + \frac{220 \text{ m}^2/\text{s}^2}{2} = 234.22 \text{ J/kg}$

$\Rightarrow T_2 = 254.15 \text{ K}$ (from Table A-22).

Interpolating with Table A-22, $P_2 = 20.74 \text{ kPa}$.

For a polytropic process from a to 1:

$P_1 = \left( \frac{P_2}{P_a} \right) P_a = \left( \frac{0.74}{0.544} \right) 26 \text{ kPa} = 36.91 \text{ kPa}$

State 3: $P_3 = P_2 \left( \frac{P_a}{P_2} \right) = 0.74 \times 20.74 \text{ kPa} = 150.42 \text{ kPa}$

$h_3 = h_2 - (h_2 - h_1) = 598.71 - 234.22 = 364.49 \text{ J/kg}$

State 4: The turbine is assumed to drive the compressor only: $W_b = W_c$

$h_4 = h_3 - (h_3 - h_4) = 1515.42 - (598.71 - 234.22) = 1219.33 \text{ J/kg}$

$P_4 = P_3 \left( \frac{P_{3.5}}{P_3} \right) = 121.95 \text{ kPa}$

Then

$\Rightarrow P_4 = P_2 \left( \frac{P_a}{P_2} \right) \left( \frac{181.32}{0.544} \right) = 163.4 \text{ kPa}$
**Problem 9.53 (Continued)**

State 5

\[ P_{35} \cdot P_{45} \left( \frac{P_5}{P_4} \right) = 200.564 \left( \frac{26}{163.4} \right) = 31.913 \]

Interpolating,

\[ h_5 = 734.12 \text{ kJ/kg} \]

\[ T_5 = 719.3 \text{ K} \]

(a) Summary

<table>
<thead>
<tr>
<th>State</th>
<th>( p ) (kPa)</th>
<th>( T ) (K)</th>
<th>( h ) (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.91</td>
<td>259.15</td>
<td>259.22</td>
</tr>
<tr>
<td>2</td>
<td>406.01</td>
<td>545.2</td>
<td>549.71</td>
</tr>
<tr>
<td>3</td>
<td>406.01</td>
<td>700</td>
<td>1515.42</td>
</tr>
<tr>
<td>4</td>
<td>163.4</td>
<td>1130.6</td>
<td>1219.93</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>719.3</td>
<td>734.12</td>
</tr>
</tbody>
</table>

(b) \( \dot{Q}_{in} = m (h_3 - h_2) \)

\[ = (25 \text{ kg/s})(1515.42 - 549.71) \text{ kJ/kg} = 2.914 \times 10^4 \text{ kJ/s} \]

(c) For the nozzle

\[ \theta = (h_4 - h_5) + \sqrt{\frac{2 \cdot 8 \cdot V_5^2}{\rho}} \]

Thus

\[ V_5 = \sqrt{2 (h_4 - h_5)} \]

\[ = \sqrt{2 (1219.93 - 734.12)} \text{ (kJ/kg)} \]

\[ = 985.7 \text{ m/s} \]
PROBLEM 9.62

Air enters the diffuser of a ramjet engine (Fig. 9.27c) at 6 lb/ft², 420°F, with a velocity of 1600 ft/s, and decelerates essentially to zero velocity. After combustion, the gases reach a temperature of 2200°F before being discharged through the nozzle at 6 lb/ft². On the basis of an air-standard analysis, determine

(a) the pressure at the diffuser exit, in lb/ft².
(b) the velocity at the nozzle exit, in ft/s.

Neglect kinetic energy except at the diffuser inlet and the nozzle exit. Assume combustion occurs at constant pressure and flow through the diffuser and nozzle is isentropic.

KNOWN: Air enters the diffuser of a ramjet with known conditions. The temperature after combustion is specified.

FIND: Using an air-standard analysis, determine (a) the pressure at the diffuser exit and (b) the velocity at the nozzle exit.

SCHEMATIC & GIVEN DATA:

\[ T_1 = 420°F \]
\[ P_1 = 6 \text{ lb/ft}^2 \]
\[ T_2 = 2200°F \]
\[ V_{2} = 0 \]
\[ P_4 = 6 \text{ lb/ft}^2 \]
\[ V_4 = 1600 \text{ ft/s} \]

ENERG. MODEL: (1) Each component is analyzed as a control volume at steady state. (2) The combustion process is modeled as a constant pressure heat addition. (3) The diffuser and nozzle operate isentropically. (4) Neglect kinetic energy at locations 2 and 3. (5) The working fluid is air modeled as an ideal gas.

ANALYSIS: (a) For the diffuser: \( O = (h_1 + \frac{V_{2}^2}{2}) - h_2 \). Thus,

\[ h_2 = h_1 + \frac{V_{2}^2}{2} = 100.32 + \frac{1600^2 \text{ ft}^2/\text{s}^2}{2} = 151.41 \text{ Btu/lb} \]

With \( T_1 \) and \( h_2 \), Table A-22 E gives \( P_{r1} = 0.3960 \) and \( P_{r2} = 2.4214 \). Then, since the flow occurs isentropically,

\[ P_2 = \left( \frac{P_{r2}}{P_{r1}} \right) P_1 = \left( \frac{2.4214}{0.3960} \right) (6 \text{ lb/ft}^2) = 25.22 \text{ lb/ft}^2 \]

(b) \( T_2 = 2200°F \) \( \Rightarrow \) \( h_3 = 560.59 \text{ Btu/lb} \), \( P_{r3} = 256.6 \). For isentropic expansion through the nozzle

\[ P_{r4} = P_{r3} \left( \frac{P_4}{P_3} \right) = 256.6 \left( \frac{6}{25.22} \right) = 61.047 \]

\[ h_4 = 318.34 \text{ Btu/lb} \]

The velocity is found from

\[ 0 = h_3 - (h_4 + \frac{V_{4}^2}{2}) \]

\[ \Rightarrow \]

\[ V_4 = \sqrt{2(h_3 - h_4)} \]

\[ = \sqrt{2(560.59 - 318.34) \frac{\text{Btu}}{1\text{ lb}} \frac{32.2 \text{ lb-ft/lb}}{1\text{ Btu}} \frac{778 \text{ ft-lb}}{1\text{ Btu}}} \]

\[ = 3022 \text{ ft/s} \]