**Problem 8.81**

**Known:** A combined heat and power system provides turbine power, process steam, and stream for a space heating load. Data are given at key states.

**Find:** Determine (a) the role steam is extracted, (b) the rates of heat transfer for each load, and (c) the net power. Derive and evaluate an overall energy-based efficiency for the combined heat and power system.

**Schematic & Given Data:**

**Engineerin Model:** (1) Each component is modeled as a control volume at steady-state. (2) Turbine stages, pumps, and feedwater heater operate adiabatically, and $y_i = 0.85$. (3) Kinetic and potential energy effects are negligible. (4) Saturated liquid exits the condenser.

**Analysis:** First, fix each of the principal states.

**State 1:** $p = 450$ psia, $T_i = 600°F$, $h_i = 1302.5$ Btu/lb, $s_i = 1.5732$ Btu/lb

**State 2:** $p = 100$ psia, $h_2 = h_{25}$, $s_2 = s_{25} = 0.9783 \Rightarrow h_{25} = 1164.1$ Btu/lb. With the turbine-stage efficiency $h_2 = h_i - n_t \cdot c_p \cdot (h_2 - h_{25}) = 1184.9$ Btu/lb.

Using $h_2$, $x_2 = (h_2 - h_{25})/h_{fg} = 0.9967 \Rightarrow s_2 = 1.5497$ Btu/lb

**State 3:** $p_3 = 20$ psia, $s_3 = s_{35} = 0.9082$, $h_3 = 1065.3$ Btu/lb

Thus $h_4 = h_3 - n_t \cdot c_p \cdot (h_3 - h_{25}) = 1083.2$ Btu/lb. Also, $x_3 = 0.9238$, $s_3 = 1.6251$ Btu/lb

**State 4:** $x_4 = 1$, $s_4 = s_{45} = 0.8049$, $h_4 = 907.8$ Btu/lb

Thus $h_5 = h_4 - n_t \cdot c_p \cdot (h_4 - h_{25}) = 934.2$ Btu/lb

**State 5:** $p_i = 100$ psia

**State 6:** $p_6 = 20$ psia

With the pump efficiency, $h_6 = h_5 + c_p \cdot (P_6 - P_5) = 69.74$ Btu/lb

**State 1:** $p_1 = 100$ psia, $h_{10} = h_{25} = 198.6$ Btu/lb,

**State 2:** $h_{11} = h_{10} + v_{10} (P_{11} - P_{10}) = 198.24 + (0.01683)(1450 - 20) = 197.6$ Btu/lb

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Problem 8-81 continued

(a) For the steam extracted at state 2: \( y = \frac{m_2}{m_1} \Rightarrow \frac{m_2}{m_1} = 0.4 \left( \frac{10^4 \text{ lb/h}}{1410 \text{ lb/h}} \right) = 4 \times 10^3 \text{ lb/h} \)

To find \( m_3 \):
\[ m_3 = y \frac{m_1}{m_1} = y \frac{m_1}{m_1} = 0.2763 \]

For the open feedwater heater: \( Q = y h_8 + \left( y' - y \right) h_9 + (1 - y') h_6 - h_{10} \)
Solving for \( y' \):
\[ y' = \frac{y (h_6 - h_8) + h_{10} - h_6}{(h_9 - h_6)} = 0.4 \left( \frac{69.81 - 29.86}{196.26 - 69.81} \right) = 0.2763 \]
Thus:
\[ m_3 = (0.2763) (10^4 \text{ lb/h}) = 2.763 \times 10^3 \text{ lb/h} \]

(b) \( Q_{\text{Process}} = m_2 (h_2 - h_7) = (4 \times 10^3 \text{ lb/h}) (1184.9 - 29.86) \frac{\text{Btu}}{\text{lb}} = 3.545 \times 10^6 \text{ Btu/h} \)
\( Q_{\text{Heating}} = m_3 (h_3 - h_9) = (2.763 \times 10^3 \text{ lb/h}) (1083.2 - 196.26) = 2.451 \times 10^6 \text{ Btu/h} \)

(c) For the control volume enclosing the turbine stages:
\[ W_t = \dot{m}_1 \left[ h_1 - y h_2 - y' h_3 - (1-y-y') h_4 \right] \]
\[ = (10^4 \text{ lb/h}) \left[ 302.5 - (0.4)(1184.9) - (0.2763)(1083.2) - (0.3207)(934.2) \right] \frac{\text{Btu}}{\text{lb}} \]
\[ = 2.268 \times 10^6 \frac{\text{Btu}}{\text{h}} \]

For the pumps:
\[ W_p = W_{p1} + W_{p2} = \dot{m}_1 \left[ (1-y-y') (h_6-h_5) + (h_{11}-h_{10}) \right] \]
\[ = (10^4 \text{ lb/h}) \left[ 0.3237(69.80-69.74) + (197.84 - 196.26) \right] \frac{\text{Btu}}{\text{lb}} = 1.6 \times 10^4 \frac{\text{Btu}}{\text{h}} \]

\( W_{\text{Cycle}} = W_t - W_p = 2.252 \times 10^6 \frac{\text{Btu}}{\text{h}} \)

Energy-based Efficiency: The energy transfers \( Q_{\text{Process}}, Q_{\text{Heating}}, \) and \( W_{\text{Cycle}} \) all have economic values. Thus, a rational energy-based efficiency is
\[ \eta_{\text{overall}} = \frac{Q_{\text{Process}} + Q_{\text{Heating}} + W_{\text{Cycle}}}{m_1 (h_1-h_{11})} \]
\[ = \frac{3.545 \times 10^6 + 2.451 \times 10^6 + 2.252 \times 10^6}{10^4 (1310.2 - 197.84)} \]
\[ = \frac{8.248 \times 10^6}{1.1047 \times 10^7} = 0.747 (74.7\%) \]

1. In early printing of the sixth edition, Fig 8.81 was incorrect. The corrected version is used in this solution. We apologize for the error.
2. An exergetic efficiency would provide a more accurate picture of the economic value provided with the combined heating and power cycle.