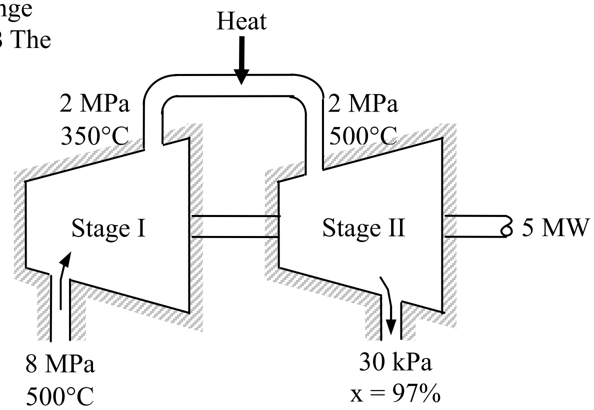
8-114 Steam expands in a two-stage adiabatic turbine from a specified state to another specified state. Steam is reheated between the stages. For a given power output, the reversible power output and the rate of exergy destruction are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** The turbine is adiabatic and thus heat transfer is negligible. **4** The environment temperature is given to be T_0 = 25°C.



Properties From the steam tables (Tables A-4 through 6)

$$\left.\begin{array}{l} P_1 = 8\text{ MPa} \\ T_1 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3399.5\text{ kJ/kg} \\ s_1 = 6.7266\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 2\text{ MPa} \\ T_2 = 350°\text{C} \end{array}\right\} \begin{array}{l} h_2 = 3137.7\text{ kJ/kg} \\ s_2 = 6.9583\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_3 = 2\text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3468.3\text{ kJ/kg} \\ s_3 = 7.4337\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 30\text{ kPa} \\ x_4 = 0.97 \end{array}\right\} \begin{array}{l} h_4 = h_f + x_4 h_{fg} = 289.27 + 0.97\times 2335.3 = 2554.5\text{ kJ/kg} \\ s_4 = s_f + x_4 s_{fg} = 0.9441 + 0.97\times 6.8234 = 7.5628\text{ kJ/kg}\cdot\text{K} \end{array}$$

Analysis We take the entire turbine, excluding the reheat section, as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}^{\nearrow 0\text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}h_1 + \dot{m}h_3 = \dot{m}h_2 + \dot{m}h_4 + \dot{W}_{out}$$

$$\dot{W}_{out} = \dot{m}[(h_1 - h_2) + (h_3 - h_4)]$$

Substituting, the mass flow rate of the steam is determined from the steady-flow energy equation applied to the actual process,

$$\dot{m} = \frac{\dot{W}_{out}}{h_1 - h_2 + h_3 - h_4} = \frac{5000\text{ kJ/s}}{(3399.5 - 3137.7 + 3468.3 - 2554.5)\text{kJ/kg}} = 4.253\text{ kg/s}$$

The reversible (or maximum) power output is determined from the rate form of the exergy balance applied on the turbine and setting the exergy destruction term equal to zero,

$$\underbrace{\dot{X}_{in} - \dot{X}_{out}}_{\substack{\text{Rate of net exergy transfer}\\ \text{by heat, work, and mass}}} - \underbrace{\dot{X}_{destroyed}^{\nearrow 0\text{ (reversible)}}}_{\substack{\text{Rate of exergy}\\ \text{destruction}}} = \underbrace{\Delta \dot{X}_{system}^{\nearrow 0\text{ (steady)}}}_{\substack{\text{Rate of change}\\ \text{of exergy}}} = 0$$

$$\dot{X}_{in} = \dot{X}_{out}$$

$$\dot{m}\psi_1 + \dot{m}\psi_3 = \dot{m}\psi_2 + \dot{m}\psi_4 + \dot{W}_{rev,out}$$

$$\begin{aligned} \dot{W}_{rev,out} &= \dot{m}(\psi_1 - \psi_2) + \dot{m}(\psi_3 - \psi_4) \\ &= \dot{m}[(h_1 - h_2) + T_0(s_2 - s_1) - \Delta\text{ke}^{\nearrow 0} - \Delta\text{pe}^{\nearrow 0}] \\ &\quad + \dot{m}[(h_3 - h_4) + T_0(s_4 - s_3) - \Delta\text{ke}^{\nearrow 0} - \Delta\text{pe}^{\nearrow 0}] \end{aligned}$$

Then the reversible power becomes

$$\begin{aligned} \dot{W}_{rev,out} &= \dot{m}\left[h_1 - h_2 + h_3 - h_4 + T_0(s_2 - s_1 + s_4 - s_3)\right] \\ &= (4.253\text{ kg/s})[(3399.5 - 3137.7 + 3468.3 - 2554.5)\text{kJ/kg} \\ &\quad +(298\text{ K})(6.9583 - 6.7266 + 7.5628 - 7.4337)\text{kJ/kg}\cdot\text{K}] \\ &= \mathbf{5457\text{ kW}} \end{aligned}$$

Then the rate of exergy destruction is determined from its definition,

$$\dot{X}_{destroyed} = \dot{W}_{rev,out} - \dot{W}_{out} = 5457 - 5000 = \mathbf{457\text{ kW}}$$