4-61 Air is accelerated in a nozzle from 30 m/s to 180 m/s. The mass flow rate, the exit temperature, and the exit area of the nozzle are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Air is an ideal gas with constant specific heats. **3** Potential energy changes are negligible. **4** The device is adiabatic and thus heat transfer is negligible. **5** There are no work interactions.

Properties The gas constant of air is 0.287 kPa.m³/kg.K (Table A-1). The specific heat of air at the anticipated average temperature of 450 K is $C_p = 1.02$ kJ/kg.°C (Table A-2).

Analysis (*a*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Using the ideal gas relation, the specific volume and the mass flow rate of air are determined to be

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(473 \text{ K})}{300 \text{ kPa}} = 0.4525 \text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{1}{v_1} A_1 \mathbf{V}_1 = \frac{1}{0.4525 \text{m}^3/\text{kg}} (0.008 \text{m}^2)(30 \text{m/s}) = \textbf{0.5304 kg/s}$$

(*b*) We take nozzle as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

$$\dot{m}(h_1 + \mathbf{V}_1^2 / 2) = \dot{m}(h_2 + \mathbf{V}_2^2/2) \quad (\text{since } \dot{Q} \cong \dot{W} \cong \Delta pe \cong 0)$$

$$0 = h_2 - h_1 + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} \longrightarrow 0 = C_{p,ave}(T_2 - T_1) + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2}$$

Substituting,

$$0 = (1.02 \text{ kJ/kg} \cdot \text{K})(T_2 - 200°\text{C}) + \frac{(180 \text{ m/s})^2 - (30 \text{ m/s})^2}{2} \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right)$$
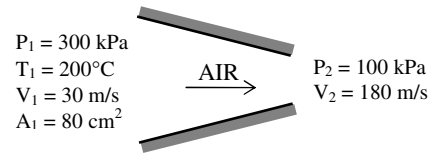
It yields $\qquad\qquad\qquad\qquad T_2 = \textbf{184.6°C}$

(*c*) The specific volume of air at the nozzle exit is

$$v_2 = \frac{RT_2}{P_2} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(184.6 + 273 \text{ K})}{100 \text{ kPa}} = 1.313 \text{ m}^3/\text{kg}$$

$P_1 = 300$ kPa
$T_1 = 200$°C
$V_1 = 30$ m/s
$A_1 = 80$ cm²

AIR

$P_2 = 100$ kPa
$V_2 = 180$ m/s

$$\dot{m} = \frac{1}{v_2} A_2 \mathbf{V}_2 \longrightarrow 0.5304 \text{kg/s} = \frac{1}{1.313 \text{m}^3/\text{kg}} A_2 (180 \text{m/s})$$

$$A_2 = 0.00387 \text{ m}^2 = \textbf{38.7 cm}^2$$

4-62 EES solution of this (and other comprehensive problems designated with the *computer icon*) is available to instructors at the *Instructor Manual* section of the *Online Learning Center* (OLC) at www.mhhe.com/cengel-boles. See the Preface for access information.

4-67 Air is decelerated in a diffuser from 230 m/s to 30 m/s. The exit temperature of air and the exit area of the diffuser are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Air is an ideal gas with variable specific heats. **3** Potential energy changes are negligible. **4** The device is adiabatic and thus heat transfer is negligible. **5** There are no work interactions.

Properties The gas constant of air is 0.287 kPa.m^3/kg.K (Table A-1). The enthalpy of air at the inlet temperature of 400 K is $h_1 = 400.98$ kJ/kg (Table A-17).

Analysis (a) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take diffuser as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

$$\dot{m}(h_1 + \mathbf{V}_1^2 / 2) = \dot{m}(h_2 + \mathbf{V}_2^2/2) \quad (\text{since } \dot{Q} \cong \dot{W} \cong \Delta\text{pe} \cong 0)$$

$$0 = h_2 - h_1 + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2}$$

or,

$$h_2 = h_1 - \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} = 400.98\text{kJ/kg} - \frac{(30\text{m/s})^2 - (230\text{m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000\text{m}^2/\text{s}^2}\right) = 426.98\text{kJ/kg}$$
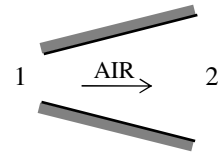
From Table A-17, $T_2 = $ **425.6 K**

(*b*) The specific volume of air at the diffuser exit is

$$v_2 = \frac{RT_2}{P_2} = \frac{(0.287\text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(425.6\text{K})}{(100\text{kPa})} = 1.221\text{m}^3/\text{kg}$$

From conservation of mass,

$$\dot{m} = \frac{1}{v_2} A_2 \mathbf{V}_2 \longrightarrow A_2 = \frac{\dot{m}v_2}{\mathbf{V}_2} = \frac{(6000/3600 \text{ kg/s})(1.221 \text{ m}^3/\text{kg})}{30 \text{ m/s}} = \mathbf{0.0678 \ m^2}$$

Turbines and Compressors

4-75C Yes.

4-76C The volume flow rate at the compressor inlet will be greater than that at the compressor exit.

4-77C Yes. Because energy (in the form of shaft work) is being added to the air.

4-78C No.

4-79 Steam expands in a turbine. The change in kinetic energy, the power output, and the turbine inlet area are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Potential energy changes are negligible. **3** The device is adiabatic and thus heat transfer is negligible.

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

$$\left. \begin{array}{l} P_1 = 10\text{MPa} \\ T_1 = 450°\text{C} \end{array} \right\} \begin{array}{l} v_1 = 0.02975\text{m}^3/\text{kg} \\ h_1 = 3240.9\text{kJ/kg} \end{array}$$

and

$$\left. \begin{array}{l} P_2 = 10\text{ kPa} \\ x_2 = 0.92 \end{array} \right\} h_2 = h_f + x_2 h_{fg} = 191.83 + 0.92 \times 2392.8 = 2393.2\text{kJ/kg}$$

$P_1 = 10$ MPa
$T_1 = 450°C$
$V_1 = 80$ m/s

STEAM
$\dot{m} = 12$ kg/s

$\dot{W}$

$P_2 = 10$ kPa
$x_2 = 0.92$
$V_2 = 50$ m/s

Analysis (a) The change in kinetic energy is determined from

$$\Delta ke = \frac{V_2^2 - V_1^2}{2} = \frac{(50\text{m/s})^2 - (80\text{m/s})^2}{2} \left(\frac{1\text{kJ/kg}}{1000\text{m}^2/\text{s}^2} \right) = -1.95\text{kJ/kg}$$

(*b*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

$$\dot{m}(h_1 + V_1^2/2) = \dot{W}_{out} + \dot{m}(h_2 + V_2^2/2) \quad (\text{since } \dot{Q} \cong \Delta pe \cong 0)$$
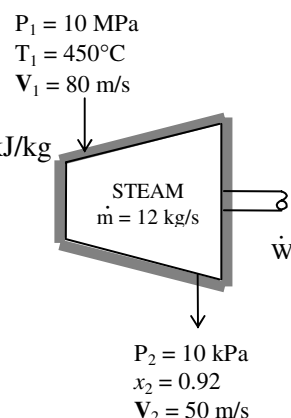
$$\dot{W}_{out} = -\dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} \right)$$

Then the power output of the turbine is determined by substitution to be

$$\dot{W}_{out} = -(12 \text{ kg/s})(2393.2 - 3240.9 - 1.95)\text{kJ/kg} = \textbf{10.2 MW}$$

(*c*) The inlet area of the turbine is determined from the mass flow rate relation,

$$\dot{m} = \frac{1}{v_1} A_1 V_1 \longrightarrow A_1 = \frac{\dot{m}v_1}{V_1} = \frac{(12 \text{ kg/s})(0.02975 \text{ m}^3/\text{kg})}{80 \text{ m/s}} = \textbf{0.00446 m}^2$$

4-86 Refrigerant-134a is compressed steadily by a compressor. The power input to the compressor and the volume flow rate of the refrigerant at the compressor inlet 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 device is adiabatic and thus heat transfer is negligible.

Properties From the refrigerant tables (Tables A-11 through 13)

$$\left. T_1 = -20°C \atop sat.vapor \right\} \begin{array}{l} v_1 = 0.1464 m^3/kg \\ h_1 = 235.31 kJ/kg \end{array}$$

$$\left. P_2 = 0.7MPa \atop T_2 = 70°C \right\} h_2 = 307.01 kJ/kg$$

Analysis (*a*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the compressor as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

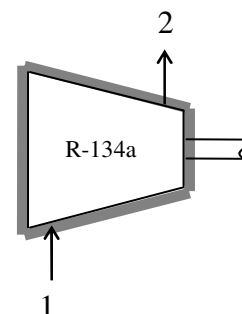$$\dot{W}_{in} + \dot{m}h_1 = \dot{m}h_2 \quad (\text{since } \dot{Q} \cong \Delta ke \cong \Delta pe \cong 0)$$

$$\dot{W}_{in} = \dot{m}(h_2 - h_1)$$

Substituting,

$$\dot{W}_{in} = (1.2 kg/s)(307.01 - 235.31) kJ/kg$$

$$= \mathbf{86.04 kJ/s}$$

(*b*) The volume flow rate of the refrigerant at the compressor inlet is

$$\dot{V}_1 = \dot{m}v_1 = (1.2 kg/s)(0.1464 m^3/kg) = \mathbf{0.176 m^3/s}$$

Throttling Valves

4-92C Because usually there is a large temperature drop associated with the throttling process.

4-93C Yes.

4-94C No. Because air is an ideal gas and h = h(T) for ideal gases. Thus if h remains constant, so does the temperature.

4-95C If it remains in the liquid phase, no. But if some of the liquid vaporizes during throttling, then yes.

4-96 Refrigerant-134a is throttled by a valve. The temperature drop of the refrigerant and specific volume after expansion are to be determined. $\sqrt{}$

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** Heat transfer to or from the fluid is negligible. **4** There are no work interactions involved.

Properties The inlet enthalpy of R-134a is, from the refrigerant tables (Tables A-11 through 13),

$$P_1 = 0.8MPa \left.\begin{array}{l} T_1 = T_{sat} = 31.33°C \\ h_1 = h_f = 93.42kJ/kg \end{array}\right.$$
sat.liquid

Analysis There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the throttling valve as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0 \text{ (steady)}} = 0 \quad \rightarrow \quad \dot{E}_{in} = \dot{E}_{out} \quad \rightarrow \quad \dot{m}h_1 = \dot{m}h_2 \quad \rightarrow \quad h_1 = h_2$$

since $\dot{Q} \cong \dot{W} = \Delta ke \cong \Delta pe \cong 0$. Then,

$$P_2 = 0.14MPa \left.\begin{array}{l} h_f = 25.77kJ/kg, \quad T_{sat} = -18.8°C \\ h_g = 236.04kJ/kg \end{array}\right.$$
$(h_2 = h_1)$

P_1 = 800 kPa
Sat. liquid

R-134a

P_2 = 140 kPa

Obviously $h_f < h_2 < h_g$, thus the refrigerant exists as a saturated mixture at the exit state and thus $T_2 = T_{sat} = -18.8°C$. Then the temperature drop becomes
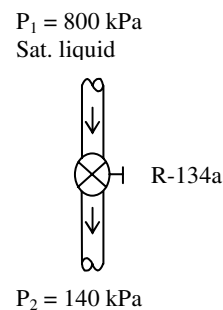
$$\Delta T = T_2 - T_1 = -18.8 - 31.33 = \mathbf{-50.13°C}$$

The quality at this state is determined from

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{93.42 - 25.77}{210.27 - 25.77} = 0.322$$

Thus,

$$v_2 = v_f + x_2 v_{fg} = 0.0007381 + 0.322 \times 0.13876 = \mathbf{0.0454 m^3/kg}$$

4-106 Feedwater is heated in a chamber by mixing it with superheated steam. If the mixture is saturated liquid, the ratio of the mass flow rates of the feedwater and the superheated vapor is 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** There are no work interactions. **4** The device is adiabatic and thus heat transfer is negligible.

Properties Noting that $T < T_{sat\ @\ 800\ kPa} = 170.43°C$, the cold water stream and the mixture exist as a compressed liquid, which can be approximated as a saturated liquid at the given temperature. Thus,

$$h_1 \cong h_{f\ @\ 50\text{-}C} = 209.33 \text{ kJ/kg}$$
$$h_3 \cong h_{f\ @\ 800\ kPa} = 721.11 \text{ kJ/kg}$$

and

$$\left. \begin{matrix} P_2 = 800\text{kPa} \\ T_2 = 200°\text{C} \end{matrix} \right\} h_2 = 2839.3\text{kJ/kg}$$

Analysis   We take the mixing chamber as the system, which is a control volume since mass crosses the boundary. The mass and energy balances for this steady-flow system can be expressed in the rate form as
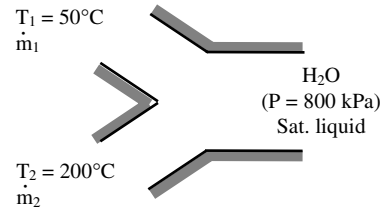
Mass balance: $\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{system}^{\nearrow 0 \ \text{(steady)}} = 0 \quad \rightarrow \quad \dot{m}_{in} = \dot{m}_{out} \quad \rightarrow \quad \dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy balance:

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

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

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (\text{since } \dot{Q} \cong \dot{W} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

$T_1 = 50°C$
$\dot{m}_1$

H_2O
$(P = 800 \text{ kPa})$
Sat. liquid

$T_2 = 200°C$
$\dot{m}_2$

Combining the two, $\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2)h_3$

Dividing by $\dot{m}_2$ yields $y h_1 + h_2 = (y+1)h_3$

Solving for *y*: $y = \dfrac{h_3 - h_2}{h_1 - h_3}$

where $y = \dot{m}_1 / \dot{m}_2$ is the desired mass flow rate ratio. Substituting,

$$y = \frac{721.11 - 2839.3}{209.33 - 721.11} = \textbf{4.14}$$

4-110 Refrigerant-134a is to be cooled by air in the condenser. For a specified volume flow rate of air, the mass flow rate of the refrigerant is 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** There are no work interactions. **4** Heat loss from the device to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. **5** Air is an ideal gas with constant specific heats at room temperature.

Properties The gas constant of air is 0.287 kPa.m³/kg.K (Table A-1). The constant pressure specific heat of air is C_p = 1.005 kJ/kg· °C (Table A-2). The enthalpies of the R-134a at the inlet and the exit states are (Tables A-11 through A-13)

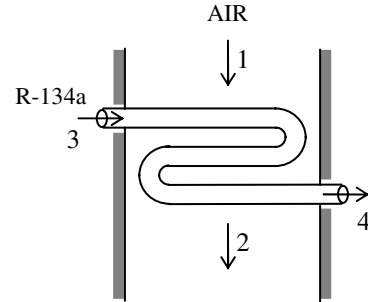$$\left. \begin{array}{l} P_3 = 1\text{MPa} \\ T_3 = 80°\text{C} \end{array} \right\} h_3 = 313.20\text{kJ/kg}$$

$$\left. \begin{array}{l} P_4 = 1\text{MPa} \\ T_4 = 30°\text{C} \end{array} \right\} h_4 \cong h_{f@30°C} = 91.49\text{kJ/kg}$$

Analysis The inlet specific volume and the mass flow rate of air are

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(300\text{K})}{100\text{kPa}} = 0.861\text{m}^3/\text{kg}$$

and

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{800\text{m}^3/\text{min}}{0.861\text{m}^3/\text{kg}} = 929.2\text{kg/min}$$

We take the entire heat exchanger as the system, which is a control volume. The mass and energy balances for this steady-flow system can be expressed in the rate form as

Mass balance (*for each fluid stream*):

$$\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{\text{system}}^{\nearrow 0 \text{ (steady)}} = 0 \;\; \rightarrow \;\; \dot{m}_{in} = \dot{m}_{out} \;\; \rightarrow \;\; \dot{m}_1 = \dot{m}_2 = \dot{m}_a \;\; \text{and} \;\; \dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Energy balance (for the entire heat exchanger):

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

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

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} = \dot{W} = \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

Combining the two, $\qquad\qquad \dot{m}_a (h_2 - h_1) = \dot{m}_R (h_3 - h_4)$

Solving for $\dot{m}_R$: $\qquad\qquad \dot{m}_R = \dfrac{h_2 - h_1}{h_3 - h_4} \dot{m}_a \cong \dfrac{C_p (T_2 - T_1)}{h_3 - h_4} \dot{m}_a$

Substituting,

$$\dot{m}_R = \frac{(1.005 \text{ kJ/kg·°C})(60 - 27)°\text{C}}{(313.20 - 91.49) \text{ kJ/kg}} (929.2 \text{ kg/min}) = \textbf{139.0 kg/min}$$

4-112 Refrigerant-134a is condensed in a water-cooled condenser. The mass flow rate of the cooling water required is 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** There are no work interactions. **4** Heat loss from the device to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid.

Properties The enthalpies of R-134a at the inlet and the exit states are (Tables A-5 and A-6)

$$\left.\begin{array}{l} P_3 = 800\text{kPa} \\ T_3 = 70^\circ\text{C} \end{array}\right\} h_3 = 305.50\text{kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 800\text{kPa} \\ sat.liquid \end{array}\right\} h_4 = h_{f@800\text{kPa}} = 93.42\text{kJ/kg}$$
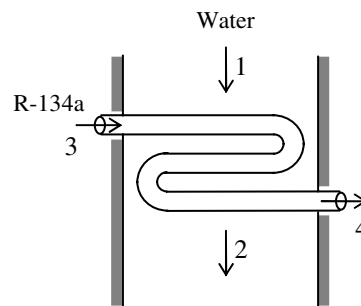
Water exists as compressed liquid at both states, and thus

$$h_1 \cong h_{f @ 15\circ C} = 62.99 \text{ kJ/kg}$$
$$h_2 \cong h_{f @ 30\circ C} = 125.79 \text{ kJ/kg}$$

Analysis We take the heat exchanger as the system, which is a control volume. The mass and energy balances for this steady-flow system can be expressed in the rate form as

Mass balance (for each fluid stream):

$$\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{system}^{\nearrow 0 \text{ (steady)}} = 0 \rightarrow \dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_w \quad \text{and} \quad \dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Energy balance (for the heat exchanger):

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

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

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} = \dot{W} = \Delta ke \cong \Delta pe \cong 0)$$

Combining the two,

$$\dot{m}_w (h_2 - h_1) = \dot{m}_R (h_3 - h_4)$$

Solving for $\dot{m}_w$:

$$\dot{m}_w = \frac{h_3 - h_4}{h_2 - h_1} \dot{m}_R$$

Substituting,

$$\dot{m}_w = \frac{(305.50 - 93.42) \text{ kJ/kg}}{(125.79 - 62.99) \text{ kJ/kg}} (8 \text{ kg/min}) = \mathbf{27.0 \text{ kg/min}}$$