

Entropy and the Increase of Entropy Principle

- Q1)** Yes. Because we used the relation $(QH/TH) = (QL/TL)$ in the proof, which is the defining relation of absolute temperature.
- Q2)** The entropy change will be the same for both cases since entropy is a property and it has a fixed value at a fixed state.
- Q3)** No. Because the entropy of the surrounding air increases even more during that process, making the total entropy change positive.
- Q4)** It is possible to create entropy, but it is not possible to destroy it.
- Q5A)** Sometimes. **Q5B)** Never. **Q5C)** Always. **Q5D)** Increase. **Q5E)** Increases. **Q5F)** Greater than.
- Q6)** They are heat transfer, irreversibilities, and entropy transport with mass.
- Q7)** Yes, because an internally reversible, adiabatic process involves no irreversibilities or heat transfer.

Entropy Changes of Ideal Gases

Q8) No. The entropy of an ideal gas depends on the pressure as well as the temperature.

Q9)

For ideal gases, $c_p = c_v + R$ and

$$\frac{P_2 V_2}{T_2} = \frac{R U_1}{T_1} \longrightarrow \frac{V_2}{V_1} = \frac{T_2 R_1}{T_1 P_2}$$

Thus,

$$\begin{aligned} s_2 - s_1 &= c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{V_2}{V_1}\right) \\ &= c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{T_2 R_1}{T_1 P_2}\right) \\ &= c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) \\ &= c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) \end{aligned}$$

Q11)

Setting $\Delta s = 0$ gives

$$c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) = 0 \longrightarrow \ln\left(\frac{T_2}{T_1}\right) = \frac{R}{c_p} \ln\left(\frac{P_2}{P_1}\right) \longrightarrow \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{R/c_p}$$

But

$$\frac{R}{c_p} = \frac{c_p - c_v}{c_p} = 1 - \frac{1}{k} = \frac{k-1}{k} \quad \text{since } k = c_p / c_v. \quad \text{Thus, } \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

Reversible Steady-Flow Work

- Q12)** The work associated with steady-flow devices is proportional to the specific volume of the gas. Cooling a gas during compression will reduce its specific volume, and thus the power consumed by the compressor.
- Q13)** Cooling the steam as it expands in a turbine will reduce its specific volume, and thus the work output of the turbine. Therefore, this is not a good proposal.
- Q14)** We would not support this proposal since the steady-flow work input to the pump is proportional to the specific volume of the liquid, and cooling will not affect the specific volume of a liquid significantly.

Q10)

For an ideal gas, $dh = c_p dT$ and $v = RT/P$. From the second Tds relation

$$ds = \frac{dh}{T} - \frac{vdP}{T} = \frac{c_p dP}{T} - \frac{RT}{P} \frac{dP}{T} = c_p \frac{dT}{T} - R \frac{dP}{P}$$

Integrating,

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

Since c_p is assumed to be constant.

Problems

Entropy and the Increase of Entropy Principle

Q1)

Assumptions 1 This is a steady-flow process since there is no change with time. 2 Kinetic and potential energy changes are negligible. 3 Air is an ideal gas. 4 The process involves no internal irreversibilities such as friction, and thus it is an isothermal, internally reversible process.

Properties Noting that $h = h(T)$ for ideal gases, we have $h_1 = h_2$ since $T_1 = T_2 = 25^\circ \text{C}$.

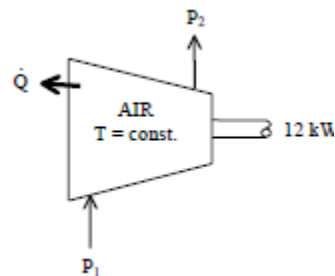
Analysis We take the compressor as the system. Noting that the enthalpy of air remains constant, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\Delta \dot{E}_{system}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} \stackrel{\text{no (steady)}}{=} 0$$

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

$$\dot{W}_{in} = \dot{Q}_{out}$$

Therefore, $Q_{out} = W_{in} = 12 \text{ kW}$



Noting that the process is assumed to be an isothermal and internally reversible process, the rate of entropy change of air is determined to be

$$\Delta \dot{S}_{air} = -\frac{\dot{Q}_{out,air}}{T_{sys}} = -\frac{12 \text{ kW}}{298 \text{ K}} = -0.0403 \text{ kW/K}$$

Q2)

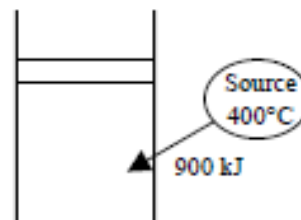
Analysis (a) This is a reversible isothermal process, and the entropy change during such a process is given by $\Delta S = Q/T$. Noting that heat transferred from the source is equal to the heat transferred to the working fluid, the entropy changes of the fluid and of the source become

$$\Delta S_{fluid} = \frac{Q_{fluid}}{T_{fluid}} = \frac{Q_{in,fluid}}{T_{fluid}} = \frac{900 \text{ kJ}}{673 \text{ K}} = 1.337 \text{ kJ/K}$$

$$(b) \quad \Delta S_{source} = \frac{Q_{source}}{T_{source}} = -\frac{Q_{out,source}}{T_{source}} = -\frac{900 \text{ kJ}}{673 \text{ K}} = -1.337 \text{ kJ/K}$$

(c) Thus the total entropy change of the process is

$$S_{gen} = \Delta S_{total} = \Delta S_{fluid} + \Delta S_{source} = 1.337 - 1.337 = 0$$



Q3)

Analysis (a) This is a reversible isothermal process, and the entropy change during such a process is given by $\Delta S = Q/T$. Noting that heat transferred from the working fluid is equal to the heat transferred to the sink, the heat transfer become

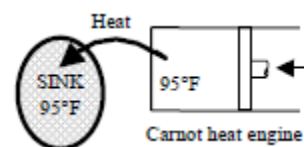
$$Q_{fluid} = T_{fluid} \Delta S_{fluid} = (555 \text{ R})(-0.7 \text{ Btu/R}) = -388.5 \text{ Btu} \rightarrow Q_{fluid,out} = 388.5 \text{ Btu}$$

(b) The entropy change of the sink is determined from

$$\Delta S_{sink} = \frac{Q_{sink,in}}{T_{sink}} = \frac{388.5 \text{ Btu}}{555 \text{ R}} = 0.7 \text{ Btu/R}$$

(c) Thus the total entropy change of the process is

$$S_{gen} = \Delta S_{total} = \Delta S_{fluid} + \Delta S_{sink} = -0.7 + 0.7 = 0$$



This is expected since all processes of the **Carnot cycle are reversible processes**, and no entropy is generated during a reversible process.

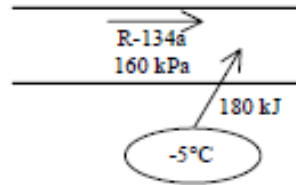
Q4)

Analysis Noting that both the refrigerant and the cooled space undergo reversible isothermal processes, the entropy change for them can be determined from $\Delta S = Q/T$ (a) The pressure of the refrigerant is maintained constant. Therefore, the temperature of the refrigerant also remains constant at the saturation value,

$$T = T_{\text{sat}@160 \text{ kPa}} = -15.6^\circ\text{C} = 257.4 \text{ K} \quad (\text{Table A-12})$$

Then,

$$\Delta S_{\text{refrigerant}} = \frac{Q_{\text{refrigerant, in}}}{T_{\text{refrigerant}}} = \frac{180 \text{ kJ}}{257.4 \text{ K}} = 0.699 \text{ kJ/K}$$



(b) Similarly,

$$\Delta S_{\text{space}} = -\frac{Q_{\text{space, out}}}{T_{\text{space}}} = -\frac{180 \text{ kJ}}{268 \text{ K}} = -0.672 \text{ kJ/K}$$

(c) The total entropy change of the process is

$$S_{\text{gen}} = S_{\text{total}} = \Delta S_{\text{refrigerant}} + \Delta S_{\text{space}} = 0.699 - 0.672 = 0.027 \text{ kJ/K}$$

Entropy Changes of Pure Substances

Q5) From the steam tables

$$\left. \begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 150^\circ\text{C} \end{array} \right\} \begin{array}{l} v_1 = 0.95986 \text{ m}^3/\text{kg} \\ s_1 = 7.2810 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} T_2 = 40^\circ\text{C} \\ v_2 = v_1 \end{array} \right\} x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.95986 - 0.001008}{19.515 - 0.001008} = 0.04914$$

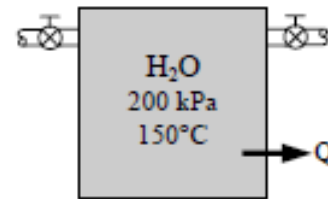
$$s_2 = s_f + x_2 s_{fg} = 0.5724 + (0.04914)(7.6832) = 0.9499 \text{ kJ/kg} \cdot \text{K}$$

The mass of the steam is

$$m = \frac{V}{v_1} = \frac{0.020 \text{ m}^3}{0.95986 \text{ m}^3/\text{kg}} = 0.02084 \text{ kg}$$

Then the entropy change of the steam during this process becomes

$$\Delta S = m(s_2 - s_1) = (0.02084 \text{ kg})(0.9499 - 7.2810) \text{ kJ/kg} \cdot \text{K} = -0.132 \text{ kJ/K}$$



Q6) (a) From the refrigerant tables

$$\begin{array}{l}
 P_1 = 200 \text{ kPa} \\
 x_1 = 0.4
 \end{array}
 \left.
 \begin{array}{l}
 u_1 = u_f + x_1 u_{fg} = 38.28 + (0.4)(186.21) = 112.76 \text{ kJ/kg} \\
 s_1 = s_f + x_1 s_{fg} = 0.15457 + (0.4)(0.78316) = 0.4678 \text{ kJ/kg} \cdot \text{K} \\
 v_1 = v_f + x_1 v_{fg} = 0.0007533 + (0.4)(0.099867 - 0.0007533) = 0.04040 \text{ m}^3/\text{kg}
 \end{array}
 \right\}$$

$$\begin{array}{l}
 P_2 = 400 \text{ kPa} \\
 v_2 = v_1
 \end{array}
 \left.
 \begin{array}{l}
 x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.04040 - 0.0007907}{0.051201 - 0.0007907} = 0.7857 \\
 u_2 = u_f + x_2 u_{fg} = 63.62 + (0.7857)(171.45) = 198.34 \text{ kJ/kg} \\
 s_2 = s_f + x_2 s_{fg} = 0.24761 + (0.7857)(0.67929) = 0.7813 \text{ kJ/kg} \cdot \text{K}
 \end{array}
 \right\}$$

The mass of the refrigerant is

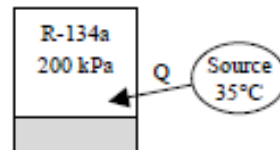
$$m = \frac{V}{v_1} = \frac{0.5 \text{ m}^3}{0.04040 \text{ m}^3/\text{kg}} = 12.38 \text{ kg}$$

Then the entropy change of the refrigerant becomes

$$\Delta S_{\text{system}} = m(s_2 - s_1) = (12.38 \text{ kg})(0.7813 - 0.4678) \text{ kJ/kg} \cdot \text{K} = 3.880 \text{ kJ/K}$$

(b) We take the tank as the system. This is a closed system since no mass enters or leaves. Noting that the volume of the system is constant and thus there is no boundary work, the energy balance for this stationary closed system can be expressed as

$$\begin{array}{l}
 \underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc. energies}} \\
 Q_{\text{in}} = \Delta U = m(u_2 - u_1)
 \end{array}$$



Substituting,

$$Q_{\text{in}} = m(u_2 - u_1) = (12.38 \text{ kg})(198.34 - 112.76) = 1059 \text{ kJ}$$

The heat transfer for the source is equal in magnitude but opposite in direction. Therefore,

$$Q_{\text{source, out}} = -Q_{\text{tank, in}} = -1059 \text{ kJ}$$

and

$$\Delta S_{\text{source}} = -\frac{Q_{\text{source, out}}}{T_{\text{source}}} = -\frac{1059 \text{ kJ}}{308 \text{ K}} = -3.439 \text{ kJ/K}$$

(c) The total entropy change for this process is

$$\Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{source}} = 3.880 + (-3.439) = 0.442 \text{ kJ/K}$$

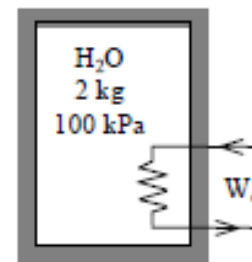
Q7) From the steam tables

$$\begin{array}{l}
 P_1 = 100 \text{ kPa} \\
 x_1 = 0.25
 \end{array}
 \left.
 \begin{array}{l}
 v_1 = v_f + x_1 v_{fg} = 0.001 + (0.25)(1.6941 - 0.001) = 0.4243 \text{ m}^3/\text{kg} \\
 s_1 = s_f + x_1 s_{fg} = 1.3028 + (0.25)(6.0562) = 2.8168 \text{ kJ/kg} \cdot \text{K}
 \end{array}
 \right\}$$

$$\begin{array}{l}
 v_2 = v_1 \\
 \text{sat. vapor}
 \end{array}
 \left.
 \begin{array}{l}
 s_2 = 6.8649 \text{ kJ/kg} \cdot \text{K}
 \end{array}
 \right\}$$

Then the entropy change of the steam becomes

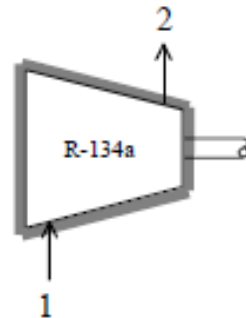
$$\Delta S = m(s_2 - s_1) = (2 \text{ kg})(6.8649 - 2.8168) \text{ kJ/kg} \cdot \text{K} = 8.10 \text{ kJ/K}$$



Q8)

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. **Analysis** The power input to an adiabatic compressor will be a minimum when the compression process is reversible. For the reversible adiabatic process we have $s_2 = s_1$. From the refrigerant tables

$$\begin{aligned}
 & \left. \begin{array}{l} P_1 = 160 \text{ kPa} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} v_1 = v_{g@160 \text{ kPa}} = 0.12348 \text{ m}^3/\text{kg} \\ h_1 = h_{g@160 \text{ kPa}} = 241.11 \text{ kJ/kg} \\ s_1 = s_{g@160 \text{ kPa}} = 0.9419 \text{ kJ/kg} \cdot \text{K} \end{array} \\
 & \left. \begin{array}{l} P_2 = 900 \text{ kPa} \\ s_2 = s_1 \end{array} \right\} h_2 = 277.06 \text{ kJ/kg}
 \end{aligned}$$



Also,

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{2 \text{ m}^3/\text{min}}{0.12348 \text{ m}^3/\text{kg}} = 16.20 \text{ kg/min} = 0.27 \text{ kg/s}$$

There is only one inlet and one exit, and thus $m_1 = m_2 = m$. 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

$$\begin{aligned}
 \dot{E}_{in} &= \dot{E}_{out} \\
 \dot{W}_{in} + \dot{m}h_1 &= \dot{m}h_2 \quad (\text{since } \dot{Q} \cong \Delta ke \cong \Delta pe \cong 0) \\
 \dot{W}_{in} &= \dot{m}(h_2 - h_1)
 \end{aligned}$$

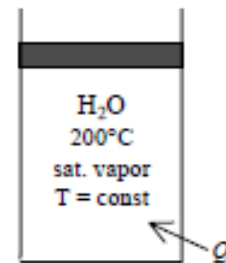
Substituting, the minimum power supplied to the compressor is determined to be

$$\dot{W}_{in} = (0.27 \text{ kg/s})(277.06 - 241.11) \text{ kJ/kg} = 9.71 \text{ kW}$$

Q9)

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

$$\begin{aligned}
 & \left. \begin{array}{l} T_1 = 200^\circ\text{C} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} u_1 = u_{g@200^\circ\text{C}} = 2594.2 \text{ kJ/kg} \\ s_1 = s_{g@200^\circ\text{C}} = 6.4302 \text{ kJ/kg} \cdot \text{K} \end{array} \\
 & \left. \begin{array}{l} P_2 = 800 \text{ kPa} \\ T_2 = T_1 \end{array} \right\} \begin{array}{l} u_2 = 2631.1 \text{ kJ/kg} \\ s_2 = 6.8177 \text{ kJ/kg} \cdot \text{K} \end{array}
 \end{aligned}$$



The heat transfer for this reversible isothermal process can be determined from

$$Q = T\Delta S = Tm(s_2 - s_1) = (473 \text{ K})(1.2 \text{ kg})(6.8177 - 6.4302) \text{ kJ/kg} \cdot \text{K} = 219.9 \text{ kJ}$$

We take the contents of the cylinder as the system. This is a closed system since no mass enters or leaves. The energy balance for this closed system can be expressed as

$$\begin{aligned}
 \underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} &= \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc. energies}} \\
 Q_{in} - \dot{W}_{b,out} &= \Delta U = m(u_2 - u_1) \\
 \dot{W}_{b,out} &= Q_{in} - m(u_2 - u_1)
 \end{aligned}$$

Substituting, the work done during this process is determined to be

$$\dot{W}_{b,out} = 219.9 \text{ kJ} - (1.2 \text{ kg})(2631.1 - 2594.2) \text{ kJ/kg} = 175.6 \text{ kJ}$$

Entropy Change of Incompressible Substances

Q10)

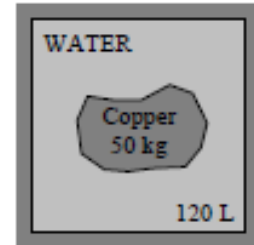
Assumptions **1** Both the water and the copper block are incompressible substances with constant specific heats at room temperature. **2** The system is stationary and thus the kinetic and potential energies are negligible. **3** The tank is well-insulated and thus there is no heat transfer.

Properties The density and specific heat of water at 25° C are $\rho = 997 \text{ kg/m}^3$ and $cp = 4.18 \text{ kJ/kg} \cdot ^\circ \text{C}$. The specific heat of copper at 27° C is $cp = 0.386 \text{ kJ/kg} \cdot ^\circ \text{C}$.

Analysis We take the entire contents of the tank, water + copper block, as the *system*. This is a *closed system* since no mass crosses the system boundary during the process. The energy balance for this system can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$0 = \Delta U$$



or,

$$\Delta U_{Cu} + \Delta U_{water} = 0$$

$$[mc(T_2 - T_1)]_{Cu} + [mc(T_2 - T_1)]_{water} = 0$$

where

$$m_{water} = \rho V = (997 \text{ kg/m}^3)(0.120 \text{ m}^3) = 119.6 \text{ kg}$$

Using specific heat values for copper and liquid water at room temperature and substituting,

$$(50 \text{ kg})(0.386 \text{ kJ/kg} \cdot ^\circ \text{C})(T_2 - 80)^\circ \text{C} + (119.6 \text{ kg})(4.18 \text{ kJ/kg} \cdot ^\circ \text{C})(T_2 - 25)^\circ \text{C} = 0$$

$$T_2 = 27.0^\circ \text{C}$$

The entropy generated during this process is determined from

$$\Delta S_{copper} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (50 \text{ kg})(0.386 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{300.0 \text{ K}}{353 \text{ K}}\right) = -3.140 \text{ kJ/K}$$

$$\Delta S_{water} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (119.6 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{300.0 \text{ K}}{298 \text{ K}}\right) = 3.344 \text{ kJ/K}$$

Thus,

$$\Delta S_{total} = \Delta S_{copper} + \Delta S_{water} = -3.140 + 3.344 = 0.204 \text{ kJ/K}$$

Q11)

Assumptions **1** Both the water and the iron block are incompressible substances with constant specific heats at room temperature. **2** The system is stationary and thus the kinetic and potential energies are negligible. **3** The tank is well-insulated and thus there is no heat transfer. **4** The water that evaporates, condenses back.

Properties The specific heat of water at 25° C is $cp = 4.18 \text{ kJ/kg} \cdot ^\circ \text{C}$. The specific heat of iron at room temperature is $cp = 0.45 \text{ kJ/kg} \cdot ^\circ \text{C}$

Analysis We take the entire contents of the tank, water + iron block, as the *system*. This is a *closed system* since no mass crosses the system boundary during the process. The energy balance for this system can be expressed as

$$\frac{E_{in} - E_{out}}{\text{Net energy transfer by heat, work, and mass}} = \frac{\Delta E_{system}}{\text{Change in internal, kinetic, potential, etc. energies}}$$

$$0 = \Delta U$$

or,

$$\Delta U_{iron} + \Delta U_{water} = 0$$

$$[mc(T_2 - T_1)]_{iron} + [mc(T_2 - T_1)]_{water} = 0$$

Substituting,

$$(25 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K})(T_2 - 350^\circ\text{C}) + (100 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K})(T_2 - 18^\circ\text{C}) = 0$$

$$T_2 = 26.7^\circ\text{C}$$

The entropy generated during this process is determined from

$$\Delta S_{iron} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (25 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{299.7 \text{ K}}{623 \text{ K}}\right) = -8.232 \text{ kJ/K}$$

$$\Delta S_{water} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (100 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{299.7 \text{ K}}{291 \text{ K}}\right) = 12.314 \text{ kJ/K}$$

Thus,

$$S_{gen} = \Delta S_{total} = \Delta S_{iron} + \Delta S_{water} = -8.232 + 12.314 = 4.08 \text{ kJ/K}$$

Discussion The results can be improved somewhat by using specific heats at average temperature

Q12)

Assumptions 1 Both the water and the iron block are incompressible substances with constant specific heats at room temperature. 2 Kinetic and potential energies are negligible.

Properties The specific heats of iron and copper at room temperature are $c_{iron} = 0.45 \text{ kJ/kg} \cdot \text{C}$ and $c_{copper} = 0.386 \text{ kJ/kg} \cdot \text{C}$.

Analysis The thermal-energy capacity of the lake is very large, and thus the temperatures of both the iron and the copper blocks will drop to the lake temperature (15°C) when the thermal equilibrium is established. Then the entropy changes of the blocks become

$$\Delta S_{iron} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (50 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{288 \text{ K}}{353 \text{ K}}\right) = -4.579 \text{ kJ/K}$$

$$\Delta S_{copper} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (20 \text{ kg})(0.386 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{288 \text{ K}}{353 \text{ K}}\right) = -1.571 \text{ kJ/K}$$

We take both the iron and the copper blocks, as the *system*. This is a *closed system* since no mass crosses the *system boundary* during the process. The energy balance for this *system* can be expressed as

$$-Q_{out} = \Delta U = \Delta U_{iron} + \Delta U_{copper}$$

or,

$$Q_{out} = [mc(T_1 - T_2)]_{iron} + [mc(T_1 - T_2)]_{copper}$$

Substituting,

$$Q_{out} = (50 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K})(353 - 288)\text{K} + (20 \text{ kg})(0.386 \text{ kJ/kg} \cdot \text{K})(353 - 288)\text{K}$$

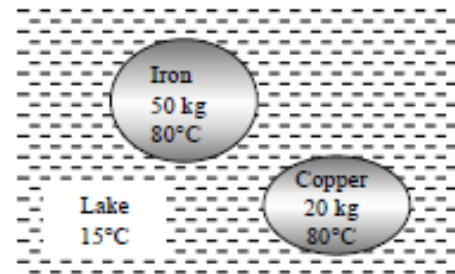
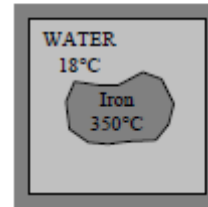
$$= 1964 \text{ kJ}$$

Thus,

$$\Delta S_{lake} = \frac{Q_{lake,in}}{T_{lake}} = \frac{1964 \text{ kJ}}{288 \text{ K}} = 6.820 \text{ kJ/K}$$

Then the total entropy change for this process is

$$\Delta S_{total} = \Delta S_{iron} + \Delta S_{copper} + \Delta S_{lake} = -4.579 - 1.571 + 6.820 = 0.670 \text{ kJ/K}$$



Entropy Changes of Ideal Gases

Q13)

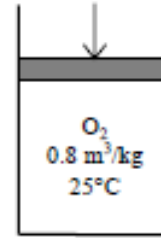
Properties The gas constant and molar mass of oxygen are $R = 0.2598 \text{ kJ/kg}\cdot\text{K}$ and $M = 32 \text{ kg/kmol}$ (Table A-1).

Analysis The constant volume specific heat of oxygen at the average temperature is

$$T_{\text{avg}} = \frac{298 + 560}{2} = 429 \text{ K} \longrightarrow c_{v,\text{avg}} = 0.690 \text{ kJ/kg}\cdot\text{K}$$

Thus,

$$\begin{aligned} s_2 - s_1 &= c_{v,\text{avg}} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \\ &= (0.690 \text{ kJ/kg}\cdot\text{K}) \ln \frac{560 \text{ K}}{298 \text{ K}} + (0.2598 \text{ kJ/kg}\cdot\text{K}) \ln \frac{0.1 \text{ m}^3/\text{kg}}{0.8 \text{ m}^3/\text{kg}} \\ &= -0.105 \text{ kJ/kg}\cdot\text{K} \end{aligned}$$



Q14)

Assumptions At specified conditions, CO_2 can be treated as an ideal gas with constant specific heats at room temperature.

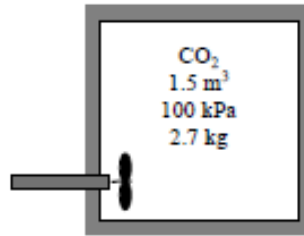
Properties The specific heat of CO_2 is $c_v = 0.657 \text{ kJ/kg}\cdot\text{K}$ (Table A-2).

Analysis Using the ideal gas relation, the entropy change is determined to be

$$\frac{P_2 V}{T_2} = \frac{P_1 V}{T_1} \longrightarrow \frac{T_2}{T_1} = \frac{P_2}{P_1} = \frac{150 \text{ kPa}}{100 \text{ kPa}} = 1.5$$

Thus,

$$\begin{aligned} \Delta S &= m(s_2 - s_1) = m \left(c_{v,\text{avg}} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \right) = m c_{v,\text{avg}} \ln \frac{T_2}{T_1} \\ &= (2.7 \text{ kg}) (0.657 \text{ kJ/kg}\cdot\text{K}) \ln(1.5) \\ &= 0.719 \text{ kJ/K} \end{aligned}$$



Q15)

Assumptions 1 At specified conditions, N_2 can be treated as an ideal gas. **2** Nitrogen has constant specific heats at room temperature.

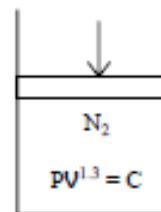
Properties The gas constant of nitrogen is $R = 0.297 \text{ kJ/kg}\cdot\text{K}$ (Table A-1). The constant volume specific heat of nitrogen at room temperature is $c_v = 0.743 \text{ kJ/kg}\cdot\text{K}$ (Table A-2).

Analysis From the polytropic relation,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{n-1} \longrightarrow T_2 = T_1 \left(\frac{v_1}{v_2} \right)^{n-1} = (300 \text{ K}) (2)^{1.3-1} = 369.3 \text{ K}$$

Then the entropy change of nitrogen becomes

$$\begin{aligned} \Delta S_{\text{N}_2} &= m \left(c_{v,\text{avg}} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \right) \\ &= (1.2 \text{ kg}) \left((0.743 \text{ kJ/kg}\cdot\text{K}) \ln \frac{369.3 \text{ K}}{300 \text{ K}} + (0.297 \text{ kJ/kg}\cdot\text{K}) \ln(0.5) \right) = -0.0617 \text{ kJ/K} \end{aligned}$$



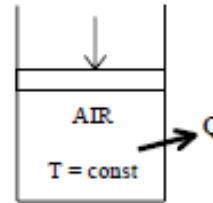
Q16)

Assumptions 1 At specified conditions, air can be treated as an ideal gas. **2** The process is specified to be reversible.

Properties The gas constant of air is $R = 0.287 \text{ kJ/kg}\cdot\text{K}$ (Table A-1).

Analysis (a) Noting that the temperature remains constant, the entropy change of air is determined from

$$\begin{aligned} \Delta S_{\text{air}} &= c_{p,\text{avg}} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} = -R \ln \frac{P_2}{P_1} \\ &= -(0.287 \text{ kJ/kg}\cdot\text{K}) \ln \left(\frac{400 \text{ kPa}}{90 \text{ kPa}} \right) = -0.428 \text{ kJ/kg}\cdot\text{K} \end{aligned}$$



Also, for a reversible isothermal process,

$$q = T\Delta s = (293 \text{ K})(-0.428 \text{ kJ/kg}\cdot\text{K}) = -125.4 \text{ kJ/kg} \longrightarrow q_{\text{out}} = 125.4 \text{ kJ/kg}$$

(b) The work done during this process is determined from the closed system energy balance,

$$\begin{aligned} \underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} &= \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}} \\ W_{\text{in}} - Q_{\text{out}} &= \Delta U = mc_v(T_2 - T_1) = 0 \\ W_{\text{in}} &= Q_{\text{out}} = 125.4 \text{ kJ/kg} \end{aligned}$$

Q17)

Assumptions 1 Air is an ideal gas with constant specific heats. **2** The nozzle operates steadily.

Properties The properties of air at room temperature are $c_p = 1.005 \text{ kJ/kg}\cdot\text{K}$, $k = 1.4$ (Table A-2a).

Analysis The exit temperature is determined from ideal gas isentropic relation to be

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{(k-1)/k} = (400 + 273 \text{ K}) \left(\frac{100 \text{ kPa}}{800 \text{ kPa}} \right)^{0.4/1.4} = 371.5 \text{ K}$$

We take the nozzle as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

$$\begin{aligned} \underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} &= \underbrace{\Delta \dot{E}_{\text{system}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} \stackrel{\text{no}}{=} \text{(steady)} = 0 \\ \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\ \dot{m} \left(h_1 + V_1^2 / 2 \right) &= \dot{m} \left(h_2 + V_2^2 / 2 \right) \\ 0 &= h_2 - h_1 + \frac{V_2^2 - 0}{2} \\ 0 &= c_p(T_2 - T_1) + \frac{V_2^2}{2} \end{aligned}$$



Therefore,

$$V_2 = \sqrt{2c_p(T_2 - T_1)} = \sqrt{2(1.005 \text{ kJ/kg}\cdot\text{K})(673 - 371.5)\text{K}} = 778.5 \text{ m/s}$$

Q18)

Assumptions 1 Air is an ideal gas with constant specific heats.

Properties The specific heat of air at room temperature is $c_v = 0.718 \text{ kJ/kg}\cdot\text{K}$ (Table A-2a).

Analysis (a) The entropy change of air is determined from

$$\begin{aligned} \Delta S_{\text{air}} &= mc_v \ln \frac{T_2}{T_1} \\ &= (5 \text{ kg})(0.718 \text{ kJ/kg}\cdot\text{K}) \ln \frac{(27 + 273) \text{ K}}{(327 + 273) \text{ K}} \\ &= -2.488 \text{ kJ/K} \end{aligned}$$

(b) An energy balance on the system gives

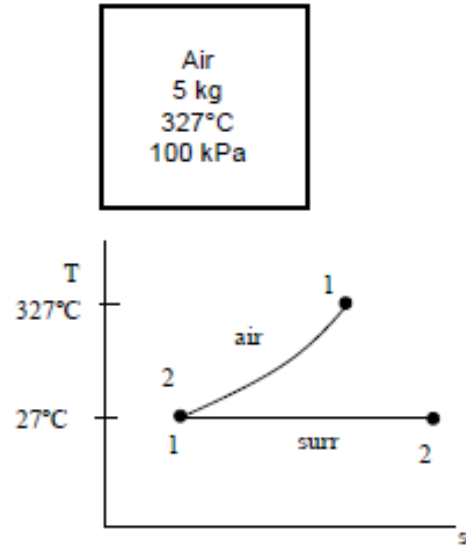
$$\begin{aligned} Q_{\text{out}} &= mc_v(T_2 - T_1) \\ &= (5 \text{ kg})(0.718 \text{ kJ/kg}\cdot\text{K})(327 - 27) \\ &= 1077 \text{ kJ} \end{aligned}$$

The entropy change of the surroundings is

$$\Delta s_{\text{surr}} = \frac{Q_{\text{out}}}{T_{\text{surr}}} = \frac{1077 \text{ kJ}}{300 \text{ K}} = 3.59 \text{ kJ/K}$$

The entropy change of universe due to this process is

$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{air}} + \Delta S_{\text{surr}} = -2.488 + 3.59 = 1.10 \text{ kJ/K}$$



Reversible Steady-Flow Work

Q19)

Assumptions 1 Liquid water is an incompressible substance. **2** Kinetic and potential energy changes are negligible. **3** The process is reversible.

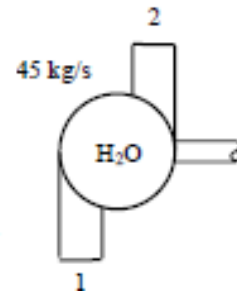
Properties The specific volume of saturated liquid water at 20 kPa is $v_1 = v_f @ 20 \text{ kPa} = 0.001017 \text{ m}^3/\text{kg}$ (Table A-5).

Analysis The power input to the pump can be determined directly from the 2 steady-flow work relation for a liquid,

$$\dot{W}_{\text{in}} = \dot{m} \left(\int_1^2 v dP + \Delta ke^{e0} + \Delta pe^{e0} \right) = \dot{m} v_1 (P_2 - P_1)$$

Substituting,

$$\dot{W}_{\text{in}} = (45 \text{ kg/s})(0.001017 \text{ m}^3/\text{kg})(6000 - 20) \text{ kPa} \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) = 274 \text{ kW}$$



Q20)

Assumptions 1 Liquid water is an incompressible substance. **2** Kinetic and potential energy changes are negligible. **3** The process is assumed to be reversible since we will determine the limiting case.

Properties The specific volume of liquid water is given to be $v_1 = 0.001 \text{ m}^3/\text{kg}$.

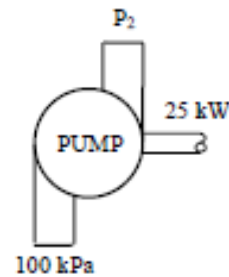
Analysis The highest pressure the liquid can have at the pump exit can be determined from the reversible steady-flow work relation for a liquid,

$$\dot{W}_{in} = \dot{m} \left(\int_1^2 \nu dP + \Delta ke^{s^0} + \Delta pe^{s^0} \right) = \dot{m} \nu_1 (P_2 - P_1)$$

Thus,

$$25 \text{ kJ/s} = (5 \text{ kg/s})(0.001 \text{ m}^3/\text{kg})(P_2 - 100) \text{ kPa} \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right)$$

It yields $P_2 = 5100 \text{ kPa}$



Q21)

Assumptions 1 Liquid water is an incompressible substance. 2 Kinetic energy changes are negligible, but potential energy changes may be significant. 3 The process is assumed to be reversible since we will determine the limiting case.

Properties The specific volume of liquid water is given to be $\nu_1 = 0.001 \text{ m}^3/\text{kg}$.

Analysis The highest mass flow rate will be realized when the entire process is reversible. Thus it is determined from the reversible steady flow work relation for a liquid,

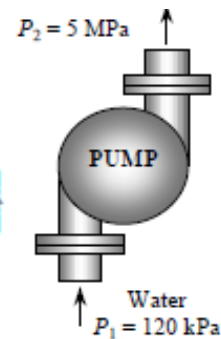
$$\dot{W}_{in} = \dot{m} \left(\int_1^2 \nu dP + \Delta ke^{s^0} + \Delta pe^{s^0} \right) = \dot{m} \left(\nu(P_2 - P_1) + g(z_2 - z_1) \right)$$

Thus,

$$7 \text{ kJ/s} = \dot{m} \left\{ (0.001 \text{ m}^3/\text{kg})(5000 - 120) \text{ kPa} \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) + (9.8 \text{ m/s}^2)(10 \text{ m}) \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \right\}$$

It yields

$$\dot{m} = 1.41 \text{ kg/s}$$



Isentropic Efficiencies of Steady-Flow Devices

Q22) 7-101C The ideal process for all three devices is the reversible adiabatic (i.e., isentropic) process. The adiabatic efficiencies of these devices are defined as

$$\eta_T = \frac{\text{actual work output}}{\text{isentropic work output}}, \quad \eta_C = \frac{\text{isentropic work input}}{\text{actual work input}}, \quad \text{and} \quad \eta_N = \frac{\text{actual exit kinetic energy}}{\text{isentropic exit kinetic energy}}$$

Q23)

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.

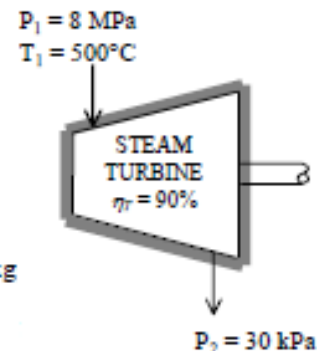
Analysis (a) From the steam tables (Tables A-4 through A-6),

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

$$\left. \begin{array}{l} P_{2s} = 30 \text{ kPa} \\ s_{2s} = s_1 \end{array} \right\} \begin{array}{l} x_{2s} = \frac{s_{2s} - s_f}{s_{fg}} = \frac{6.7266 - 0.9441}{6.8234} = 0.8475 \\ h_{2s} = h_f + x_{2s} h_{fg} = 289.27 + (0.8475)(2335.3) = 2268.3 \text{ kJ/kg} \end{array}$$

From the isentropic efficiency relation,

$$\eta_T = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \longrightarrow h_{2a} = h_1 - \eta_T (h_1 - h_{2s}) = 3399.5 - (0.9)(3399.5 - 2268.3) = 2381.4 \text{ kJ/kg}$$



Thus

$$\left. \begin{array}{l} P_{2a} = 30 \text{ kPa} \\ h_{2a} = 2381.4 \text{ kJ/kg} \end{array} \right\} T_{2a} = T_{\text{sat}@30 \text{ kPa}} = 69.09^\circ\text{C}$$

(b) There is only one inlet and one exit, and thus $m_1 = m_2 = m$. We take the actual 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

$$\begin{aligned} \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\ \dot{m}h_1 &= \dot{W}_{\text{a,out}} + \dot{m}h_2 \quad (\text{since } \dot{Q} \cong \Delta \text{ke} \cong \Delta \text{pe} \cong 0) \\ \dot{W}_{\text{a,out}} &= \dot{m}(h_1 - h_2) \end{aligned}$$

Substituting,

$$\dot{W}_{\text{a,out}} = (3 \text{ kg/s})(3399.5 - 2381.4) \text{ kJ/kg} = 3054 \text{ kW}$$

Q24)

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.

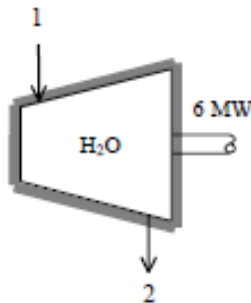
Analysis (a) From the steam tables (Tables A-4 and A-6),

$$\left. \begin{array}{l} P_1 = 7 \text{ MPa} \\ T_1 = 600^\circ\text{C} \end{array} \right\} \begin{array}{l} h_1 = 3650.6 \text{ kJ/kg} \\ s_1 = 7.0910 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 50 \text{ kPa} \\ T_2 = 150^\circ\text{C} \end{array} \right\} h_{2a} = 2780.2 \text{ kJ/kg}$$

There is only one inlet and one exit, and thus $m_1 = m_2 = m$. We take the actual 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

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



Substituting, the mass flow rate of the steam is determined to be

$$6000 \text{ kJ/s} = -\dot{m} \left(2780.2 - 3650.6 + \frac{(140 \text{ m/s})^2 - (80 \text{ m/s})^2}{2} \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \right)$$

$$\dot{m} = 6.95 \text{ kg/s}$$

(b) The isentropic exit enthalpy of the steam and the power output of the isentropic turbine are

$$\left. \begin{array}{l} P_{2s} = 50 \text{ kPa} \\ s_{2s} = s_1 \end{array} \right\} \begin{array}{l} x_{2s} = \frac{s_{2s} - s_f}{s_{fg}} = \frac{7.0910 - 1.0912}{6.5019} = 0.9228 \\ h_{2s} = h_f + x_{2s} h_{fg} = 340.54 + (0.9228)(2304.7) = 2467.3 \text{ kJ/kg} \end{array}$$

and

$$\dot{W}_{s,\text{out}} = -\dot{m} (h_{2s} - h_1 + \{ (V_2^2 - V_1^2) / 2 \})$$

$$\dot{W}_{s,\text{out}} = -(6.95 \text{ kg/s}) \left(2467.3 - 3650.6 + \frac{(140 \text{ m/s})^2 - (80 \text{ m/s})^2}{2} \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \right)$$

$$= 8174 \text{ kW}$$

Then the isentropic efficiency of the turbine becomes

$$\eta_T = \frac{\dot{W}_a}{\dot{W}_s} = \frac{6000 \text{ kW}}{8174 \text{ kW}} = 0.734 = 73.4\%$$

Q25)

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. 4 Air is an ideal gas with variable specific heats.

Analysis (a) From the air table (Table A-17),

$$T_1 = 300 \text{ K} \longrightarrow h_1 = 300.19 \text{ kJ/kg}, \quad P_{r1} = 1.386$$

$$T_2 = 550 \text{ K} \longrightarrow h_{2a} = 554.74 \text{ kJ/kg}$$

From the isentropic relation,

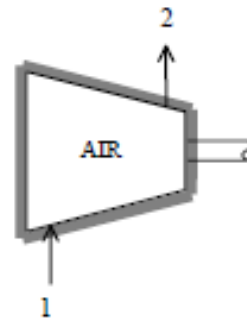
$$P_{r2} = \left(\frac{P_2}{P_1} \right) P_{r1} = \left(\frac{600 \text{ kPa}}{95 \text{ kPa}} \right) (1.386) = 8.754 \longrightarrow h_{2s} = 508.72 \text{ kJ/kg}$$

Then the isentropic efficiency becomes

$$\eta_c = \frac{h_{2s} - h_1}{h_{2a} - h_1} = \frac{508.72 - 300.19}{554.74 - 300.19} = 0.819 = 81.9\%$$

(b) If the process were isentropic, the exit temperature would be

$$h_{2s} = 508.72 \text{ kJ/kg} \longrightarrow T_{2s} = 505.5 \text{ K}$$



Q26)

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. 4 Air is an ideal gas with variable specific heats.

Analysis From the air table (Table A-17E), There is only one inlet and one exit, and thus $m_1 = m_2 = m$. We take the 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 as

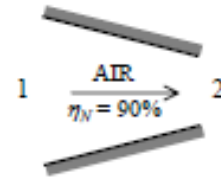
$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}(h_1 + V_1^2/2) = \dot{m}(h_2 + V_2^2/2) \quad (\text{since } \dot{W} = \dot{Q} \cong \Delta p e \cong 0)$$

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2}$$

Substituting, the exit temperature of air is determined to be

$$h_2 = 363.89 \text{ kJ/kg} - \frac{(800 \text{ ft/s})^2 - 0}{2} \left(\frac{1 \text{ Btu/lbm}}{25,037 \text{ ft}^2/\text{s}^2} \right) = 351.11 \text{ Btu/lbm}$$



From the air table we read $T_{2a} = 1431.3 \text{ R}$

From the isentropic efficiency relation $\eta_N = \frac{h_{2a} - h_1}{h_{2s} - h_1}$,

$$h_{2s} = h_1 + (h_{2a} - h_1)/\eta_N = 363.89 + (351.11 - 363.89)/(0.90) = 349.69 \text{ Btu/lbm} \longrightarrow P_{r_2} = 46.04$$

Then the exit pressure is determined from the isentropic relation to be

$$\frac{P_2}{P_1} = \frac{P_{r_2}}{P_{r_1}} \longrightarrow P_2 = \left(\frac{P_{r_2}}{P_{r_1}} \right) P_1 = \left(\frac{46.04}{53.04} \right) (60 \text{ psia}) = 52.1 \text{ psia}$$