

Chapter 7

ENTROPY

Entropy and the Increase of Entropy Principle

7-1C Yes. Because we used the relation $(Q_H/T_H) = (Q_L/T_L)$ in the proof, which is the defining relation of absolute temperature.

7-2C No. The $\oint \delta Q$ represents the net heat transfer during a cycle, which could be positive.

7-3C Yes.

7-4C No. A system may reject more (or less) heat than it receives during a cycle. The steam in a steam power plant, for example, receives more heat than it rejects during a cycle.

7-5C No. A system may produce more (or less) work than it receives during a cycle. A steam power plant, for example, produces more work than it receives during a cycle, the difference being the net work output.

7-6C 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.

7-7C No. In general, that integral will have a different value for different processes. However, it will have the same value for all reversible processes.

7-8C Yes.

7-9C That integral should be performed along a reversible path to determine the entropy change.

7-10C No. An isothermal process can be irreversible. Example: A system that involves paddle-wheel work while losing an equivalent amount of heat.

7-11C The value of this integral is always larger for reversible processes.

7-12C No. Because the entropy of the surrounding air increases even more during that process, making the total entropy change positive.

7-13C It is possible to create entropy, but it is not possible to destroy it.

7-14C Sometimes.

7-15C Never.

7-16C Always.

7-17C Increase.

7-18C Increases.

7-19C Decreases.

7-20C Sometimes.

7-21C Yes. This will happen when the system is losing heat, and the decrease in entropy as a result of this heat loss is equal to the increase in entropy as a result of irreversibilities.

7-22C They are heat transfer, irreversibilities, and entropy transport with mass.

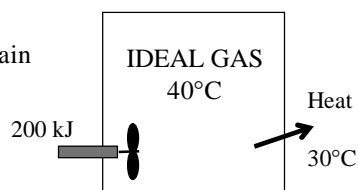
7-23C Greater than.

7-24 A rigid tank contains an ideal gas that is being stirred by a paddle wheel. The temperature of the gas remains constant as a result of heat transfer out. The entropy change of the gas is to be determined.

Assumptions The gas in the tank is given to be an ideal gas.

Analysis The temperature and the specific volume of the gas remain constant during this process. Therefore, the initial and the final states of the gas are the same. Then $s_2 = s_1$ since entropy is a property. Therefore,

$$\Delta S_{sys} = 0$$



7-25 Air is compressed steadily by a compressor. The air temperature is maintained constant by heat rejection to the surroundings. The rate of entropy change of air 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** Air is an ideal gas. **4** The process involves no internal irreversibilities such as friction, and thus it is an isothermal, internally reversible process.

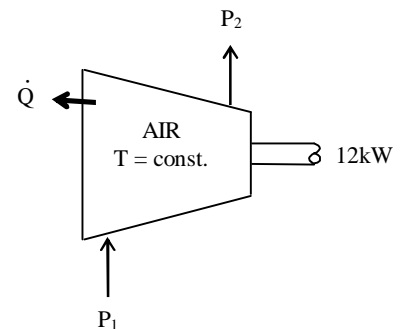
Properties Noting that $h = h(T)$ for ideal gases, we have $h_1 = h_2$ since $T_1 = T_2 = 25^\circ\text{C}$.

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

$$\begin{aligned} \dot{E}_{\text{in}} - \dot{E}_{\text{out}} &= \Delta \dot{E}_{\text{system}} \quad \dot{a}0 \text{ (steady)} = 0 \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\ \dot{W}_{\text{in}} &= \dot{Q}_{\text{out}} \end{aligned}$$

Therefore,

$$\dot{Q}_{\text{out}} = \dot{W}_{\text{in}} = 12 \text{ kW}$$



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

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

7-26 Heat is transferred isothermally from a source to the working fluid of a Carnot engine. The entropy change of the working fluid, the entropy change of the source, and the total entropy change during this process are to be determined.

Analysis (a) This is a reversible isothermal process, and the entropy change during such a process is given by

$$\Delta S = \frac{Q}{T}$$

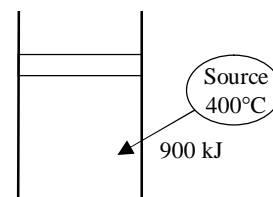
Noting that heat transferred from the source is equal to the heat transferred to the working fluid, the entropy changes of the fluid and of the source become

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

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

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

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



7-27 Problem 7-26 is reconsidered. The effects of the varying the heat transferred to the working fluid and the source temperature on the entropy change of the working fluid, the entropy change of the source, and the total entropy change for the process as the source temperature varies from 100°C to 1000°C are to be investigated. The entropy changes of the source and of the working fluid are to be plotted against the source temperature for heat transfer amounts of 500 kJ, 900 kJ, and 1300 kJ.

"Knowns:"

$$\{T_H = 400^\circ\text{C}\}$$

$$Q_H = 1300\text{ kJ}$$

$$T_{\text{Sys}} = T_H$$

"Analysis:"

(a) & (b) 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 "

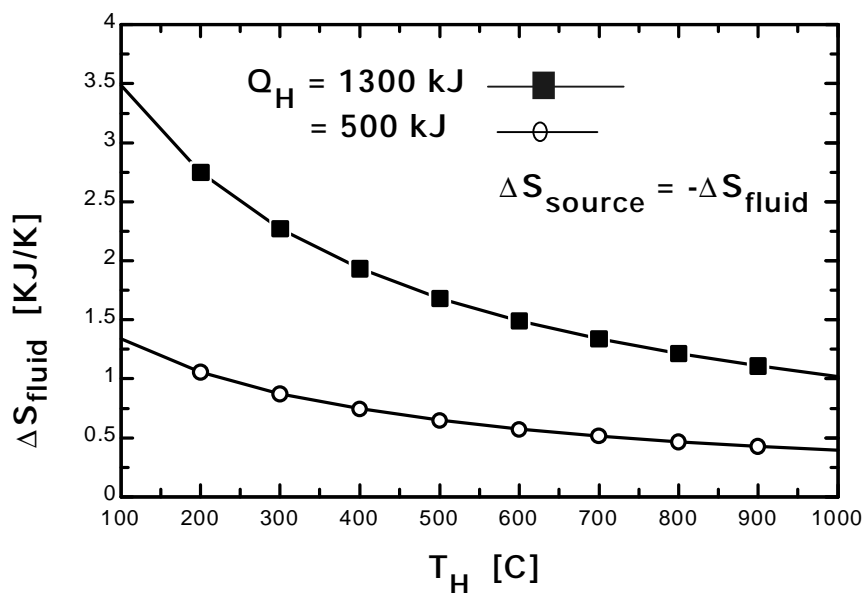
$$\Delta S_{\text{source}} = -Q_H/(T_H+273)\text{ [KJ/K]}$$

$$\Delta S_{\text{fluid}} = +Q_H/(T_{\text{Sys}}+273)\text{ [KJ/K]}$$

"(c) entropy generation for the process:"

$$S_{\text{gen}} = \Delta S_{\text{source}} + \Delta S_{\text{fluid}}\text{ [KJ/K]}$$

ΔS_{fluid} [kJ/K]	ΔS_{source} [kJ/K]	S_{gen} [kJ/K]	T_H [C]
3.485	-3.485	0	100
2.748	-2.748	0	200
2.269	-2.269	0	300
1.932	-1.932	0	400
1.682	-1.682	0	500
1.489	-1.489	0	600
1.336	-1.336	0	700
1.212	-1.212	0	800
1.108	-1.108	0	900
1.021	-1.021	0	1000



7-28E Heat is transferred isothermally from the working fluid of a Carnot engine to a heat sink. The entropy change of the working fluid is given. The amount of heat transfer, the entropy change of the sink, and the total entropy change during the process are to be determined.

Analysis (a) This is a reversible isothermal process, and the entropy change during such a process is given by

$$\Delta S = \frac{Q}{T}$$

Noting that heat transferred from the working fluid is equal to the heat transferred to the sink, the heat transfer become

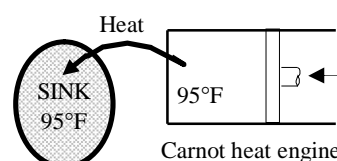
$$Q_{fluid} = T_{fluid} \Delta S_{fluid} = (555 \text{ R})(-0.7 \text{ Btu/R}) = -388.5 \text{ Btu} \rightarrow Q_{fluid, out} = 388.5 \text{ Btu}$$

(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.

7-29 R-134a enters an evaporator as a saturated liquid-vapor at a specified pressure. Heat is transferred to the refrigerant from the cooled space, and the liquid is vaporized. The entropy change of the refrigerant, the entropy change of the cooled space, and the total entropy change for this process are to be determined.

Assumptions 1 Both the refrigerant and the cooled space involve no internal irreversibilities such as friction. 2 Any temperature change occurs within the wall of the tube, and thus both the refrigerant and the cooled space remain isothermal during this process. Thus it is an isothermal, internally reversible process.

Analysis Noting that both the refrigerant and the cooled space undergo reversible isothermal processes, the entropy change for them can be determined from

$$\Delta S = \frac{Q}{T}$$

(a) The pressure of the refrigerant is maintained constant. Therefore, the temperature of the refrigerant also remains constant at the saturation value,

$$T = T_{sat @ 200 \text{ kPa}} = -10.09^\circ \text{C} = 263 \text{ K}$$

Then,

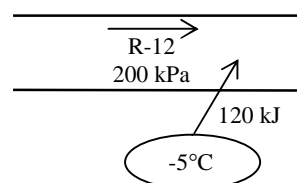
$$\Delta S_{refrigerant} = \frac{Q_{refrigerant, in}}{T_{refrigerant}} = \frac{120 \text{ kJ}}{263 \text{ K}} = 0.456 \text{ kJ/K}$$

(b) Similarly,

$$\Delta S_{space} = -\frac{Q_{space, out}}{T_{space}} = -\frac{120 \text{ kJ}}{268 \text{ K}} = -0.448 \text{ kJ/K}$$

(c) The total entropy change of the process is

$$S_{gen} = \Delta S_{total} = \Delta S_{refrigerant} + \Delta S_{space} = 0.456 - 0.448 = 0.008 \text{ kJ/K}$$



Entropy Changes of Pure Substances

7-30C Yes, because an internally reversible, adiabatic process involves no irreversibilities or heat transfer.

7-31 The radiator of a steam heating system is initially filled with superheated steam. The valves are closed, and steam is allowed to cool until the temperature drops to a specified value by transferring heat to the room. The entropy change of the steam during this process is to be determined. \checkmark

Analysis From the steam tables,

$$\left. \begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 200^\circ \text{C} \end{array} \right\} \begin{array}{l} v_1 = 1.0803 \text{ m}^3/\text{kg} \\ s_1 = 7.5066 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} T_2 = 80^\circ \text{C} \\ v_2 = v_1 \end{array} \right\} x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{1.0803 - 0.001029}{3.407 - 0.001029} = 0.317$$

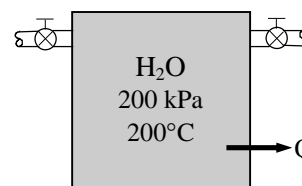
$$\begin{aligned} s_2 &= s_f + x_2 s_{fg} = 1.0753 + (0.317)(6.5369) \\ &= 3.1475 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

The mass of the steam is

$$m = \frac{V}{v_1} = \frac{0.020 \text{ m}^3}{1.0803 \text{ m}^3/\text{kg}} = 0.0185 \text{ kg}$$

Then the entropy change of the steam during this process becomes

$$\Delta S = m(s_2 - s_1) = (0.0185 \text{ kg})(3.1475 - 7.5066) \text{ kJ/kg} \cdot \text{K} = \mathbf{-0.0806 \text{ kJ/K}}$$



7-32 A rigid tank is initially filled with a saturated mixture of R-134a. Heat is transferred to the tank from a source until the pressure inside rises to a specified value. The entropy change of the refrigerant, entropy change of the source, and the total entropy change for this process are to be determined. ✓

Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions.

Analysis (a) From the refrigerant tables (Tables A-11 through A-13),

$$\left. \begin{array}{l} P_1 = 200 \text{ kPa} \\ x_1 = 0.4 \end{array} \right\} \begin{array}{l} u_1 = u_f + x_1 u_{fg} = 36.69 + (0.4)(221.43 - 36.69) = 110.59 \text{ kJ/kg} \\ s_1 = s_f + x_1 s_{fg} = 0.1481 + (0.4)(0.9253 - 0.1481) = 0.4590 \text{ kJ/kg} \cdot \text{K} \\ v_1 = v_f + x_1 v_{fg} = 0.0007532 + (0.4)(0.0993 - 0.0007532) = 0.04017 \text{ m}^3/\text{kg} \end{array}$$

$$\left. \begin{array}{l} P_2 = 400 \text{ kPa} \\ v_2 = v_1 \end{array} \right\} \begin{array}{l} x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.04017 - 0.0007904}{0.0509 - 0.0007904} = 0.7859 \\ u_2 = u_f + x_2 u_{fg} = 61.69 + (0.7859)(231.97 - 61.69) = 195.51 \text{ kJ/kg} \\ s_2 = s_f + x_2 s_{fg} = 0.2399 + (0.7859)(0.9145 - 0.2399) = 0.7701 \text{ kJ/kg} \cdot \text{K} \end{array}$$

The mass of the refrigerant is

$$m = \frac{V}{v_1} = \frac{0.5 \text{ m}^3}{0.04017 \text{ m}^3/\text{kg}} = 12.45 \text{ kg}$$

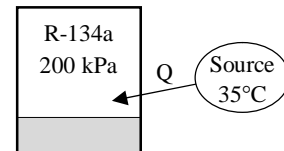
Then the entropy change of the refrigerant becomes

$$\Delta S_{\text{system}} = m(s_2 - s_1) = (12.45 \text{ kg})(0.7701 - 0.4590) \text{ kJ/kg} \cdot \text{K} = \mathbf{3.873 \text{ kJ/K}}$$

(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

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

$$Q_{\text{in}} = \Delta U = m(u_2 - u_1)$$



Substituting,

$$Q_{\text{in}} = m(u_2 - u_1) = (12.45 \text{ kg})(195.51 - 110.59) = 1057 \text{ kJ}$$

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

$Q_{\text{source, out}} = -Q_{\text{tank, in}} = -1057 \text{ kJ}$, and

$$\Delta S_{\text{source}} = -\frac{Q_{\text{source, out}}}{T_{\text{source}}} = -\frac{1057 \text{ kJ}}{308 \text{ K}} = \mathbf{-3.432 \text{ kJ/K}}$$

(c) The total entropy change for this process is

$$\Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{source}} = 3.873 + (-3.432) = \mathbf{0.441 \text{ kJ/K}}$$

7-33 Problem 7-32 is reconsidered. The effects of the source temperature and final pressure on the total entropy change for the process as the source temperature varies from 30°C to 210°C, and the final pressure varies from 250 kPa to 500 kPa are to be investigated. The total entropy change for the process is to be plotted as a function of the source temperature for final pressures of 250 kPa, 400 kPa, and 500 kPa.

"Knowns:"

$$P_1 = 200 \text{ [kPa]}$$

$$x_1 = 0.4$$

$$V_{\text{sys}} = 0.5 \text{ [m}^3\text{]}$$

$$P_2 = 400 \text{ [kPa]}$$

$$\{T_{\text{source}} = 35 \text{ [C]}\}$$

"Analysis: "

" Treat the rigid tank as a closed system, with no work in, neglect changes in KE and PE of the R134a."

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{sys}}$$

$$E_{\text{out}} = 0 \text{ [kJ]}$$

$$E_{\text{in}} = Q \text{ [kJ]}$$

$$\Delta E_{\text{sys}} = m_{\text{sys}}(u_2 - u_1) \text{ [kJ]}$$

$$u_1 = \text{INTENERGY}(\text{R134a}, P=P_1, x=x_1) \text{ [kJ/kg]}$$

$$v_1 = \text{volume}(\text{R134a}, P=P_1, x=x_1) \text{ [m}^3\text{/kg]}$$

$$V_{\text{sys}} = m_{\text{sys}} v_1$$

"Rigid Tank: The process is constant volume. Then P_2 and v_2 specify state 2."

$$v_2 = v_1 \text{ [m}^3\text{/kg]}$$

$$u_2 = \text{INTENERGY}(\text{R134a}, P=P_2, v=v_2) \text{ [kJ/kg]}$$

"Entropy calculations:"

$$s_1 = \text{entropy}(\text{R134a}, P=P_1, x=x_1) \text{ [kJ/kg-K]}$$

$$s_2 = \text{entropy}(\text{R134a}, P=P_2, v=v_2) \text{ [kJ/kg-K]}$$

$$\Delta S_{\text{sys}} = m_{\text{sys}}(s_2 - s_1) \text{ [kJ/K]}$$

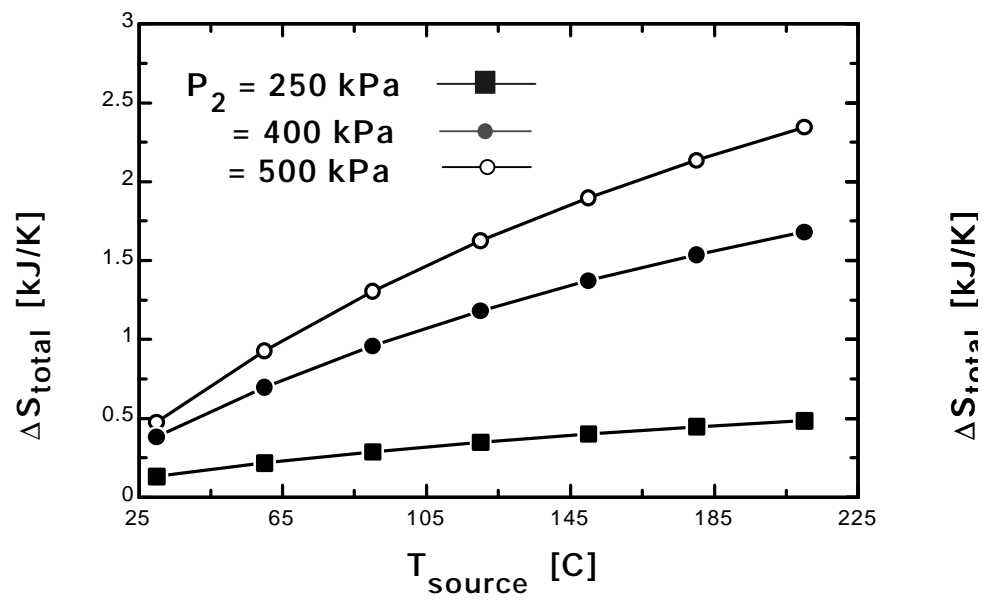
"Heat is leaving the source, thus:"

$$\Delta S_{\text{source}} = -Q/(T_{\text{source}} + 273) \text{ [kJ/K]}$$

"Total Entropy Change:"

$$\Delta S_{\text{total}} = \Delta S_{\text{source}} + \Delta S_{\text{sys}} \text{ [kJ/K]}$$

ΔS_{total} [kJ/K]	T_{source} [C]
0.3837	30
0.6977	60
0.9598	90
1.182	120
1.372	150
1.538	180
1.683	210



7-34 An insulated rigid tank contains a saturated liquid-vapor mixture of water at a specified pressure. An electric heater inside is turned on and kept on until all the liquid vaporized. The entropy change of the water during this process is to be determined.

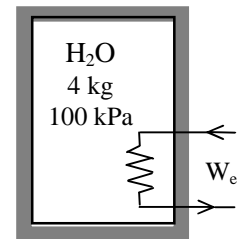
Analysis From the steam tables (Tables A-4 through A-6)

$$\begin{aligned} P_1 = 100 \text{ kPa} \quad \left\{ \begin{aligned} v_1 &= v_f + x_1 v_{fg} = 0.001 + (0.25)(1.694 - 0.001) = 0.4243 \text{ m}^3/\text{kg} \\ x_1 &= 0.25 \quad \left\{ \begin{aligned} s_1 &= s_f + x_1 s_{fg} = 1.3026 + (0.25)(6.0568) = 2.8168 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned} \right. \end{aligned}$$

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

Then the entropy change of the steam becomes

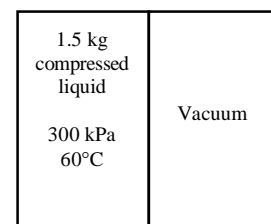
$$\Delta S = m(s_2 - s_1) = (4 \text{ kg})(6.8649 - 2.8168) \text{ kJ/kg} \cdot \text{K} = \mathbf{16.19 \text{ kJ/K}}$$



7-35 [Also solved by EES on enclosed CD] A rigid tank is divided into two equal parts by a partition. One part is filled with compressed liquid water while the other side is evacuated. The partition is removed and water expands into the entire tank. The entropy change of the water during this process is to be determined.

Analysis The properties of the water are

$$\begin{aligned} P_1 = 300 \text{ kPa} \quad \left\{ \begin{aligned} v_1 &\cong v_f @ 60^\circ \text{C} = 0.001017 \text{ m}^3/\text{kg} \\ T_1 = 60^\circ \text{C} \quad \left\{ \begin{aligned} s_1 &= s_f @ 60^\circ \text{C} = 0.8312 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned} \right. \end{aligned}$$



$$\text{Noting that } v_2 = 2v_1 = (2)(0.001017) = 0.002034 \text{ m}^3/\text{kg}$$

$$\begin{aligned} P_2 = 15 \text{ kPa} \quad \left\{ \begin{aligned} x_2 &= \frac{v_2 - v_f}{v_{fg}} = \frac{0.002034 - 0.001014}{10.02 - 0.001014} = 0.0001018 \\ v_2 = 0.002034 \quad \left\{ \begin{aligned} s_2 &= s_f + x_2 s_{fg} = 0.7549 + (0.0001018)(7.2536) = 0.7556 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned} \right. \end{aligned}$$

Then the entropy change of the water becomes

$$\Delta S = m(s_2 - s_1) = (1.5 \text{ kg})(0.7556 - 0.8312) \text{ kJ/kg} \cdot \text{K} = \mathbf{-0.1134 \text{ kJ/K}}$$

7-36 Problem 7-35 is reconsidered. The entropy generated is to be evaluated and plotted as a function of surroundings temperature, and the values of the surroundings temperatures that are valid for this problem are to be determined. The surrounding temperature is to vary from 0°C to 100°C.

"Input Data"

P[1]=300"kJPa"

T[1]=60"C"

m=1.5"kg"

P[2]=15"kJPa"

V[1]=m*spv[1]

spv[1]=volume(steam,T=T[1], P=P[1]) "specific volume of steam at state 1, m³/kg"

s[1]=entropy(steam,T=T[1],P=P[1]) "entropy of steam at state 1, kJ/kgK"

V[2]=2*V[1] "Steam expands to fill entire volume at state 2"

"State 2 is identified by P[2] and spv[2]"

spv[2]=V[2]/m "specific volume of steam at state 2, m³/kg"

s[2]=entropy(steam,P=P[2],v=spv[2]) "entropy of steam at state 2, kJ/kgK"

T[2]=temperature(steam,P=P[2],v=spv[2])

DELTAS_sys=m*(s[2]-s[1]) "Total entropy change of steam, kJ/K"

"What does the first law tell us about this problem?"

"Conservation of Energy for the entire, closed system"

E_in - E_out = DELTAE_sys

"neglecting changes in KE and PE for the system:"

DELTAE_sys=m*(intenergy(steam, P=P[2], v=spv[2]) - intenergy(steam,T=T[1],P=P[1])) "kJ"

E_in = 0

"How do you interpret the energy leaving the system, E_out? Recall this is a constant volume system."

Q_out = E_out

"What is the maximum value of the Surroundings temperature?"

"The maximum possible value for the surroundings temperature occurs when we set

S_gen = 0=Delta S_sys+sum(DeltaS_surr)"

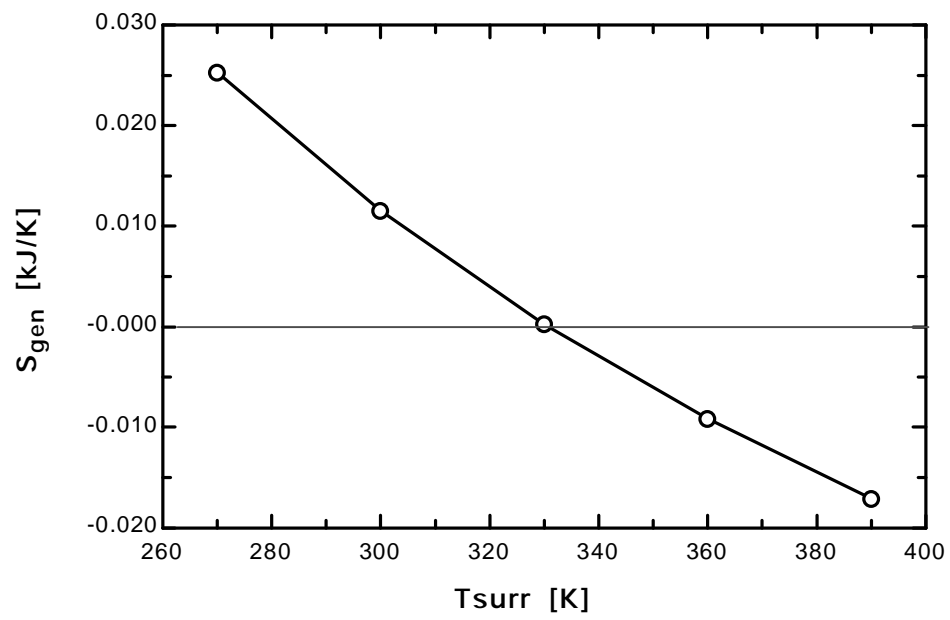
Q_net_surr=Q_out

S_gen = 0

S_gen = DELTAS_sys+Q_net_surr/(T_surr)

"Establish a parametric table for the variables S_gen, Q_net_surr, T_surr, and DELTAS_sys. In the Parametric Table window select T_surr and insert a range of values. Then place '{' and '}' about the S_gen = 0 line; press F3 to solve the table. The results are shown in Plot Window 1. What values of T_surr are valid for this problem?"

S _{gen} [kJ/K]	Q _{net,surr} [kJ]	T _{surr} [K]	ΔS _{sys} [kJ/K]
0.02527	37.17	270	-0.1124
0.0115	37.17	300	-0.1124
0.0002402	37.17	330	-0.1124
-0.009145	37.17	360	-0.1124
-0.01709	37.17	390	-0.1124



7-37E A cylinder is initially filled with R-134a at a specified state. The refrigerant is cooled and condensed at constant pressure. The entropy change of refrigerant during this process is to be determined

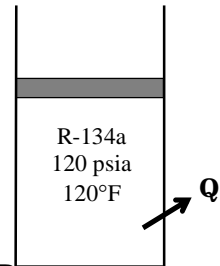
Analysis From the refrigerant tables,

$$\left. \begin{array}{l} P_1 = 120 \text{ psia} \\ T_1 = 120^\circ \text{F} \end{array} \right\} s_1 = 0.2301 \text{ Btu/lbm} \cdot \text{R}$$

$$\left. \begin{array}{l} T_2 = 90^\circ \text{F} \\ P_2 = 120 \text{ psia} \end{array} \right\} s_2 \cong s_{f@90^\circ \text{F}} = 0.0836 \text{ Btu/lbm} \cdot \text{R}$$

Then the entropy change of the refrigerant becomes

$$\Delta S = m(s_2 - s_1) = (3 \text{ lbm})(0.0836 - 0.2301) \text{ Btu/lbm} \cdot \text{R} = \mathbf{-0.4395 \text{ Btu/R}}$$



7-38 An insulated cylinder is initially filled with saturated liquid water at a specified pressure. The water is heated electrically at constant pressure. The entropy change of the water during this process is to be determined.

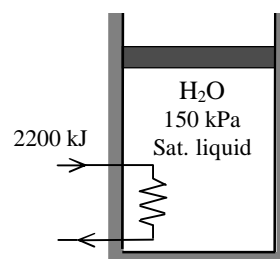
Assumptions **1** The kinetic and potential energy changes are negligible. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis From the steam tables,

$$P_1 = 150 \text{ kPa} \left\{ \begin{array}{l} v_1 = v_{f@150 \text{ kPa}} = 0.001053 \text{ m}^3/\text{kg} \\ h_1 = h_{f@150 \text{ kPa}} = 467.1 \text{ kJ/kg} \\ s_1 = s_{f@150 \text{ kPa}} = 1.4336 \text{ kJ/kg} \cdot \text{K} \end{array} \right. \quad \text{sat. liquid}$$

Also,

$$m = \frac{V}{v_1} = \frac{0.005 \text{ m}^3}{0.001053 \text{ m}^3/\text{kg}} = 4.748 \text{ kg}$$



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 stationary closed system can be expressed as

$$\cancel{E_{in}} - \cancel{E_{out}} = \Delta E_{\text{system}}$$

Net energy transfer by heat, work, and mass Change in internal, kinetic, potential, etc. energies

$$W_{e,in} - W_{b,out} = \Delta U$$

$$W_{e,in} = m(h_2 - h_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. Solving for h_2 ,

$$h_2 = h_1 + \frac{W_{e,in}}{m} = 467.11 + \frac{2200 \text{ kJ}}{4.748 \text{ kg}} = 930.5 \text{ kJ/kg}$$

Thus,

$$\left. \begin{array}{l} P_2 = 150 \text{ kPa} \\ h_2 = 930.5 \text{ kJ/kg} \end{array} \right\} \quad \begin{array}{l} x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{930.5 - 467.11}{2226.5} = 0.208 \\ s_2 = s_f + x_2 s_{fg} = 1.4336 + (0.208)(5.7897) = 2.638 \text{ kJ/kg} \cdot \text{K} \end{array}$$

Then the entropy change of the water becomes

$$\Delta S = m(s_2 - s_1) = (4.748 \text{ kg})(2.638 - 1.4336) \text{ kJ/kg} \cdot \text{K} = \mathbf{5.72 \text{ kJ/K}}$$

7-39 An insulated cylinder is initially filled with saturated R-134a vapor at a specified pressure. The refrigerant expands in a reversible manner until the pressure drops to a specified value. The final temperature in the cylinder and the work done by the refrigerant are to be determined.

Assumptions **1** The kinetic and potential energy changes are negligible. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The process is stated to be reversible.

Analysis (a) This is a reversible adiabatic (i.e., isentropic) process, and thus $s_2 = s_1$. From the refrigerant tables,

$$P_1 = 0.8 \text{ MPa} \left\{ \begin{array}{l} v_1 = v_{g@0.8 \text{ MPa}} = 0.0255 \text{ m}^3/\text{kg} \\ u_1 = u_{g@0.8 \text{ MPa}} = 243.78 \text{ kJ/kg} \\ s_1 = s_{g@0.8 \text{ MPa}} = 0.9066 \text{ kJ/kg} \cdot \text{K} \end{array} \right. \quad \text{sat. vapor}$$

Also,

$$m = \frac{V}{v_1} = \frac{0.05 \text{ m}^3}{0.0255 \text{ m}^3/\text{kg}} = 1.961 \text{ kg}$$

and

$$P_2 = 0.4 \text{ MPa} \left\{ \begin{array}{l} x_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{0.9066 - 0.2399}{0.9145 - 0.2399} = 0.988 \\ u_2 = u_f + x_2 u_{fg} = 61.69 + (0.988)(231.97 - 61.69) = 229.93 \text{ kJ/kg} \end{array} \right. \quad s_2 = s_1$$

$$T_2 = T_{\text{sat}@0.4 \text{ MPa}} = \mathbf{8.93^\circ \text{C}}$$

(b) 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 adiabatic closed system can be expressed as

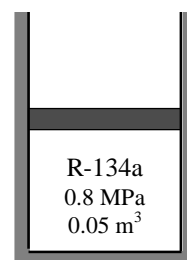
$$\begin{array}{ccc} \cancel{E_1} - \cancel{E_2} & = & \cancel{\Delta E_{\text{system}}} \\ \text{Net energy transfer} & & \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & & \text{potential, etc. energies} \end{array}$$

$$-W_{b,\text{out}} = \Delta U$$

$$W_{b,\text{out}} = m(u_1 - u_2)$$

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

$$W_{b,\text{out}} = m(u_1 - u_2) = (1.961 \text{ kg})(243.78 - 229.93) \text{ kJ/kg} = \mathbf{27.16 \text{ kJ}}$$



7-40 Problem 7-39 is reconsidered. The work done by the refrigerant is to be calculated and plotted as a function of final pressure as the pressure varies from 0.8 MPa to 0.4 MPa. The work done for this process is to be compared to one for which the temperature is constant over the same pressure range.

Procedure

IsothermWork(P_1,x_1,m_sys,P_2:Work_out_Isotherm,Q_isotherm,DELTAE_isotherm,T_isotherm)

T_isotherm=Temperature(R134a,P=P_1,x=x_1)"[k]"

T=T_isotherm

u_1 = INTENERGY(R134a,P=P_1,x=x_1)"[kJ/kg]"

v_1 = volume(R134a,P=P_1,x=x_1)"[m^3/kg]"

s_1 = entropy(R134a,P=P_1,x=x_1)"[kJ/kg-K]"

u_2 = INTENERGY(R134a,P=P_2,T=T)"[kJ/kg]"

s_2 = entropy(R134a,P=P_2,T=T)"[kJ/kg-K]"

"The process is reversible and Isothermal thus the heat transfer is determined by:"

Q_isotherm = (T+273)*m_sys*(s_2 - s_1)"[kJ]"

DELTAE_isotherm = m_sys*(u_2 - u_1)"[kJ]"

E_in = Q_isotherm"[kJ]"

E_out = DELTAE_isotherm+E_in"[kJ]"

Work_out_isotherm=E_out "[kJ]"

END

"Knowns:"

P_1 = 800"[kPa]"

x_1 = 1.0

V_sys = 0.01"[m^3]"

P_2 = 400"[kPa]"

"Analysis: "

" Treat the rigid tank as a closed system, with no heat transfer in, neglect changes in KE and PE of the R134a."

"The isentropic work is determined from:"

E_in - E_out = DELTAE_sys

E_out = Work_out_isen"[kJ]"

E_in = 0"[kJ]"

DELTAE_sys = m_sys*(u_2 - u_1)"[kJ]"

u_1 = INTENERGY(R134a,P=P_1,x=x_1)"[kJ/kg]"

v_1 = volume(R134a,P=P_1,x=x_1)"[m^3/kg]"

s_1 = entropy(R134a,P=P_1,x=x_1)"[kJ/kg-K]"

V_sys = m_sys*v_1"[m^3]"

"Rigid Tank: The process is reversible and adiabatic or isentropic.

Then P_2 and s_2 specify state 2."

s_2 = s_1"[kJ/kg-K]"

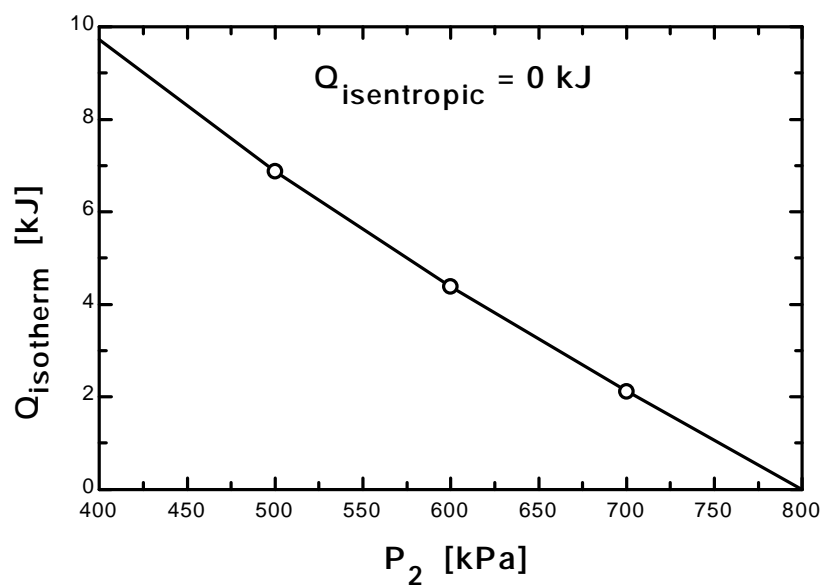
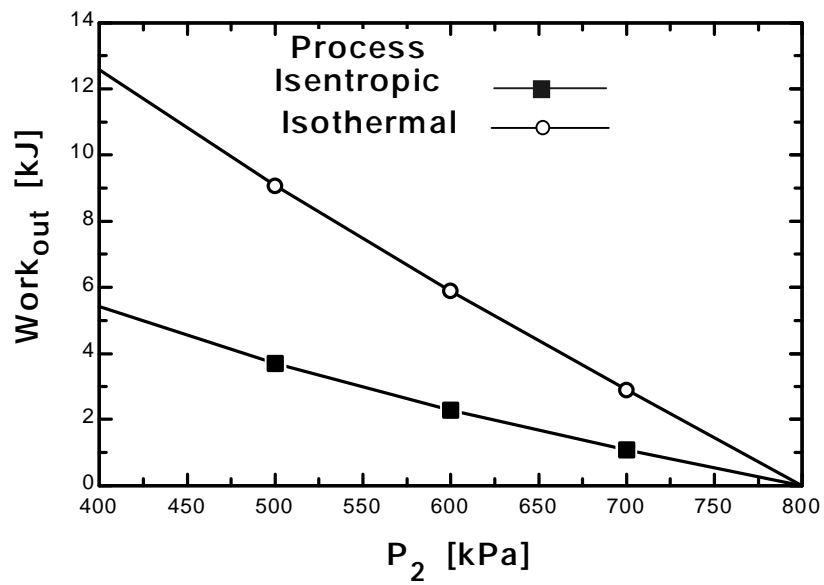
u_2 = INTENERGY(R134a,P=P_2,s=s_2)"[kJ/kg]"

T_2_isen = temperature(R134a,P=P_2,s=s_2)"[C]"

Call

IsothermWork(P_1,x_1,m_sys,P_2:Work_out_Isotherm,Q_isotherm,DELTAE_isotherm,T_isotherm)

P_2 [kPa]	$W_{\text{out,isen}}$ [kJ]	$W_{\text{out,isotherm}}$ [kJ]	Q_{isotherm} [kJ]
400	5.406	12.57	9.72
500	3.702	9.072	6.874
600	2.284	5.893	4.384
700	1.067	2.9	2.121
800	0	0	0



7-41 Saturated Refrigerant-134a vapor at 140 kPa is compressed steadily by an adiabatic compressor. The minimum power input to the compressor 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** 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,

$$\left. \begin{array}{l} P_1 = 140 \text{ kPa} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} v_1 = v_{g@140\text{kPa}} = 0.1395 \text{ m}^3/\text{kg} \\ h_1 = h_{g@140\text{kPa}} = 236.04 \text{ kJ/kg} \\ s_1 = s_{g@140\text{kPa}} = 0.9322 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 700 \text{ kPa} \\ s_2 = s_1 \end{array} \right\} h_2 = 269.23 \text{ kJ/kg}$$

Also,

$$\dot{m} = \frac{v_1}{v_1} = \frac{2 \text{ m}^3/\text{min}}{0.1395 \text{ m}^3/\text{kg}} = 14.34 \text{ kg/min} = 0.239 \text{ kg/s}$$

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

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

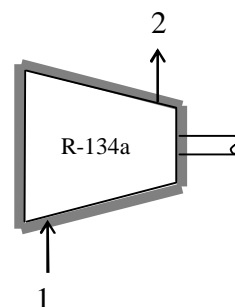
$$\dot{E}_{in} = \dot{E}_{out}$$

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

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

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

$$\dot{W}_{in} = (0.239 \text{ kg/s})(269.23 - 236.04) \text{ kJ/kg} = \mathbf{7.93 \text{ kW}}$$



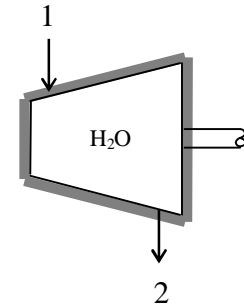
7-42E Steam expands in an adiabatic turbine. The maximum amount of work that can be done by the turbine is to be determined.

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

Analysis The work output of an adiabatic turbine is maximum when the expansion process is reversible. For the reversible adiabatic process we have $s_2 = s_1$. From the steam tables,

$$\left. \begin{array}{l} P_1 = 800 \text{ psia} \\ T_1 = 900^\circ \text{F} \end{array} \right\} \begin{array}{l} h_1 = 1455.6 \text{ Btu/lbm} \\ s_1 = 1.6408 \text{ Btu/lbm} \cdot \text{R} \end{array}$$

$$\left. \begin{array}{l} P_2 = 40 \text{ psia} \\ s_2 = s_1 \end{array} \right\} \begin{array}{l} x_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{1.6408 - 0.39214}{1.2845} = 0.972 \\ h_2 = h_f + x_2 h_{fg} = 236.16 + (0.972)(933.8) = 1143.8 \text{ Btu/lbm} \end{array}$$



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

$$\underbrace{\dot{Q}_{in} - \dot{Q}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} \quad \dot{E}_{in} = \dot{E}_{out}$$

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

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

Dividing by mass flow rate and substituting,

$$w_{out} = h_1 - h_2 = 1455.6 - 1143.8 = \mathbf{311.8 \text{ Btu/lbm}}$$

7-43E Problem 7-42E is reconsidered. The work done by the steam is to be calculated and plotted as a function of final pressure as the pressure varies from 800 psia to 40 psia. Also the effect of varying the turbine inlet temperature from the saturation temperature at 800 psia to 900°F on the turbine work is to be investigated.

"Knowns:"

P_1 = 800"[psia]"

T_1 = 900"[F]"

P_2 = 40"[psia]"

T_sat_P_1= temperature(Steam,P=P_1,x=1.0)"[F]"

"Analysis: "

" Treat the turbine as a steady-flow control volume, with no heat transfer in, neglect changes in KE and PE of the Steam."

"The isentropic work is determined from the steady-flow energy equation written per unit mass:"

E_in - E_out = DELTAE_sys

E_out = Work_out+h_2"[Btu/lbm]"

E_in = h_1"[Btu/lbm]"

DELTA E_sys = 0"[Btu/lbm]"

h_1 = enthalpy(Steam,P=P_1,T=T_1)"[Btu/lbm]"

s_1 = entropy(Steam,P=P_1,T=T_1)"[Btu/lbm-R]"

" The process is reversible and adiabatic or isentropic.

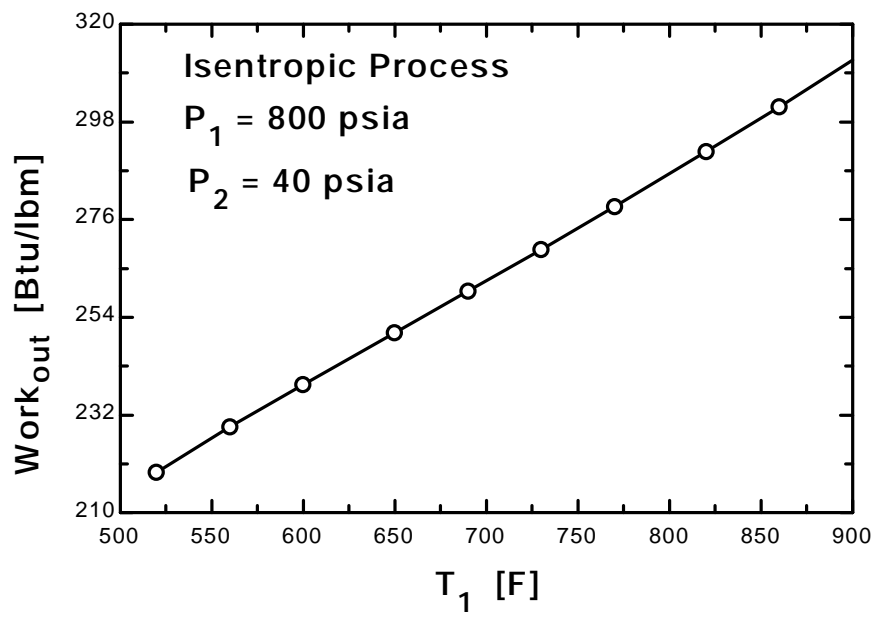
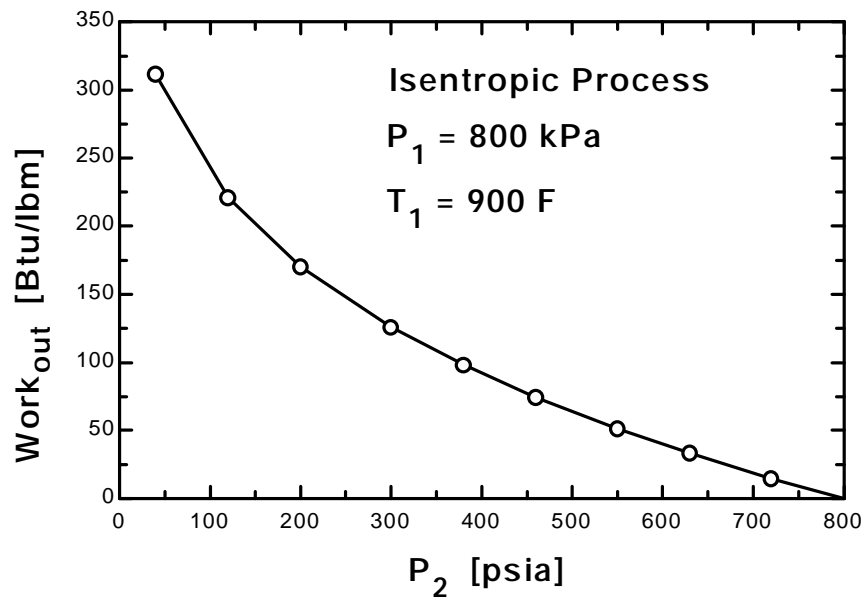
Then P_2 and s_2 specify state 2."

s_2 = s_1"[Btu/lbm-R]"

h_2 = enthalpy(Steam,P=P_2,s=s_2)"[Btu/kg]"

T_2_isen = temperature(Steam,P=P_2,s=s_2)"[F]"

T ₁ [F]	Work _{out} [Btu/lbm]
520	219.2
560	229.4
600	238.9
650	250.5
690	259.9
730	269.3
770	278.9
820	291.3
860	301.4
900	311.8



7-44 An insulated cylinder is initially filled with superheated steam at a specified state. The steam is compressed in a reversible manner until the pressure drops to a specified value. The work input during this process is to be determined. ✓

Assumptions **1** The kinetic and potential energy changes are negligible. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The process is stated to be reversible.

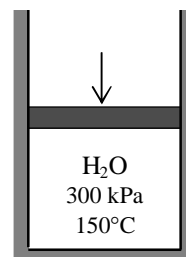
Analysis This is a reversible adiabatic (i.e., isentropic) process, and thus $s_2 = s_1$. From the steam tables,

$$\left. \begin{array}{l} P_1 = 300 \text{ kPa} \\ T_1 = 150^\circ \text{C} \end{array} \right\} \begin{array}{l} v_1 = 0.6339 \text{ m}^3/\text{kg} \\ u_1 = 2570.8 \text{ kJ/kg} \\ s_1 = 7.0778 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 1 \text{ MPa} \\ s_2 = s_1 \end{array} \right\} \begin{array}{l} u_2 = 2774.2 \text{ kJ/kg} \end{array}$$

Also,

$$m = \frac{V}{v_1} = \frac{0.05 \text{ m}^3}{0.6339 \text{ m}^3/\text{kg}} = 0.0789 \text{ kg}$$



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 adiabatic closed system can be expressed as

$$\begin{array}{ccc} \cancel{E_{12}} \cancel{E_{21}} & = & \cancel{\Delta E_{\text{system}}} \\ \text{Net energy transfer} & & \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & & \text{potential, etc. energies} \end{array}$$

$$W_{b,in} = \Delta U = m(u_2 - u_1)$$

Substituting, the work input during this adiabatic process is determined to be

$$W_{b,in} = m(u_2 - u_1) = (0.0789 \text{ kg})(2774.2 - 2570.8) \text{ kJ/kg} = \mathbf{16.05 \text{ kJ}}$$

7-45 Problem 7-44 is reconsidered. The work done on the steam is to be determined and plotted as a function of final pressure as the pressure varies from 300 kPa to 1 MPa.

"Knowns:"

$$P_1 = 300 \text{ [kPa]}$$

$$T_1 = 150 \text{ [C]}$$

$$V_{\text{sys}} = 0.05 \text{ [m}^3\text{]}$$

$$P_2 = 1000 \text{ [kPa]}$$

"Analysis: "

"Treat the piston-cylinder as a closed system, with no heat transfer in, neglect changes in KE and PE of the Steam. The process is reversible and adiabatic thus isentropic."

"The isentropic work is determined from:"

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{sys}}$$

$$E_{\text{out}} = 0 \text{ [kJ]}$$

$$E_{\text{in}} = \text{Work}_{\text{in}} \text{ [kJ]}$$

$$\Delta E_{\text{sys}} = m_{\text{sys}}(u_2 - u_1) \text{ [kJ]}$$

$$u_1 = \text{INTENERGY}(\text{Steam}, P=P_1, T=T_1) \text{ [kJ/kg]}$$

$$v_1 = \text{volume}(\text{Steam}, P=P_1, T=T_1) \text{ [m}^3\text{/kg]}$$

$$s_1 = \text{entropy}(\text{Steam}, P=P_1, T=T_1) \text{ [kJ/kg-K]}$$

$$V_{\text{sys}} = m_{\text{sys}} v_1 \text{ [m}^3\text{]}$$

"The process is reversible and adiabatic or isentropic."

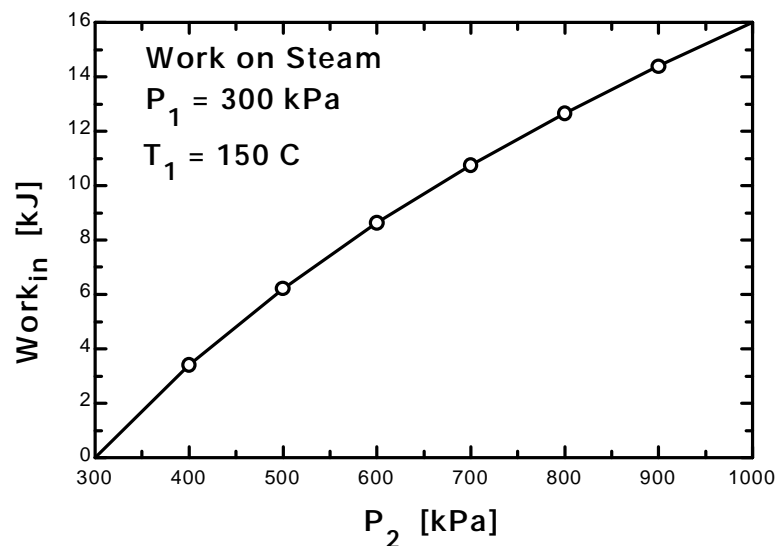
Then P_2 and s_2 specify state 2."

$$s_2 = s_1 \text{ [kJ/kg-K]}$$

$$u_2 = \text{INTENERGY}(\text{Steam}, P=P_2, s=s_2) \text{ [kJ/kg]}$$

$$T_{2,\text{isen}} = \text{temperature}(\text{Steam}, P=P_2, s=s_2) \text{ [C]}$$

P_2 [kPa]	Work _{in} [kJ]
300	0
400	3.406
500	6.218
600	8.632
700	10.76
800	12.67
900	14.4
1000	15.99



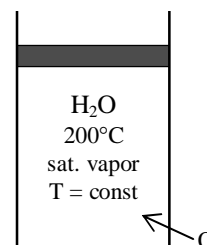
7-46 A cylinder is initially filled with saturated water vapor at a specified temperature. Heat is transferred to the steam, and it expands in a reversible and isothermal manner until the pressure drops to a specified value. The heat transfer and the work output for this process are to be determined.

Assumptions **1** The kinetic and potential energy changes are negligible. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The process is stated to be reversible and isothermal.

Analysis From the steam tables,

$$\left. \begin{array}{l} T_1 = 200^\circ\text{C} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} u_1 = u_{g@200^\circ\text{C}} = 2595.3\text{kJ/kg} \\ s_1 = s_{g@200^\circ\text{C}} = 6.4323\text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 800\text{kPa} \\ T_2 = T_1 \end{array} \right\} \begin{array}{l} u_2 = 2630.6\text{kJ/kg} \\ s_2 = 6.8158\text{kJ/kg}\cdot\text{K} \end{array}$$



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

$$Q = T\Delta S = Tm(s_2 - s_1) = (473\text{ K})(1.2\text{ kg})(6.8158 - 6.4323)\text{kJ/kg}\cdot\text{K} = \mathbf{217.7\text{ kJ}}$$

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

$$\cancel{E_{in}} - \cancel{E_{out}} = \Delta E_{\text{system}}$$

Net energy transfer Change in internal, kinetic,
by heat, work, and mass potential, etc. energies

$$Q_{in} - W_{b,out} = \Delta U = m(u_2 - u_1)$$

$$W_{b,out} = Q_{in} - m(u_2 - u_1)$$

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

$$W_{b,out} = 217.7\text{ kJ} - (1.2\text{ kg})(2630.6 - 2595.3)\text{kJ/kg} = \mathbf{175.3\text{ kJ}}$$

7-47 Problem 7-46 is reconsidered. The heat transferred to the steam and the work done are to be determined and plotted as a function of final pressure as the pressure varies from the initial value to the final value of 800 kPa.

"Knowns:"

$T_1 = 200$ [C]"

$x_1 = 1.0$

$m_{\text{sys}} = 0.5$ [kg]"

{ $P_2 = 800$ [kPa]}"

"Analysis: "

" Treat the piston-cylinder as a closed system, neglect changes in KE and PE of the Steam.

The process is reversible and isothermal ."

$T_2 = T_1$

$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{sys}}$

$E_{\text{in}} = Q_{\text{in}}$ [kJ]"

$E_{\text{out}} = \text{Work}_{\text{out}}$ [kJ]"

$\Delta E_{\text{sys}} = m_{\text{sys}}(u_2 - u_1)$ [kJ]"

$P_1 = \text{pressure}(\text{Steam}, T=T_1, x=1.0)$ [kPa]"

$u_1 = \text{INTENERGY}(\text{Steam}, T=T_1, x=1.0)$ [kJ/kg]"

$v_1 = \text{volume}(\text{Steam}, T=T_1, x=1.0)$ [m³/kg]"

$s_1 = \text{entropy}(\text{Steam}, T=T_1, x=1.0)$ [kJ/kg-K]"

$V_{\text{sys}} = m_{\text{sys}}v_1$ [m³]"

" The process is reversible and isothermal.

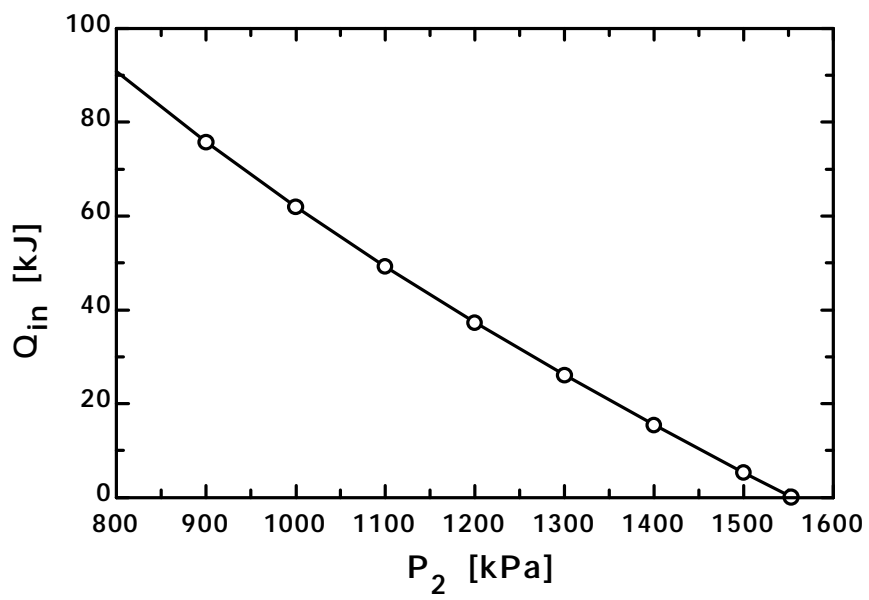
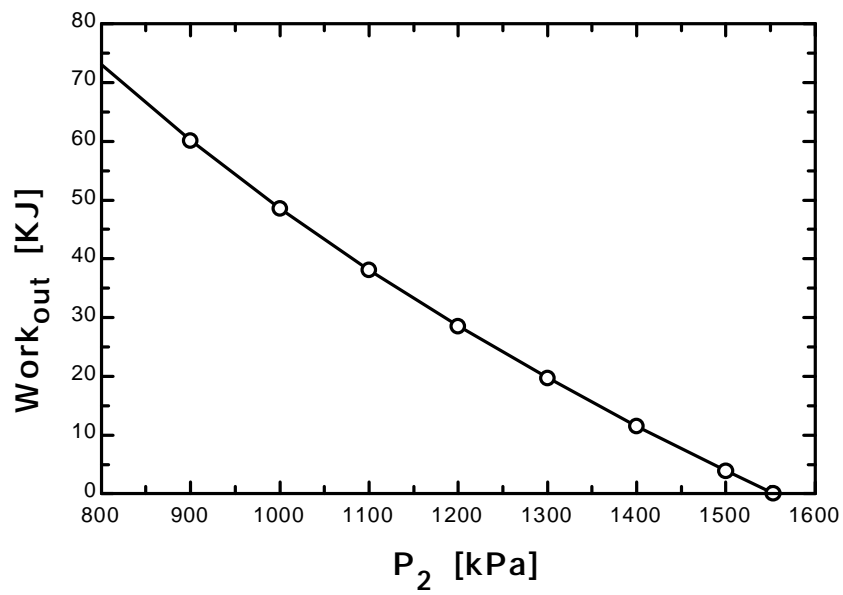
Then P_2 and T_2 specify state 2."

$u_2 = \text{INTENERGY}(\text{Steam}, P=P_2, T=T_2)$ [kJ/kg]"

$s_2 = \text{entropy}(\text{Steam}, P=P_2, T=T_2)$ [kJ/kg-K]"

$Q_{\text{in}} = (T_1 + 273)m_{\text{sys}}(s_2 - s_1)$ [kJ]"

P_2 [kPa]	Q_{in} [kJ]	Work_{out} [kJ]
800	90.79	73.05
900	75.73	60.14
1000	61.96	48.58
1100	49.22	38.11
1200	37.31	28.54
1300	26.1	19.72
1400	15.45	11.53
1500	5.285	3.897
1553	0.06338	0.04642



Entropy Change of Incompressible Substances

7-48C No, because entropy is not a conserved property.

7-49 A hot copper block is dropped into water in an insulated tank. The final equilibrium temperature of the tank and the total entropy change are to be determined.

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 $C_p = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$. The specific heat of copper at 27°C is $C_p = 0.386 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3).

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

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

$$0 = \Delta U$$

or,

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

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

where

$$m_{\text{water}} = \rho V = (997 \text{ kg/m}^3)(0.120 \text{ m}^3) = 120 \text{ kg}$$

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

$$(50 \text{ kg})(0.386 \text{ kJ/kg} \cdot ^\circ\text{C})(T_2 - 80)^\circ\text{C} + (120 \text{ kg})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(T_2 - 25)^\circ\text{C} = 0$$

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

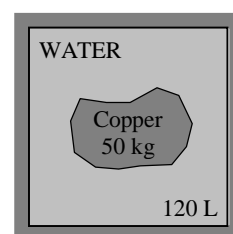
The entropy generated during this process is determined from

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

$$\Delta S_{\text{water}} = mC_{ave} \ln\left(\frac{T_2}{T_1}\right) = (120 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{300.0 \text{ K}}{298 \text{ K}}\right) = 3.355 \text{ kJ/K}$$

Thus,

$$\Delta S_{\text{total}} = \Delta S_{\text{copper}} + \Delta S_{\text{water}} = -3.140 + 3.355 = \mathbf{0.215 \text{ kJ/K}}$$



7-50 A hot iron block is dropped into water in an insulated tank. The total entropy change during this process is to be determined.

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 $C_p = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$. The specific heat of iron at room temperature is $C_p = 0.45 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3).

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

$$\begin{array}{ccc} \cancel{E_{in}} - \cancel{E_{out}} & = & \cancel{E_{system}} \\ \text{Net energy transfer} & & \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & & \text{potential, etc. energies} \end{array}$$

$$0 = \Delta U$$

or,

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

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

Substituting,

$$(12 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K})(T_2 - 350^\circ\text{C}) + (100 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K})(T_2 - 22^\circ\text{C}) = 0$$

$$T_2 = \mathbf{26.2^\circ\text{C}}$$

The entropy generated during this process is determined from

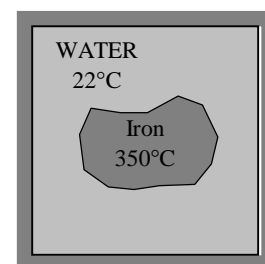
$$\Delta S_{iron} = mC_{ave} \ln\left(\frac{T_2}{T_1}\right) = (12 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{299.2 \text{ K}}{623 \text{ K}}\right) = -3.96 \text{ kJ/K}$$

$$\Delta S_{water} = mC_{ave} \ln\left(\frac{T_2}{T_1}\right) = (100 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{299.2 \text{ K}}{295 \text{ K}}\right) = 5.91 \text{ kJ/K}$$

Thus,

$$S_{gen} = \Delta S_{total} = \Delta S_{iron} + \Delta S_{water} = -3.96 + 5.91 = \mathbf{1.95 \text{ kJ/K}}$$

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



7-51 An aluminum block is brought into contact with an iron block in an insulated enclosure. The final equilibrium temperature and the total entropy change for this process are to be determined.

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

Properties The specific heat of aluminum at the anticipated average temperature of 450 K is $C_p = 0.973$ kJ/kg·°C. The specific heat of iron at room temperature (the only value available in the tables) is $C_p = 0.45$ kJ/kg·°C (Table A-3).

Analysis We take the iron+aluminum blocks as the system, which is a closed system. The energy balance for this system can be expressed as

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

$$0 = \Delta U$$

Iron	Aluminum
20 kg	20 kg
100°C	200°C

or,

$$\Delta U_{\text{alum}} + \Delta U_{\text{iron}} = 0$$

$$[mC(T_2 - T_1)]_{\text{alum}} + [mC(T_2 - T_1)]_{\text{iron}} = 0$$

Substituting,

$$(20\text{ kg})(0.45\text{ kJ/kg} \cdot \text{K})(T_2 - 100^\circ\text{C}) + (20\text{ kg})(0.973\text{ kJ/kg} \cdot \text{K})(T_2 - 200^\circ\text{C}) = 0$$

$$T_2 = \mathbf{168.4^\circ\text{C}} = 441.4\text{ K}$$

The total entropy change for this process is determined from

$$\Delta S_{\text{iron}} = mC_{\text{ave}} \ln\left(\frac{T_2}{T_1}\right) = (20\text{ kg})(0.45\text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{441.4\text{ K}}{373\text{ K}}\right) = 1.515\text{ kJ/K}$$

$$\Delta S_{\text{alum}} = mC_{\text{ave}} \ln\left(\frac{T_2}{T_1}\right) = (20\text{ kg})(0.973\text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{441.4\text{ K}}{473\text{ K}}\right) = -1.346\text{ kJ/K}$$

Thus,

$$\Delta S_{\text{total}} = \Delta S_{\text{iron}} + \Delta S_{\text{alum}} = 1.515 - 1.346 = \mathbf{0.169\text{ kJ/K}}$$

7-52 Problem 7-51 is reconsidered. The effect of the mass of the iron block on the final equilibrium temperature and the total entropy change for the process is to be studied. The mass of the iron is to vary from 1 to 10 kg. The equilibrium temperature and the total entropy change are to be plotted as a function of iron mass.

"Knowns:"

$T_{1_iron} = 100 [C]$

$\{m_{iron} = 20 [kg]\}$

$T_{1_al} = 200 [C]$

$m_{al} = 20 [kg]$

$C_{al} = 0.973 [kJ/kg-K]$ "From Table A-3 at the anticipated average temperature of 450 K."

$C_{iron} = 0.45 [kJ/kg-K]$ "From Table A-3 at room temperature, the only value available."

"Analysis: "

"Treat the iron plus aluminum as a closed system, with no heat transfer in, no work out, neglect changes in KE and PE of the system. "

"The final temperature is found from the energy balance."

$E_{in} - E_{out} = \Delta E_{sys}$

$E_{out} = 0 [kJ]$

$E_{in} = 0 [kJ]$

$\Delta E_{sys} = m_{iron} \Delta T_{iron} + m_{al} \Delta T_{al} [kJ]$

$\Delta T_{iron} = T_{2_iron} - T_{1_iron}$

$\Delta T_{al} = T_{2_al} - T_{1_al}$

"the iron and aluminum reach thermal equilibrium:"

$T_{2_iron} = T_{2_al} [C]$

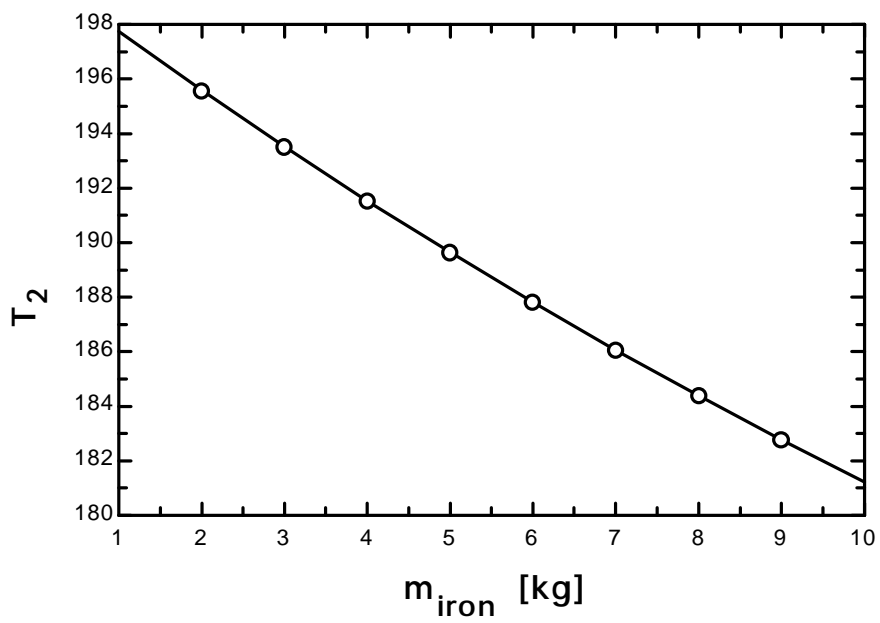
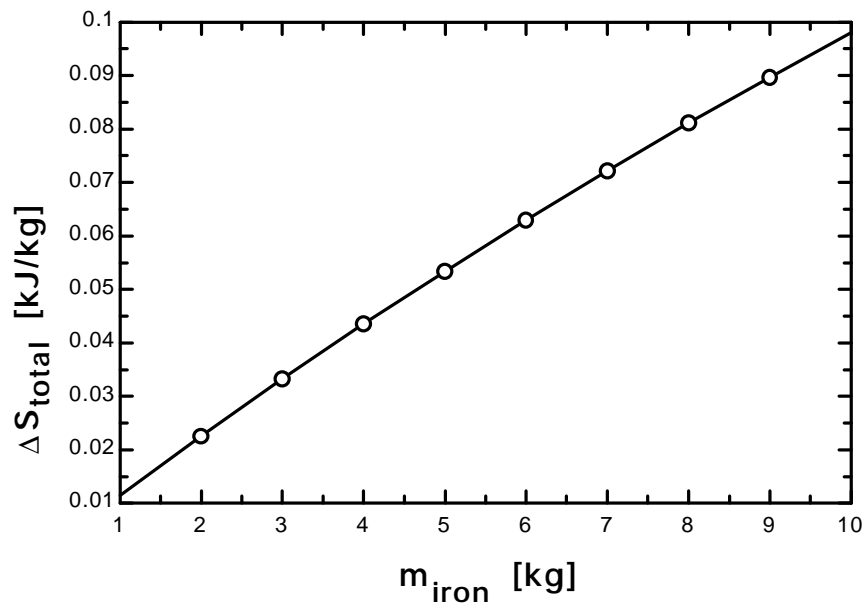
$T_{2_al} = T_{2_iron} [C]$

$\Delta S_{iron} = m_{iron} C_{iron} \ln((T_{2_iron} + 273) / (T_{1_iron} + 273)) [kJ/K]$

$\Delta S_{al} = m_{al} C_{al} \ln((T_{2_al} + 273) / (T_{1_al} + 273)) [kJ/K]$

$\Delta S_{total} = \Delta S_{iron} + \Delta S_{al} [kJ/kg]$

ΔS_{total} [kJ/kg]	m_{iron} [kg]	T_2 [C]
0.01152	1	197.7
0.0226	2	195.6
0.03326	3	193.5
0.04353	4	191.5
0.05344	5	189.6
0.06299	6	187.8
0.07221	7	186.1
0.08112	8	184.4
0.08973	9	182.8
0.09805	10	181.2



7-53 An iron block and a copper block are dropped into a large lake. The total amount of entropy change when both blocks cool to the lake temperature is to be determined.

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 $C_{p, \text{iron}} = 0.45 \text{ kJ/kg} \cdot ^\circ\text{C}$ and $C_{p, \text{copper}} = 0.386 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3).

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

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

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

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

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

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

or,

$$Q_{\text{out}} = [mC(T_1 - T_2)]_{\text{iron}} + [mC(T_1 - T_2)]_{\text{copper}} = 0$$

Substituting,

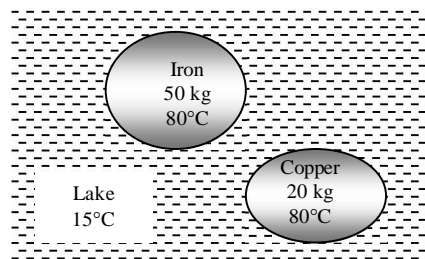
$$Q_{\text{out}} = (50 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K})(353 - 288) \text{ K} + (20 \text{ kg})(0.386 \text{ kJ/kg} \cdot \text{K})(353 - 288) \text{ K} = 1964 \text{ kJ}$$

Thus,

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

Then the total entropy change for this process is

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



Entropy Changes of Ideal Gases

7-54C For ideal gases, $C_p = C_v + R$ and

$$\frac{P_2 V_2}{T_2} = \frac{P_1 V_1}{T_1} \longrightarrow \frac{V_2}{V_1} = \frac{T_2 P_1}{T_1 P_2}$$

Thus,

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

7-55C For an ideal gas, $dh = C_p dT$ and $\nu = RT/P$. From the second Tds relation,

$$ds = \frac{dh}{T} - \frac{\nu dP}{T} = \frac{C_p dT}{T} - \frac{RT dP}{T^2} = C_p \frac{dT}{T} - R \frac{dP}{P}$$

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.

7-56C No. The entropy of an ideal gas depends on the pressure as well as the temperature.

7-57C 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

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

7-58C The P_r and ν_r are called relative pressure and relative specific volume, respectively. They are derived for isentropic processes of ideal gases, and thus their use is limited to isentropic processes only.

7-59C The entropy of a gas *can* change during an isothermal process since entropy of an ideal gas depends on the pressure as well as the temperature.

7-60C The entropy change relations of an ideal gas simplify to

$$\Delta s = C_p \ln(T_2/T_1) \text{ for a constant pressure process}$$

and $\Delta s = C_v \ln(T_2/T_1)$ for a constant volume process.

Noting that $C_p > C_v$, the entropy change will be larger for a constant pressure process.

7-61 Oxygen gas is compressed from a specified initial state to a specified final state. The entropy change of oxygen during this process is to be determined for the case of constant specific heats.

Assumptions At specified conditions, oxygen can be treated as an ideal gas.

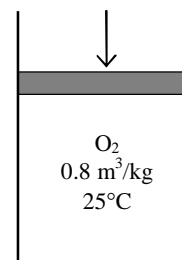
Properties The gas constant and molar mass of oxygen are $R = 0.2598 \text{ kJ/kg}\cdot\text{K}$ and $M = 32 \text{ kg/kmol}$ (Table A-1).

Analysis The constant volume specific heat of oxygen at the average temperature is (Table A-2)

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

Thus,

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



7-62 An insulated tank contains CO_2 gas at a specified pressure and volume. A paddle-wheel in the tank stirs the gas, and the pressure and temperature of CO_2 rises. The entropy change of CO_2 during this process is to be determined using constant specific heats.

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

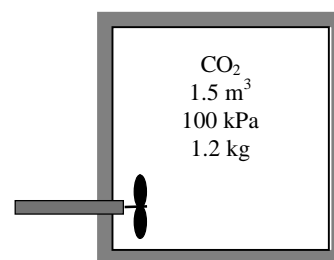
Properties The specific heat of CO_2 is $C_v = 0.657 \text{ kJ/kg}\cdot\text{K}$ (Table A-2).

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

$$\frac{P_2 V}{T_2} = \frac{P_1 V}{T_1} \longrightarrow \frac{T_2}{T_1} = \frac{P_2}{P_1} = \frac{120 \text{ kPa}}{100 \text{ kPa}} = 1.2$$

Thus,

$$\begin{aligned} \Delta S &= m(s_2 - s_1) = m \left(C_{v,ave} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \right) = m C_{v,ave} \ln \frac{T_2}{T_1} \\ &= (2.7 \text{ kg})(0.657 \text{ kJ/kg}\cdot\text{K}) \ln(1.2) \\ &= \mathbf{0.323 \text{ kJ/K}} \end{aligned}$$



7-63 An insulated cylinder initially contains air at a specified state. A resistance heater inside the cylinder is turned on, and air is heated for 15 min at constant pressure. The entropy change of air during this process is to be determined for the cases of constant and variable specific heats. ✓

Assumptions At specified conditions, air can be treated as an ideal gas.

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

Analysis The mass of the air and the electrical work done during this process are

$$m = \frac{P_1 V_1}{R T_1} = \frac{(120 \text{ kPa})(0.3 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(290 \text{ K})} = 0.4325 \text{ kg}$$

$$W_{e,in} = \dot{W}_{e,in} \Delta t = (0.2 \text{ kJ/s})(15 \times 60 \text{ s}) = 180 \text{ kJ}$$

The energy balance for this stationary closed system can be expressed as

$$\cancel{E_{1,2}} \quad \cancel{E_{2,2}} = \cancel{E_{1,2}} \quad \cancel{E_{2,2}}$$

Net energy transfer by heat, work, and mass Change in internal, kinetic, potential, etc. energies

$$W_{pw,in} - W_{b,out} = \Delta U$$

$$W_{pw,in} = m(h_2 - h_1) \cong C_p(T_2 - T_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process.

(a) Using a constant C_p value at the anticipated average temperature of 450 K, the final temperature becomes

$$\text{Thus, } T_2 = T_1 + \frac{W_{e,in}}{m C_p} = 290 \text{ K} + \frac{180 \text{ kJ}}{(0.4325 \text{ kg})(1.02 \text{ kJ/kg} \cdot \text{K})} = 698 \text{ K}$$

Then the entropy change becomes

$$\Delta S_{sys} = m(s_2 - s_1) = m \left(C_{p,ave} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \right) = m C_{p,ave} \ln \frac{T_2}{T_1}$$

$$= (0.4325 \text{ kg})(1.020 \text{ kJ/kg} \cdot \text{K}) \ln \left(\frac{698 \text{ K}}{290 \text{ K}} \right)$$

$$= \mathbf{0.387 \text{ kJ/K}}$$

(b) Assuming variable specific heats,

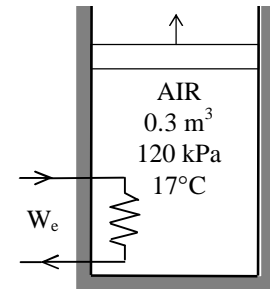
$$W_{e,in} = m(h_2 - h_1) \longrightarrow h_2 = h_1 + \frac{W_{e,in}}{m} = 290.16 \text{ kJ/kg} + \frac{180 \text{ kJ}}{0.4325 \text{ kg}} = 706.34 \text{ kJ/kg}$$

From the air table (Table A-17, we read $s_2^o = 2.5628 \text{ kJ/kg} \cdot \text{K}$ corresponding to this h_2 value. Then,

$$\Delta S_{sys} = m \left(s_2^o - s_1^o + R \ln \frac{P_2}{P_1} \right) = m(s_2^o - s_1^o)$$

$$= (0.4325 \text{ kg})(2.5628 - 1.66802) \text{ kJ/kg} \cdot \text{K}$$

$$= \mathbf{0.387 \text{ kJ/K}}$$



7-64 A cylinder contains N_2 gas at a specified pressure and temperature. A gas is compressed polytropically until the volume is reduced by half. The entropy change of nitrogen during this process is to be determined.

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

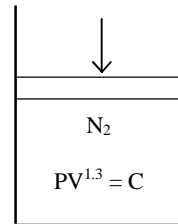
Properties The gas constant of nitrogen is $R = 0.297 \text{ kJ/kg}\cdot\text{K}$ (Table A-1). The constant volume specific heat of nitrogen at room temperature is $C_v = 0.743 \text{ kJ/kg}\cdot\text{K}$ (Table A-2).

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

$$\begin{aligned} \Delta S_{N_2} &= m \left(C_{v,ave} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \right) \\ &= (1.2 \text{ kg}) \left((0.743 \text{ kJ/kg}\cdot\text{K}) \ln \frac{369.3 \text{ K}}{300 \text{ K}} + (0.297 \text{ kJ/kg}\cdot\text{K}) \ln(0.5) \right) \\ &= \mathbf{-0.0617 \text{ kJ/K}} \end{aligned}$$



7-65 Problem 7-64 is reconsidered. The effect of varying the polytropic exponent from 1 to 1.4 on the entropy change of the nitrogen is to be investigated, and the processes are to be shown on a common P-v diagram.

Function BoundWork(P[1],V[1],P[2],V[2],n)

"This function returns the Boundary Work for the polytropic process. This function is required

since the expression for boundary work depends on whether $n=1$ or $n \neq 1$ "

If $n \neq 1$ then

BoundWork:=(P[2]*V[2]-P[1]*V[1])/(1-n)"Use Equation 3-22 when $n \neq 1$ "

else

BoundWork:= P[1]*V[1]*ln(V[2]/V[1]) "Use Equation 3-20 when $n=1$ "

endif

end

$n=1$

P[1] = 120 "kPa"

T[1] = 27 "[C]"

m = 1.2 "[kg]"

V[2]=V[1]/2 "[m^3]"

Gas\$='N2'

MM=molarmass(Gas\$) "[kg/kmol]"

R=8.314/MM "[kJ/kg-K]"

"System: The gas enclosed in the piston-cylinder device."

"Process: Polytropic expansion or compression, $P \cdot V^n = C$ "

P[1]*V[1]=m*R*(T[1]+273)

P[2]*V[2]^n=P[1]*V[1]^n

W_b = BoundWork(P[1],V[1],P[2],V[2],n) "[kJ]"

"Find the temperature at state 2 from the pressure and specific volume."

T[2]=temperature(gas\$,P=P[2],v=V[2]/m)

"The entropy at states 1 and 2 is:"

s[1]=entropy(gas\$,P=P[1],v=V[1]/m)

s[2]=entropy(gas\$,P=P[2],v=V[2]/m)

DELTAS=m*(s[2] - s[1]) "[kJ/K]"

"Remove the {} to generate the P-v plot data"

{Nsteps = 10

VP[1]=V[1]

PP[1]=P[1]

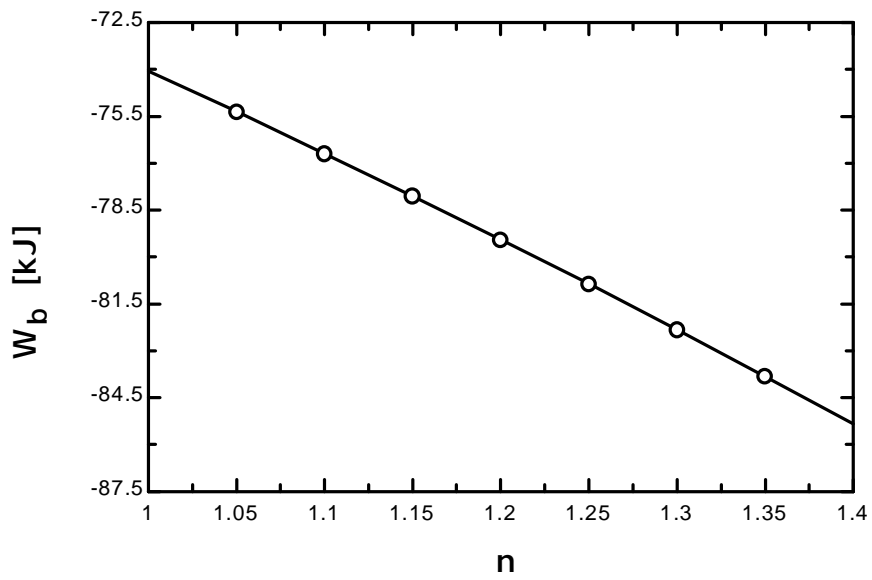
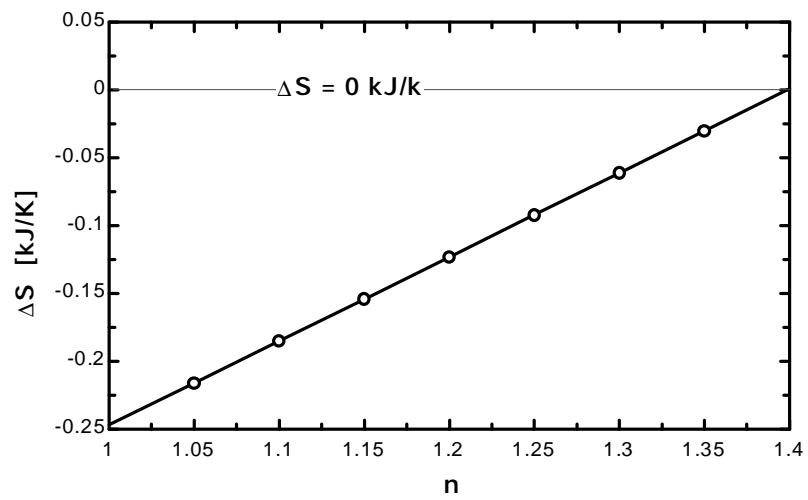
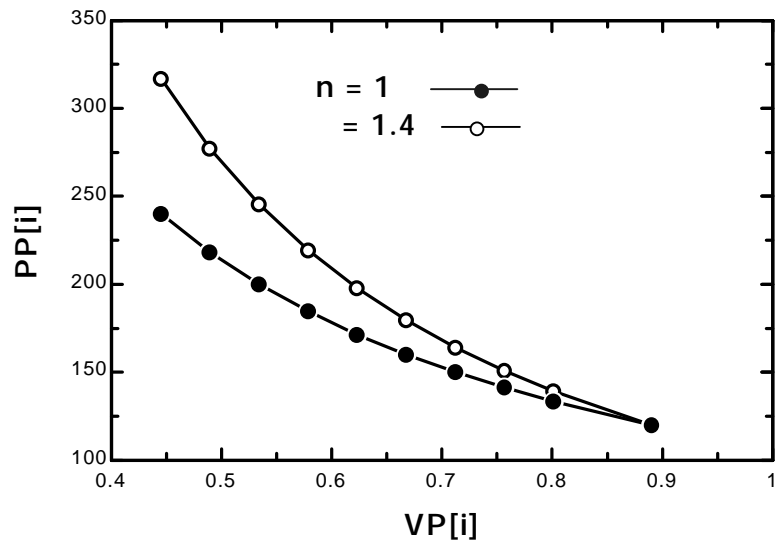
Duplicate i=2,Nsteps

VP[i]=V[1]-i*(V[1]-V[2])/Nsteps

PP[i]=P[1]*(V[1]/VP[i])^n

END }

ΔS [kJ/kg]	n	W_b [kJ]
-0.2469	1	-74.06
-0.2159	1.05	-75.36
-0.1849	1.1	-76.69
-0.1539	1.15	-78.05
-0.1229	1.2	-79.44
-0.09191	1.25	-80.86
-0.06095	1.3	-82.32
-0.02999	1.35	-83.82
0.0009849	1.4	-85.34



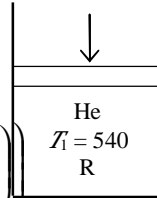
7-66E A fixed mass of helium undergoes a process from one specified state to another specified state. The entropy change of helium is to be determined for the cases of reversible and irreversible processes.

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

Properties The gas constant of helium is $R = 0.4961 \text{ Btu/lbm} \cdot \text{R}$ (Table A-1E). The constant volume specific heat of helium is $C_v = 0.753 \text{ Btu/lbm} \cdot \text{R}$ (Table A-2E).

Analysis From the ideal-gas entropy change relation,

$$\begin{aligned} \Delta S_{He} &= m \left(C_{v,ave} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \right) \\ &= (15 \text{ lbm}) \left((0.753 \text{ Btu/lbm} \cdot \text{R}) \ln \frac{660 \text{ R}}{540 \text{ R}} + (0.4961 \text{ Btu/lbm} \cdot \text{R}) \ln \left(\frac{10 \text{ ft}^3/\text{lbm}}{50 \text{ ft}^3/\text{lbm}} \right) \right) \\ &= \mathbf{-9.71 \text{ Btu/R}} \end{aligned}$$



The entropy change will be the same for both cases.

Chapter 7 Entropy

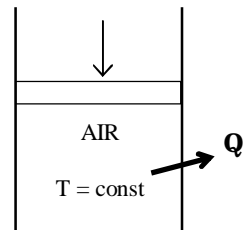
7-67 Air is compressed in a piston-cylinder device in a reversible and isothermal manner. The entropy change of air and the work done are to be determined.

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

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



Also, for a reversible isothermal process,

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

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

$$\begin{aligned}\cancel{142.43} \quad \cancel{142.43} \quad \cancel{142.43} &= \cancel{142.43} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ W_{\text{in}} - Q_{\text{out}} = \Delta U = mC_v(T_2 - T_1) = 0 \\ W_{\text{in}} = Q_{\text{out}} &= 125.4 \text{ kJ/kg}\end{aligned}$$

7-68 Air is compressed steadily by a 5-kW compressor from one specified state to another specified state. The rate of entropy change of air is to be determined. ✓

Assumptions At specified conditions, air can be treated as an ideal gas. 2 Air has variable specific heats.

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

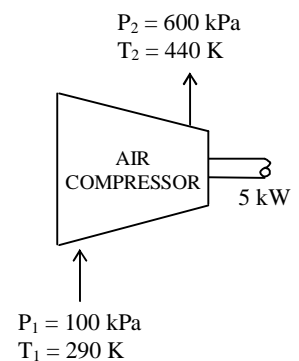
Analysis From the air table (Table A-17),

$$\left. \begin{aligned} T_1 &= 290 \text{ K} \\ P_1 &= 100 \text{ kPa} \end{aligned} \right\} s_1^0 = 1.66802 \text{ kJ/kg} \cdot \text{K}$$

$$\left. \begin{aligned} T_2 &= 440 \text{ K} \\ P_2 &= 600 \text{ kPa} \end{aligned} \right\} s_2^0 = 2.0887 \text{ kJ/kg} \cdot \text{K}$$

Then the rate of entropy change of air becomes

$$\begin{aligned}\Delta \dot{S}_{\text{sys}} &= \dot{m} \left(s_2^0 - s_1^0 - R \ln \frac{P_2}{P_1} \right) \\ &= (1.6/60 \text{ kg/s}) \left(2.0887 - 1.66802 - (0.287 \text{ kJ/kg} \cdot \text{K}) \ln \left(\frac{600 \text{ kPa}}{100 \text{ kPa}} \right) \right) \\ &= -0.00250 \text{ kW/K}\end{aligned}$$



7-70 Air is compressed in a piston-cylinder device in a reversible and adiabatic manner. The final temperature and the work are to be determined for the cases of constant and variable specific heats.

Assumptions **1** At specified conditions, air can be treated as an ideal gas. **2** The process is given to be reversible and adiabatic, and thus isentropic. Therefore, isentropic relations of ideal gases apply.

Properties The gas constant of air is $R = 0.287 \text{ kJ/kg} \cdot \text{K}$ (Table A-1). The specific heat ratio of air at low to moderately high temperatures is $k = 1.4$ (Table A-2).

Analysis (a) Assuming constant specific heats, the ideal gas isentropic relations give

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{(k-1)/k} = (290 \text{ K}) \left(\frac{800 \text{ kPa}}{100 \text{ kPa}} \right)^{0.4/1.4} = \mathbf{525.3 \text{ K}}$$

Then,

$$T_{ave} = (290 + 525.3)/2 = 407.7 \text{ K} \longrightarrow C_{v,ave} = 0.727 \text{ kJ/kg} \cdot \text{K}$$

We take the air in the cylinder as the system. The energy balance for this stationary closed system can be expressed as

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

$$W_{in} = \Delta U = m(u_2 - u_1) \cong mC_v(T_2 - T_1)$$

Thus,

$$w_{in} = C_{v,ave}(T_2 - T_1) = (0.727 \text{ kJ/kg} \cdot \text{K})(525.3 - 290) \text{ K} = \mathbf{171.1 \text{ kJ/kg}}$$

(b) Assuming variable specific heats, the final temperature can be determined using the relative pressure data (Table A-17),

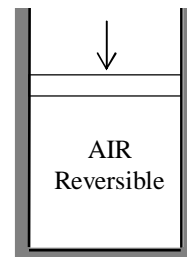
$$T_1 = 290 \text{ K} \longrightarrow \begin{matrix} P_r = 1.2311 \\ u_1 = 206.91 \text{ kJ/kg} \end{matrix}$$

and

$$P_r = \frac{P_2}{P_1} P_{r1} = \frac{800 \text{ kPa}}{100 \text{ kPa}} (1.2311) = 9.849 \longrightarrow \begin{matrix} T_2 = \mathbf{522.4 \text{ K}} \\ u_2 = 376.16 \text{ kJ/kg} \end{matrix}$$

Then the work input becomes

$$w_{in} = u_2 - u_1 = (376.16 - 206.91) \text{ kJ/kg} = \mathbf{169.25 \text{ kJ/kg}}$$



7-71 Problem 7-71 is reconsidered. The work done and final temperature during the compression process are to be calculated and plotted as functions of the final pressure for the two cases as the final pressure varies from 100 kPa to 800 kPa.

```

Procedure ConstPropSol(P_1,T_1,P_2,Gas$:Work_in_ConstProp,T2_ConstProp)
C_P=SPECHEAT(Gas$,T=27)"[kJ/kg-K]"
MM=MOLARMASS(Gas$)"[kg/kmol]"
R=8.314/MM"[kJ/kg-K]"
C_V = C_P - R"[kJ/kg]"
k = C_P/C_V
T2= (T_1+273)*(P_2/P_1)^(k-1)/k
T2_ConstProp=T2-273"[C]"
DELTAu = C_v*(T2-(T_1+273))"[kJ/kg]"
Work_in_ConstProp = DELTAu"[kJ/kg]"
End

```

"Knowns:"

P_1 = 100"[kPa]"

T_1 = 17"[C]"

P_2 = 800"[kPa]"

"Analysis: "

" Treat the piston-cylinder as a closed system, with no heat transfer in, neglect changes in KE and PE of the air. The process is reversible and adiabatic thus isentropic."

"The isentropic work is determined from:"

E_in - E_out = DELTAE_sys

E_out = 0"[kJ/kg]"

E_in = Work_in"[kJ/kg]"

DELTAE_sys = (u_2 - u_1)"[kJ/kg]"

u_1 = INTENERGY(air,T=T_1)"[kJ/kg]"

v_1 = volume(air,P=P_1,T=T_1)"[m^3/kg]"

s_1 = entropy(air,P=P_1,T=T_1)"[kJ/kg-K]"

" The process is reversible and adiabatic or isentropic.

Then P_2 and s_2 specify state 2."

s_2 = s_1"[kJ/kg-K]"

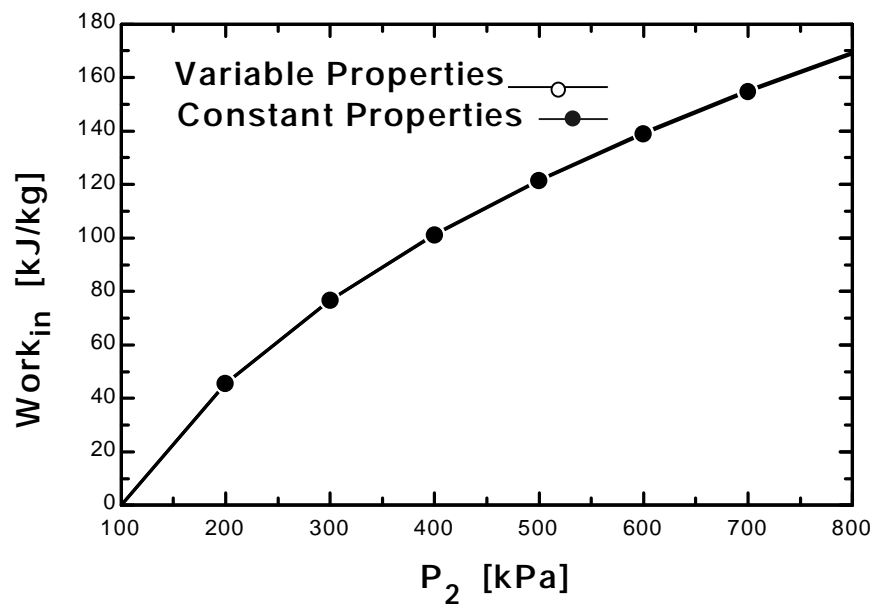
u_2 = INTENERGY(air,P=P_2,s=s_2)"[kJ/kg]"

T_2_isen = temperature(air,P=P_2,s=s_2)"[C]"

Gas\$ = 'air'

Call ConstPropSol(P_1,T_1,P_2,Gas\$:Work_in_ConstProp,T2_ConstProp)

P ₂ [kPa]	Work _{in} [kJ/kg]	Work _{in,ConstProp} [kJ/kg]
100	3.469E-15	0
200	45.63	45.6
300	76.84	76.77
400	101.3	101.2
500	121.7	121.5
600	139.4	139.1
700	155.2	154.8
800	169.3	168.9



7-72 Helium gas is compressed in a piston-cylinder device in a reversible and adiabatic manner. The final temperature and the work are to be determined for the cases of the process taking place in a piston-cylinder device and a steady-flow compressor.

Assumptions 1 Helium is an ideal gas with constant specific heats. 2 The process is given to be reversible and adiabatic, and thus isentropic. Therefore, isentropic relations of ideal gases apply.

Properties The specific heats and the specific heat ratio of helium are $C_v = 3.1156 \text{ kJ/kg}\cdot\text{K}$, $C_p = 5.1926 \text{ kJ/kg}\cdot\text{K}$, and $k = 1.667$ (Table A-2).

Analysis (a) From the ideal gas isentropic relations,

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{(k-1)/k} = (303 \text{ K}) \left(\frac{450 \text{ kPa}}{90 \text{ kPa}} \right)^{0.667/1.667} = 576.9 \text{ K}$$

(a) We take the air in the cylinder as the system. The energy balance for this stationary closed system can be expressed as

$$\begin{array}{c} \cancel{14243} \\ \dot{E}_{in} - \dot{E}_{out} \end{array} = \begin{array}{c} \cancel{14243} \\ \Delta \dot{E}_{system} \end{array}$$

Net energy transfer by heat, work, and mass Change in internal, kinetic, potential, etc. energies

$$W_{in} = \Delta U = m(u_2 - u_1) \cong mC_v(T_2 - T_1)$$

Thus,

$$w_{in} = C_v(T_2 - T_1) = (3.1156 \text{ kJ/kg}\cdot\text{K})(576.9 - 303) \text{ K} = \mathbf{853.4 \text{ kJ/kg}}$$

(b) If the process takes place in a steady-flow device, the final temperature will remain the same but the work done should be determined from an energy balance on this steady-flow device,

$$\begin{array}{c} \cancel{14243} \\ \dot{E}_{in} - \dot{E}_{out} \end{array} = \begin{array}{c} \cancel{14243} \\ \Delta \dot{E}_{system} \end{array} \quad \bar{A}0 \text{ (steady)} = 0$$

Rate of net energy transfer by heat, work, and mass Rate of change in internal, kinetic, potential, etc. energies

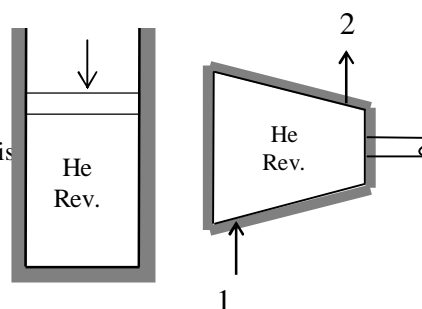
$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}h_1 = \dot{m}h_2$$

$$\dot{m}(h_2 - h_1) \cong \dot{m}C_p(T_2 - T_1)$$

Thus,

$$w_{in} = C_p(T_2 - T_1) = (5.1926 \text{ kJ/kg}\cdot\text{K})(576.9 - 303) \text{ K} = \mathbf{1422.3 \text{ kJ/kg}}$$



7-73 An insulated rigid tank contains argon gas at a specified pressure and temperature. A valve is opened, and argon escapes until the pressure drops to a specified value. The final mass in the tank is to be determined.

Assumptions **1** At specified conditions, argon can be treated as an ideal gas. **2** The process is given to be reversible and adiabatic, and thus isentropic. Therefore, isentropic relations of ideal gases apply.

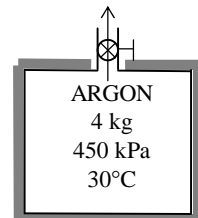
Properties The specific heat ratio of argon is $k = 1.667$ (Table A-2).

Analysis From the ideal gas isentropic relations,

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{(k-1)/k} = (303\text{K}) \left(\frac{150\text{kPa}}{450\text{kPa}} \right)^{0.667/1.667} = 195\text{K}$$

The final mass in the tank is determined from the ideal gas relation,

$$\frac{P_1 V}{P_2 V} = \frac{m_1 R T_1}{m_2 R T_2} \longrightarrow m_2 = \frac{P_2 T_1}{P_1 T_2} m_1 = \frac{(150\text{kPa})(303\text{K})}{(450\text{kPa})(195\text{K})} (4\text{kg}) = \mathbf{2.07\text{kg}}$$



7-74 Problem 7-73 is reconsidered. The effect of the final pressure on the final mass in the tank is to be investigated as the pressure varies from 450 kPa to 150 kPa, and the results are to be plotted.

"UNIFORM_FLOW SOLUTION:"

"Knowns:"

$$C_P = 0.5203 \text{ [kJ/kg-K]}$$

$$C_V = 0.3122 \text{ [kJ/kg-K]}$$

$$R = 0.2081 \text{ [kPa-m}^3\text{/kg-K]}$$

$$P_1 = 450 \text{ [kPa]}$$

$$T_1 = 30 \text{ [C]}$$

$$m_1 = 4 \text{ [kg]}$$

$$P_2 = 150 \text{ [kPa]}$$

"Analysis:"

We assume the mass that stays in the tank undergoes an isentropic expansion process. This allows us to determine the final temperature of that gas at the final pressure in the tank by using the isentropic relation:"

$$k = C_P/C_V$$

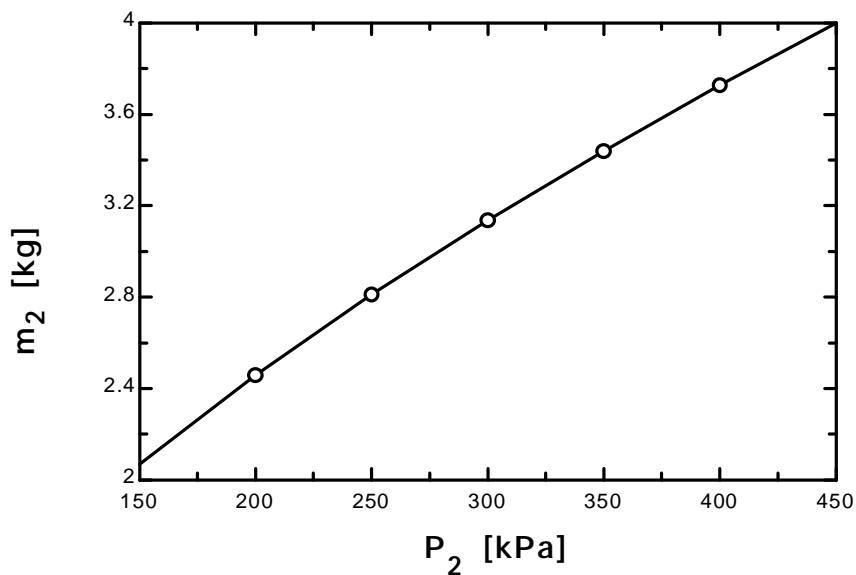
$$T_2 = ((T_1 + 273) * (P_2/P_1)^{(k-1)/k}) - 273 \text{ [C]}$$

$$V_2 = V_1$$

$$P_1 V_1 = m_1 R (T_1 + 273)$$

$$P_2 V_2 = m_2 R (T_2 + 273)$$

m_2 [kg]	P_2 [kPa]
2.069	150
2.459	200
2.811	250
3.136	300
3.44	350
3.727	400
4	450



7-75E Air is accelerated in an adiabatic nozzle. Disregarding irreversibilities, the exit velocity of air is to be determined.

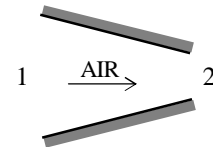
Assumptions 1 Air is an ideal gas with variable specific heats. 2 The process is given to be reversible and adiabatic, and thus isentropic. Therefore, isentropic relations of ideal gases apply. 2 The nozzle operates steadily.

Analysis Assuming variable specific heats, the inlet and exit properties are determined to be

$$T_1 = 1000\text{R} \longrightarrow \begin{aligned} P_r &= 12.30 \\ h_1 &= 240.98\text{Btu/lbm} \end{aligned}$$

and

$$P_r = \frac{P_2}{P_1} P_r = \frac{12\text{psia}}{60\text{psia}} (12.30) = 2.46 \longrightarrow \begin{aligned} T_2 &= 635.9\text{R} \\ h_2 &= 152.1\text{Btu/lbm} \end{aligned}$$



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

$$\underbrace{\dot{Q}_{in} - \dot{Q}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0$$

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

$$h_1 + \mathbf{V}_1^2 / 2 = h_2 + \mathbf{V}_2^2 / 2$$

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

Therefore,

$$\begin{aligned} \mathbf{V}_2 &= \sqrt{2(h_1 - h_2) + \mathbf{V}_1^2} = \sqrt{2(240.98 - 152.1)\text{Btu/lbm} \left(\frac{25,037\text{ft}^2/\text{s}^2}{1\text{Btu/lbm}} \right) + (200\text{ft/s})^2} \\ &= 2119\text{ft/s} \end{aligned}$$

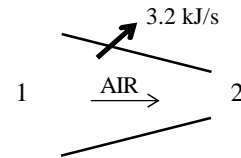
7-76 Air is accelerated in an nozzle, and some heat is lost in the process. The exit temperature of air and the total entropy change during the process are to be determined. ✓

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

Analysis (a) Assuming variable specific heats, the inlet properties are determined to be,

$$T_1 = 350 \text{ K} \longrightarrow \begin{aligned} h_1 &= 350.49 \text{ kJ/kg} \\ s_1^0 &= 1.85708 \text{ kJ/kg} \cdot \text{K} \end{aligned} \quad (\text{Table A-17})$$

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



$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \dot{E}_{system} \quad \dot{E}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} &\quad \text{potential, etc. energies} \end{aligned}$$

$$\begin{aligned} \dot{E}_{in} &= \dot{E}_{out} \\ h_1 + V_1^2/2 &= h_2 + V_2^2/2 + q_{out} \\ 0 &= q_{out} + h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} \end{aligned}$$

Therefore,

$$\begin{aligned} h_2 &= h_1 - q_{out} - \frac{V_2^2 - V_1^2}{2} = 350.49 - 3.2 - \frac{(320 \text{ m/s})^2 - (50 \text{ m/s})^2}{2} \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \\ &= 297.34 \text{ kJ/kg} \end{aligned}$$

At this h_2 value we read, from Table A-17, $T_2 = 297.2 \text{ K}$, $s_2^0 = 1.6924 \text{ kJ/kg} \cdot \text{K}$

(b) The total entropy change is the sum of the entropy changes of the air and of the surroundings, and is determined from

$$\Delta s_{total} = \Delta s_{air} + \Delta s_{surr}$$

where

$$\Delta s_{air} = s_2^0 - s_1^0 - R \ln \frac{P_2}{P_1} = 1.6924 - 1.85708 - (0.287 \text{ kJ/kg} \cdot \text{K}) \ln \frac{85 \text{ kPa}}{280 \text{ kPa}} = 0.1775 \text{ kJ/kg} \cdot \text{K}$$

and

$$\Delta s_{surr} = \frac{q_{surr, in}}{T_{surr}} = \frac{3.2 \text{ kJ/kg}}{293 \text{ K}} = 0.0109 \text{ kJ/kg} \cdot \text{K}$$

Thus,

$$\Delta s_{total} = 0.1775 + 0.0109 = \mathbf{0.1884 \text{ kJ/kg} \cdot \text{K}}$$

7-77 Problem 7-76 is reconsidered. The effect of varying the surrounding medium temperature from 10°C to 40°C on the exit temperature and the total entropy change for this process is to be studied, and the results are to be plotted.

```
Function HCal(WorkFluid$, Tx, Px)
"Function to calculate the enthalpy of an ideal gas or real gas"
If 'Air' = WorkFluid$ then
    HCal:=ENTHALPY('Air',T=Tx) "Ideal gas equ."
else
    HCal:=ENTHALPY(WorkFluid$,T=Tx, P=Px)"Real gas equ."
endif
end HCal
```

```
"System: control volume for the nozzle"
"Property relation: Air is an ideal gas"
"Process: Steady state, steady flow, adiabatic, no work"
"Knowns - obtain from the input diagram"
```

```
WorkFluid$ = 'Air'
T[1] = 77 "[C]"
P[1] = 280 "[kPa]"
Vel[1] = 50 "[m/s]"
P[2] = 85 "[kPa]"
Vel[2] = 320 "[m/s]"
q_out = 3.2"[kJ/kg]"
{T_surr = 20"[C]"}
```

```
"Property Data - since the Enthalpy function has different parameters
for ideal gas and real fluids, a function was used to determine h."
```

```
h[1]=HCal(WorkFluid$,T[1],P[1])
h[2]=HCal(WorkFluid$,T[2],P[2])
```

```
"The Volume function has the same form for an ideal gas as for a real fluid."
```

```
v[1]=volume(workFluid$,T=T[1],p=P[1])
v[2]=volume(WorkFluid$,T=T[2],p=P[2])
```

```
"If we knew the inlet or exit area, we could calculate the mass flow rate. Since we don't
know these areas, we write the conservation of energy per unit mass."
```

```
"Conservation of mass: m_dot[1]= m_dot[2]"
```

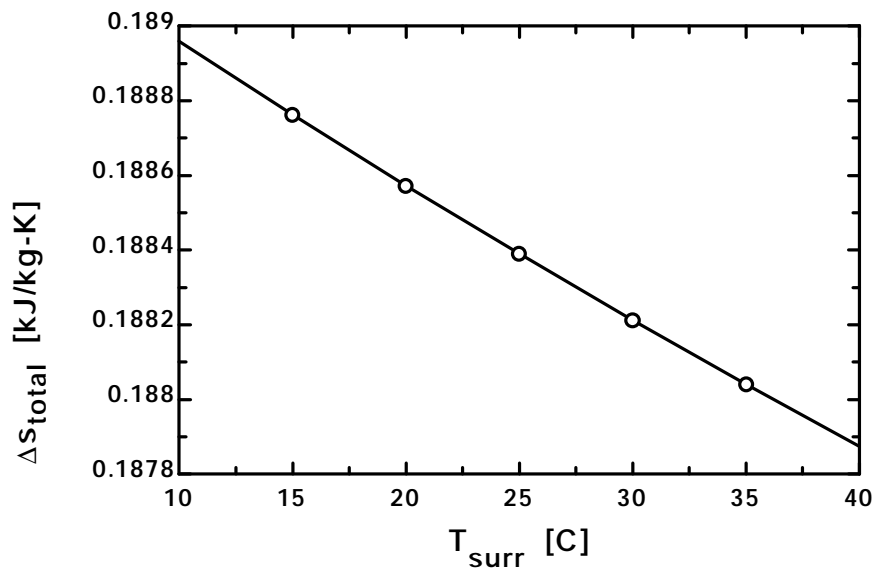
```
"Conservation of Energy - SSSF energy balance for neglecting the change in potential
energy, no work, but heat transfer out is:"
```

```
h[1]+Vel[1]^2/(2*1000) = h[2]+Vel[2]^2/(2*1000)+q_out
s[1]=entropy(workFluid$,T=T[1],p=P[1])"[kJ/kg-K]"
s[2]=entropy(WorkFluid$,T=T[2],p=P[2])"[kJ/kg-K]"
```

```
"Entropy change of the air and the surroundings are:"
```

```
DELTA_s_air = s[2] - s[1]"[kJ/kg-K]"
q_in_surr = q_out
DELTA_s_surr = q_in_surr/(T_surr+273)"[kJ/kg-K]"
DELTA_s_total = DELTA_s_air + DELTA_s_surr"[kJ/kg-K]"
```

Δs_{total} [kJ/kg-K]	T_{surr} [C]	T_2 [C]
0.189	10	24.22
0.1888	15	24.22
0.1886	20	24.22
0.1884	25	24.22
0.1882	30	24.22
0.188	35	24.22
0.1879	40	24.22



Reversible Steady-Flow Work

7-78C 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.

7-79C 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.

7-80C 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.

7-81 Liquid water is pumped reversibly to a specified pressure at a specified rate. The power input to the pump is to be determined.

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

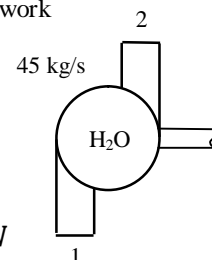
Properties The specific volume of saturated liquid water at 20 kPa is $v_1 = v_f @ 20 \text{ kPa} = 0.001017 \text{ m}^3/\text{kg}$ (Table A-5).

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

$$\dot{W}_{in} = \dot{m} \left(\int_1^2 v dP + \Delta ke^{\bar{A}0} + \Delta pe^{\bar{A}0} \right) = \dot{m} v_1 (P_2 - P_1)$$

Substituting,

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



7-82 Liquid water is to be pumped by a 10-kW pump at a specified rate. The highest pressure the water can be pumped to is to be determined.

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

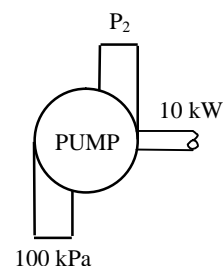
$$\dot{W}_{in} = \dot{m} \left(\int_1^2 v dP + \Delta ke^{\bar{A}0} + \Delta pe^{\bar{A}0} \right) = \dot{m} v_1 (P_2 - P_1)$$

Thus,

$$10 \text{ kJ/s} = (5 \text{ kg/s})(0.001017 \text{ m}^3/\text{kg})(P_2 - 100) \text{ kPa} \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right)$$

It yields

$$P_2 = \mathbf{2100 \text{ kPa}}$$



7-83E Saturated refrigerant-134a vapor is to be compressed reversibly to a specified pressure. The power input to the compressor is to be determined, and it is also to be compared to the work input for the liquid case.

Assumptions **1** Liquid refrigerant is an incompressible substance. **2** Kinetic and potential energy changes are negligible. **3** The process is reversible. **4** The compressor is adiabatic.

Analysis The compression process is reversible and adiabatic, and thus isentropic, $s_1 = s_2$. Then the properties of the refrigerant are (Tables A-11E through A-13E)

$$\left. \begin{array}{l} P_1 = 20 \text{ psia} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} h_1 = 101.39 \text{ Btu/lbm} \\ s_1 = 0.2227 \text{ Btu/lbm} \cdot \text{R} \end{array}$$

$$\left. \begin{array}{l} P_2 = 120 \text{ psia} \\ s_2 = s_1 \end{array} \right\} h_2 = 117.29 \text{ Btu/lbm}$$

The work input to this isentropic compressor is determined from the steady-flow energy balance to be

$$\begin{aligned} \dot{E}_{\text{in}} - \dot{E}_{\text{out}} &= \Delta \dot{E}_{\text{system}} = 0 \quad (\text{steady}) \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\ \dot{m}h_1 &= \dot{m}h_2 \\ \dot{W}_{\text{in}} &= \dot{m}(h_2 - h_1) \end{aligned}$$

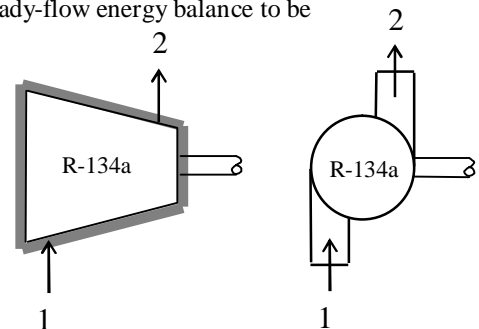
Thus, $\dot{W}_{\text{in}} = \dot{m}(h_2 - h_1) = 117.29 - 101.39 = \mathbf{15.9 \text{ Btu/lbm}}$

The pump work input is determined from the steady-flow work relation to be

$$w_{\text{in}} = \int_1^2 v dP + \Delta ke^{\bar{A}0} + \Delta pe^{\bar{A}0} = v_1(P_2 - P_1)$$

where $v_1 = v_f @ 20 \text{ psia} = 0.01181 \text{ ft}^3/\text{kg}$. Substituting,

$$w_{\text{in}} = (0.01181 \text{ ft}^3/\text{lbm})(120 - 20) \text{ psia} \left(\frac{1 \text{ Btu}}{5.4039 \text{ psia} \cdot \text{ft}^3} \right) = \mathbf{0.2185 \text{ Btu/lbm}}$$



7-84 A steam power plant operates between the pressure limits of 10 MPa and 20 kPa. The ratio of the turbine work to the pump work is to be determined.

Assumptions 1 Liquid water is an incompressible substance. 2 Kinetic and potential energy changes are negligible. 3 The process is reversible. 4 The pump and the turbine are adiabatic.

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

Analysis Both the compression and expansion processes are reversible and adiabatic, and thus isentropic, $s_1 = s_2$ and $s_3 = s_4$. Then the properties of the steam are

$$\left. \begin{array}{l} P_4 = 20 \text{ kPa} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} h_4 = h_{g@20\text{kPa}} = 2609.7 \text{ kJ/kg} \\ s_4 = s_{g@20\text{kPa}} = 7.9085 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_3 = 10 \text{ MPa} \\ s_3 = s_4 \end{array} \right\} h_3 = 4712.8 \text{ kJ/kg}$$

Also, $v_f = v_f @ 20 \text{ kPa} = 0.001017 \text{ m}^3/\text{kg}$.

The work output to this isentropic turbine is determined from the steady-flow energy balance to be

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \Delta \dot{E}_{system}^{\dot{A}0} \text{ (steady)} = 0 \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{m}h_3 &= \dot{m}h_4 + \dot{W}_{out} \\ \dot{W}_{out} &= \dot{m}(h_3 - h_4) \end{aligned}$$

Substituting,

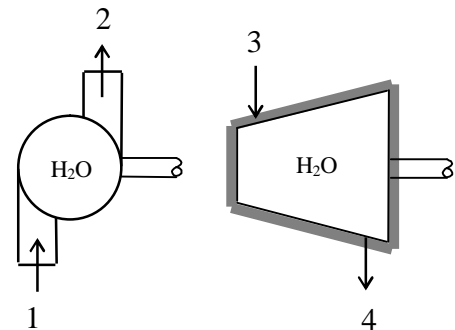
$$w_{turb, out} = h_3 - h_4 = 4712.8 - 2609.7 = 2103.1 \text{ kJ/kg}$$

The pump work input is determined from the steady-flow work relation to be

$$\begin{aligned} w_{pump, in} &= \int_1^2 v dP + \Delta ke^{\dot{A}0} + \Delta pe^{\dot{A}0} = v_f (P_2 - P_1) \\ &= (0.001017 \text{ m}^3/\text{kg})(10,000 - 20) \text{ kPa} \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) = 10.15 \text{ kJ/kg} \end{aligned}$$

Thus,

$$\frac{w_{turb, out}}{w_{pump, in}} = \frac{2103.1}{10.15} = \mathbf{207.2}$$



7-85 Problem 7-84 is reconsidered. The effect of the quality of the steam at the turbine exit on the net work output is to be investigated as the quality is varied from 0.5 to 1.0, and the net work output is to be plotted as a function of this quality.

"System: control volume for the pump and turbine"

"Property relation: Steam functions"

"Process: For Pump and Turbine: Steady state, steady flow, adiabatic, reversible or isentropic"

"Since we don't know the mass, we write the conservation of energy per unit mass."

"Conservation of mass: $\dot{m}_1 = \dot{m}_2$ "

"Knowns:"

WorkFluid\$ = 'Steam'

P[1] = 20 "[kPa]"

x[1] = 0

P[2] = 10000 "[kPa]"

x[4] = 1.0

"Pump Analysis:"

T[1]=temperature(WorkFluid\$,P=P[1],x=0)"[C]"

v[1]=volume(workFluid\$,P=P[1],x=0)"[m^3/kg]"

h[1]=enthalpy(WorkFluid\$,P=P[1],x=0)"[kJ/kg]"

s[1]=entropy(WorkFluid\$,P=P[1],x=0)"[kJ/kg-K]"

s[2] = s[1]"[kJ/kg-K]"

h[2]=enthalpy(WorkFluid\$,P=P[2],s=s[2])"[kJ/kg]"

T[2]=temperature(WorkFluid\$,P=P[2],s=s[2])"[C]"

"The Volume function has the same form for an ideal gas as for a real fluid."

v[2]=volume(WorkFluid\$,T=T[2],p=P[2])"[m^3/kg]"

"Conservation of Energy - SSSF energy balance for pump"

" -- neglect the change in potential energy, no heat transfer:"

h[1]+W_pump = h[2]

"Also the work of pump can be obtained from the incompressible fluid, steady-flow result:"

W_pump_incomp = v[1]*(P[2] - P[1])"[kJ/kg]"

"Conservation of Energy - SSSF energy balance for turbine -- neglecting the change in potential energy, no heat transfer:"

P[4] = P[1]"[kPa]"

P[3] = P[2]"[kPa]"

h[4]=enthalpy(WorkFluid\$,P=P[4],x=x[4])"[kJ/kg]"

s[4]=entropy(WorkFluid\$,P=P[4],x=x[4])"[kJ/kg-K]"

T[4]=temperature(WorkFluid\$,P=P[4],x=x[4])"[C]"

s[3] = s[4]"[kJ/kg-K]"

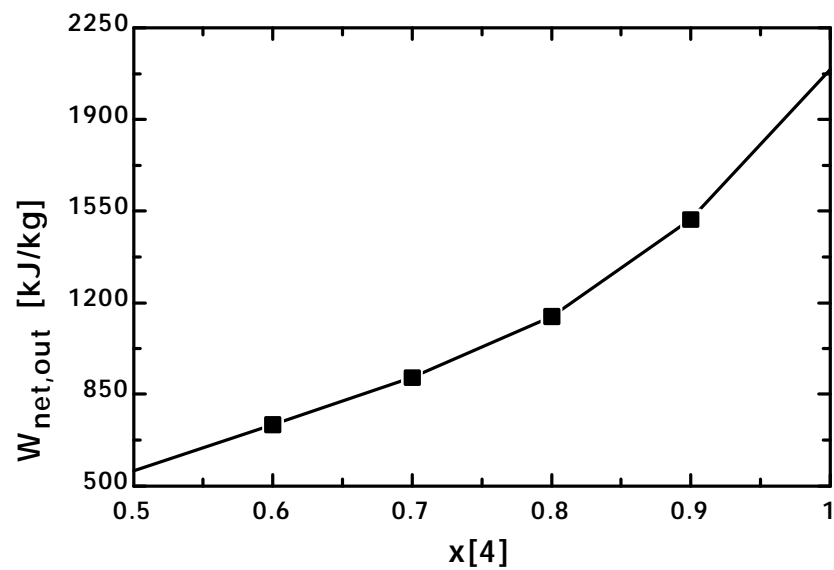
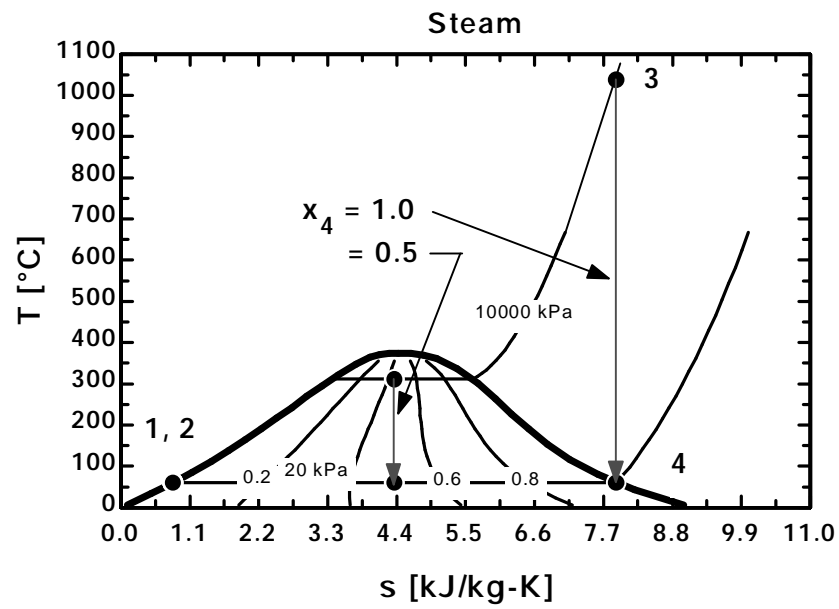
h[3]=enthalpy(WorkFluid\$,P=P[3],s=s[3])"[kJ/kg]"

T[3]=temperature(WorkFluid\$,P=P[3],s=s[3])"[C]"

h[3] = h[4] + W_turb

W_net_out = W_turb - W_pump"[kJ/kg]"

$W_{\text{net,out}}$ [kJ/kg]	W_{pump} [kJ/kg]	$W_{\text{pump,incomp}}$ [kJ/kg]	W_{turb} [kJ/kg]	x_4
557.3	10.13	10.15	567.4	0.5
734.9	10.13	10.15	745	0.6
913.9	10.13	10.15	924	0.7
1147	10.13	10.15	1157	0.8
1518	10.13	10.15	1528	0.9
2090	10.13	10.15	2100	1



7-86 Liquid water is pumped by a 10-kW pump to a specified pressure at a specified level. The highest possible mass flow rate of water is to be determined.

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,

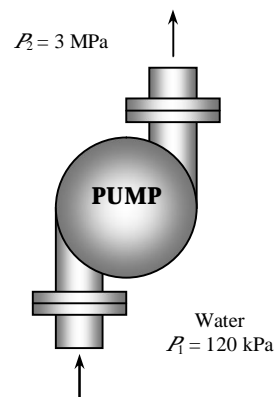
Thus,

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

$$7 \text{ kJ/s} = \dot{m} \left\{ (0.001 \text{ m}^3/\text{kg})(3000 - 120) \text{ kPa} \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) + (9.8 \text{ m/s}^2)(10 \text{ m}) \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \right\}$$

It yields

$$\dot{m} = 2.35 \text{ kg/s}$$



7-87E Helium gas is compressed from a specified state to a specified pressure at a specified rate. The power input to the compressor is to be determined for the cases of isentropic, polytropic, isothermal, and two-stage compression.

Assumptions 1 Helium is an ideal gas with constant specific heats. 2 The process is reversible. 3 Kinetic and potential energy changes are negligible.

Properties The gas constant of helium is $R = 2.6805 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R} = 0.4961 \text{ Btu}/\text{lbm} \cdot \text{R}$ (Table A-1). The specific heat ratio of helium is $k = 1.667$.

Analysis The mass flow rate of helium is

$$\dot{m} = \frac{P_1 \dot{V}_1}{RT_1} = \frac{(14 \text{ psia})(5 \text{ ft}^3/\text{s})}{(2.6805 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(530 \text{ R})} = 0.0493 \text{ lbm/s}$$

(a) Isentropic compression with $k = 1.667$:

$$\begin{aligned} \dot{W}_{\text{comp},in} &= \dot{m} \frac{kRT_1}{k-1} \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right] \\ &= (0.0493 \text{ lbm/s}) \frac{(1.667)(0.4961 \text{ Btu}/\text{lbm} \cdot \text{R})(530 \text{ R})}{1.667 - 1} \left[\left(\frac{120 \text{ psia}}{14 \text{ psia}} \right)^{0.667/1.667} - 1 \right] \\ &= 44.1 \text{ Btu/s} \\ &= \mathbf{62.4 \text{ hp}} \quad \text{since } 1 \text{ hp} = 0.7068 \text{ Btu/s} \end{aligned}$$

(b) Polytropic compression with $n = 1.2$:

$$\begin{aligned} \dot{W}_{\text{comp},in} &= \dot{m} \frac{nRT_1}{n-1} \left[\left(\frac{P_2}{P_1} \right)^{(n-1)/n} - 1 \right] \\ &= (0.0493 \text{ lbm/s}) \frac{(1.2)(0.4961 \text{ Btu}/\text{lbm} \cdot \text{R})(530 \text{ R})}{1.2 - 1} \left[\left(\frac{120 \text{ psia}}{14 \text{ psia}} \right)^{0.2/1.2} - 1 \right] \\ &= 33.47 \text{ Btu/s} \\ &= \mathbf{47.3 \text{ hp}} \quad \text{since } 1 \text{ hp} = 0.7068 \text{ Btu/s} \end{aligned}$$

(c) Isothermal compression:

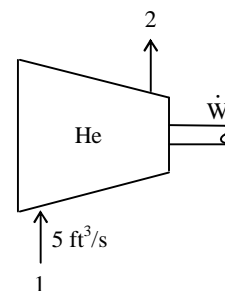
$$\dot{W}_{\text{comp},in} = \dot{m} RT \ln \frac{P_2}{P_1} = (0.0493 \text{ lbm/s})(0.4961 \text{ Btu}/\text{lbm} \cdot \text{R})(530 \text{ R}) \ln \frac{120 \text{ psia}}{14 \text{ psia}} = 27.83 \text{ Btu/s} = \mathbf{39.4 \text{ hp}}$$

(d) Ideal two-stage compression with intercooling ($n = 1.2$): In this case, the pressure ratio across each stage is the same, and its value is determined from

$$P_x = \sqrt{P_1 P_2} = \sqrt{(14 \text{ psia})(120 \text{ psia})} = 41.0 \text{ psia}$$

The compressor work across each stage is also the same, thus total compressor work is twice the compression work for a single stage:

$$\begin{aligned} \dot{W}_{\text{comp},in} &= 2 \dot{W}_{\text{comp},I} = 2 \dot{m} \frac{nRT_1}{n-1} \left[\left(\frac{P_x}{P_1} \right)^{(n-1)/n} - 1 \right] \\ &= 2(0.0493 \text{ lbm/s}) \frac{(1.2)(0.4961 \text{ Btu}/\text{lbm} \cdot \text{R})(530 \text{ R})}{1.2 - 1} \left[\left(\frac{41 \text{ psia}}{14 \text{ psia}} \right)^{0.2/1.2} - 1 \right] \\ &= 30.52 \text{ Btu/s} \\ &= \mathbf{43.2 \text{ hp}} \quad \text{since } 1 \text{ hp} = 0.7068 \text{ Btu/s} \end{aligned}$$



7-88E Problem 7-87E is reconsidered. The work of compression and entropy change of the helium is to be evaluated and plotted as functions of the polytropic exponent as it varies from 1 to 1.667.

Procedure FuncPoly(m_dot,k, R,
T1,P2,P1,n:W_dot_comp_polytropic,W_dot_comp_2stagePoly,Q_dot_Out_polytropic,Q_dot
_Out_2stagePoly)

If n =1 then

T2=T1 "[F]"

W_dot_comp_polytropic= m_dot*R*(T1+460)*ln(P2/P1)*convert(Btu/s,hp) "[hp]"

W_dot_comp_2stagePoly = W_dot_comp_polytropic "[hp]"

Q_dot_Out_polytropic=W_dot_comp_polytropic*convert(hp,Btu/s) "[Btu/s]"

Q_dot_Out_2stagePoly = Q_dot_Out_polytropic*convert(hp,Btu/s) "[Btu/s]"

Else

C_P = k*R/(k-1) "[Btu/lbm-R]"

T2=(T1+460)*((P2/P1)^((n+1)/n)-460) "[F]"

W_dot_comp_polytropic = m_dot*n*R*(T1+460)/(n-1)*((P2/P1)^((n-1)/n) -
1)*convert(Btu/s,hp) "[hp]"

Q_dot_Out_polytropic=W_dot_comp_polytropic*convert(hp,Btu/s)+m_dot*C_P*(T1-
T2) "[Btu/s]"

Px=(P1*P2)^0.5

T2x=(T1+460)*((Px/P1)^((n+1)/n)-460) "[F]"

W_dot_comp_2stagePoly = 2*m_dot*n*R*(T1+460)/(n-1)*((Px/P1)^((n-1)/n) -
1)*convert(Btu/s,hp) "[hp]"

Q_dot_Out_2stagePoly=W_dot_comp_2stagePoly*convert(hp,Btu/s)+2*m_dot*C_P*(T1-
T2x) "[Btu/s]"

endif

END

R=0.4961 "[Btu/lbm-R]"

k=1.667

{n=1.2}

P1=14 "[psia]"

T1=70 "[F]"

P2=120 "[psia]"

V_dot = 5 "[ft^3/s]"

P1*V_dot=m_dot*R*(T1+460)*convert(Btu,psia-ft^3)

W_dot_comp_isentropic = m_dot*k*R*(T1+460)/(k-1)*((P2/P1)^((k-1)/k) -
1)*convert(Btu/s,hp) "[hp]"

Q_dot_Out_isentropic = 0 "[Btu/s]"

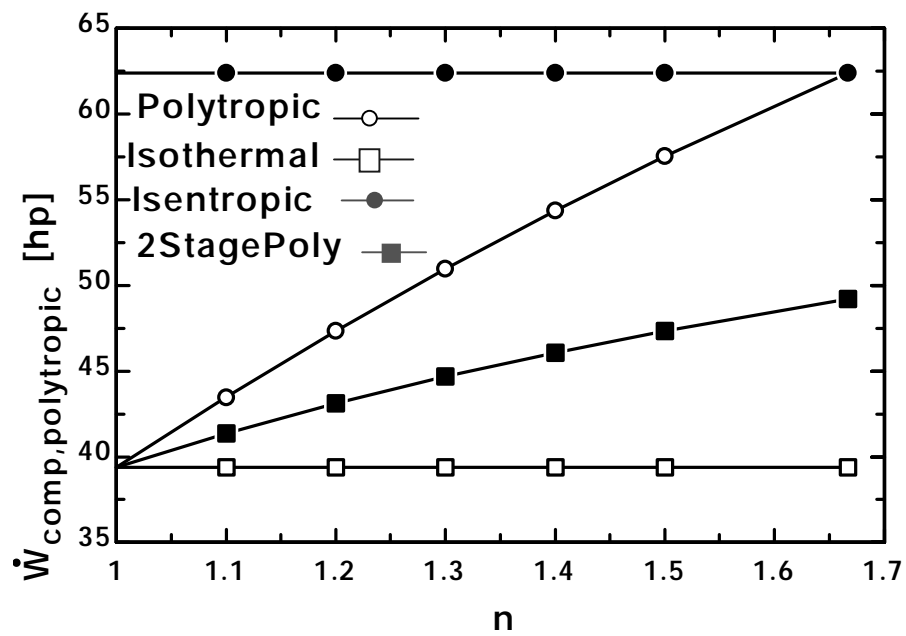
Call FuncPoly(m_dot,k, R,

T1,P2,P1,n:W_dot_comp_polytropic,W_dot_comp_2stagePoly,Q_dot_Out_polytropic,Q_dot
_Out_2stagePoly)

W_dot_comp_isothermal= m_dot*R*(T1+460)*ln(P2/P1)*convert(Btu/s,hp) "[hp]"

Q_dot_Out_isothermal = W_dot_comp_isothermal*convert(hp,Btu/s) "[Btu/s]"

n	$\dot{W}_{\text{comp2StagePoly}}$ [hp]	$\dot{W}_{\text{compisentropic}}$ [hp]	$\dot{W}_{\text{compisothermal}}$ [hp]	$\dot{W}_{\text{comppolytropic}}$ [hp]
1	39.37	62.4	39.37	39.37
1.1	41.36	62.4	39.37	43.48
1.2	43.12	62.4	39.37	47.35
1.3	44.68	62.4	39.37	50.97
1.4	46.09	62.4	39.37	54.36
1.5	47.35	62.4	39.37	57.54
1.667	49.19	62.4	39.37	62.4



7-89 Nitrogen gas is compressed by a 10-kW compressor from a specified state to a specified pressure. The mass flow rate of nitrogen through the compressor is to be determined for the cases of isentropic, polytropic, isothermal, and two-stage compression.

Assumptions 1 Nitrogen is an ideal gas with constant specific heats. 2 The process is reversible. 3 Kinetic and potential energy changes are negligible.

Properties The gas constant of nitrogen is $R = 0.297 \text{ kJ/kg} \cdot \text{K}$ (Table A-1). The specific heat ratio of Nitrogen is $k = 1.4$.

Analysis (a) Isentropic compression:

$$\dot{W}_{comp,in} = \dot{m} \frac{kRT_1}{k-1} \left\{ \left(P_2/P_1 \right)^{(k-1)/k} - 1 \right\}$$

or,

$$10 \text{ kJ/s} = \dot{m} \frac{(1.4)(0.297 \text{ kJ/kg} \cdot \text{K})(300 \text{ K})}{1.4-1} \left\{ (480 \text{ kPa}/80 \text{ kPa})^{0.4/1.4} - 1 \right\}$$

It yields

$$\dot{m} = 0.048 \text{ kg/s}$$

(b) Polytropic compression with $n = 1.3$:

$$\dot{W}_{comp,in} = \dot{m} \frac{nRT_1}{n-1} \left\{ \left(P_2/P_1 \right)^{(n-1)/n} - 1 \right\}$$

or,

$$10 \text{ kJ/s} = \dot{m} \frac{(1.3)(0.297 \text{ kJ/kg} \cdot \text{K})(300 \text{ K})}{1.3-1} \left\{ (480 \text{ kPa}/80 \text{ kPa})^{0.3/1.3} - 1 \right\}$$

It yields

$$\dot{m} = 0.051 \text{ kg/s}$$

(c) Isothermal compression:

$$\dot{W}_{comp,in} = \dot{m} RT \ln \frac{P_2}{P_1} \longrightarrow 10 \text{ kJ/s} = \dot{m} (0.297 \text{ kJ/kg} \cdot \text{K})(300 \text{ K}) \ln \left(\frac{480 \text{ kPa}}{80 \text{ kPa}} \right)$$

It yields

$$\dot{m} = 0.063 \text{ kg/s}$$

(d) Ideal two-stage compression with intercooling ($n = 1.3$): In this case, the pressure ratio across each stage is the same, and its value is determined to be

$$P_x = \sqrt{P_1 P_2} = \sqrt{(80 \text{ kPa})(480 \text{ kPa})} = 196 \text{ kPa}$$

The compressor work across each stage is also the same, thus total compressor work is twice the compression work for a single stage:

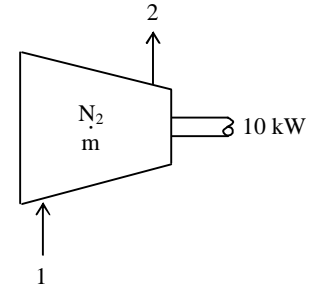
$$\dot{W}_{comp,in} = 2 \dot{W}_{comp,I} = 2 \dot{m} \frac{nRT_1}{n-1} \left\{ \left(P_x/P_1 \right)^{(n-1)/n} - 1 \right\}$$

or,

$$10 \text{ kJ/s} = 2 \dot{m} \frac{(1.3)(0.297 \text{ kJ/kg} \cdot \text{K})(300 \text{ K})}{1.3-1} \left\{ (196 \text{ kPa}/80 \text{ kPa})^{0.3/1.3} - 1 \right\}$$

It yields

$$\dot{m} = 0.056 \text{ kg/s}$$



7-90 Water mist is to be sprayed into the air stream in the compressor to cool the air as the water evaporates and to reduce the compression power. The reduction in the exit temperature of the compressed air and the compressor power saved are to be determined.

Assumptions **1** Air is an ideal gas with variable specific heats. **2** The process is reversible. **3** Kinetic and potential energy changes are negligible. **3** Air is compressed isentropically. **4** Water vaporizes completely before leaving the compressor. **4** Air properties can be used for the air-vapor mixture.

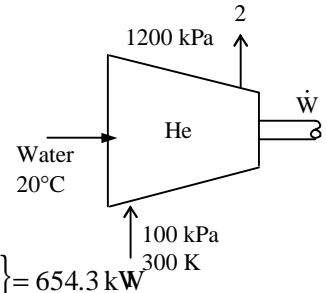
Properties The gas constant of air is $R = 0.287 \text{ kJ/kg}\cdot\text{K}$ (Table A-1). The specific heat ratio of air is $k = 1.4$. The inlet enthalpies of water and air are (Tables A-4 and A-17)

$$h_{w1} = h_{f@20^\circ\text{C}} = 83.96 \text{ kJ/kg}, \quad h_{g@20^\circ\text{C}} = 2454.1 \text{ kJ/kg} \quad \text{and} \quad h_{a1} = h_{a@300\text{ K}} = 300.19 \text{ kJ/kg}$$

Analysis In the case of isentropic operation (thus no cooling or water spray), the exit temperature and the power input to the compressor are

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{(k-1)/k} \rightarrow T_2 = (300 \text{ K}) \left(\frac{1200 \text{ kPa}}{100 \text{ kPa}} \right)^{(1.4-1)/1.4} = 610.2 \text{ K}$$

$$\begin{aligned} \dot{W}_{\text{comp, in}} &= \dot{m} \frac{kRT_1}{k-1} \left\{ \left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right\} \\ &= (2.1 \text{ kg/s}) \frac{(1.4)(0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})}{1.4-1} \left\{ (1200 \text{ kPa}/100 \text{ kPa})^{0.4/1.4} - 1 \right\} = 654.3 \text{ kW} \end{aligned}$$



When water is sprayed, we first need to check the accuracy of the assumption that the water vaporizes completely in the compressor. In the limiting case, the compression will be isothermal at the compressor inlet temperature, and the water will be a saturated vapor. To avoid the complexity of dealing with two fluid streams and a gas mixture, we disregard water in the air stream (other than the mass flow rate), and assume air is cooled by an amount equal to the enthalpy change of water.

The rate of heat absorption of water as it evaporates at the inlet temperature completely is

$$\dot{Q}_{\text{cooling, max}} = \dot{m}_w h_{fg@20^\circ\text{C}} = (0.2 \text{ kg/s})(2454.1 \text{ kJ/kg}) = 490.8 \text{ kW}$$

The minimum power input to the compressor is

$$\dot{W}_{\text{comp, in, min}} = \dot{m} RT \ln \frac{P_2}{P_1} = (2.1 \text{ kg/s})(0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K}) \ln \left(\frac{1200 \text{ kPa}}{100 \text{ kPa}} \right) = 449.3 \text{ kW}$$

This corresponds to maximum cooling from the air since, at constant temperature, $\Delta h = 0$ and thus $\dot{Q}_{\text{out}} = \dot{W}_{\text{in}} = 449.1 \text{ kW}$, which is close to 490.8 kW. Therefore, the assumption that all the water vaporizes is approximately valid. Then the reduction in required power input due to water spray becomes

$$\Delta \dot{W}_{\text{comp, in}} = \dot{W}_{\text{comp, isentropic}} - \dot{W}_{\text{comp, isothermal}} = 654.3 - 449.3 = \mathbf{205 \text{ kW}}$$

Discussion (can be ignored): At constant temperature, $\Delta h = 0$ and thus $\dot{Q}_{out} = \dot{W}_{in} = 449.1 \text{ kW}$ corresponds to maximum cooling from the air since, , which is less than 490.8 kW. Therefore, the assumption that all the water vaporizes is only roughly valid. As an alternative, we can assume the compression process to be polytropic and the water to be a saturated vapor at the compressor exit temperature, and disregard the remaining liquid. But in this case there is not a unique solution, and we will have to select either the amount of water or the exit temperature or the polytropic exponent to obtain a solution. Of course we can also tabulate the results for different cases, and then make a selection.

Sample Analysis We take the compressor exit temperature to be $T_2 = 200^\circ\text{C} = 473 \text{ K}$. Then,

$$h_{w2} = h_{g@200^\circ\text{C}} = 2793.2 \text{ kJ/kg and } h_{a2} = h_{a@473 \text{ K}} = 475.3 \text{ kJ/kg}$$

Then,

$$\begin{aligned} \frac{T_2}{T_1} &= \left(\frac{P_2}{P_1} \right)^{(n-1)/n} \rightarrow \frac{473 \text{ K}}{300 \text{ K}} = \left(\frac{1200 \text{ kPa}}{100 \text{ kPa}} \right)^{(n-1)/n} \rightarrow n = 1.224 \\ \dot{W}_{comp,in} &= \dot{m} \frac{nRT_1}{n-1} \left\{ \left(\frac{P_2}{P_1} \right)^{(n-1)/n} - 1 \right\} = \dot{m} \frac{nR}{n-1} (T_2 - T_1) \\ &= (2.1 \text{ kg/s}) \frac{(1.224)(0.287 \text{ kJ/kg} \cdot \text{K})}{1.224 - 1} (473 - 300) \text{ K} = 570 \text{ kW} \end{aligned}$$

Energy balance:

$$\begin{aligned} \dot{W}_{comp,in} - \dot{Q}_{out} &= \dot{m} (h_2 - h_1) \rightarrow \dot{Q}_{out} = \dot{W}_{comp,in} - \dot{m} (h_2 - h_1) \\ &= 569.7 \text{ kW} - (2.1 \text{ kg/s})(475.3 - 300.19) = 202.0 \text{ kW} \end{aligned}$$

Noting that this heat is absorbed by water, the rate at which water evaporates in the compressor becomes

$$\dot{Q}_{out,air} = \dot{Q}_{in,water} = \dot{m}_w (h_{w2} - h_{w1}) \rightarrow \dot{m}_w = \frac{\dot{Q}_{in,water}}{h_{w2} - h_{w1}} = \frac{202.0 \text{ kJ/s}}{(2793.2 - 83.96) \text{ kJ/kg}} = 0.0746 \text{ kg/s}$$

Then the reductions in the exit temperature and compressor power input become

$$\begin{aligned} \Delta T_2 &= T_{2,\text{isentropic}} - T_{2,\text{water cooled}} = 610.2 - 473 = \mathbf{137.2^\circ\text{C}} \\ \Delta \dot{W}_{comp,in} &= \dot{W}_{comp,\text{isentropic}} - \dot{W}_{comp,\text{water cooled}} = 654.3 - 570 = \mathbf{84.3 \text{ kW}} \end{aligned}$$

Note that selecting a different compressor exit temperature T_2 will result in different values.

7-91 A water-injected compressor is used in a gas turbine power plant. It is claimed that the power output of a gas turbine will increase when water is injected into the compressor because of the increase in the mass flow rate of the gas (air + water vapor) through the turbine. This, however, is **not necessarily right** since the compressed air in this case enters the combustor at a low temperature, and thus it absorbs much more heat. In fact, the cooling effect will most likely dominate and cause the cyclic efficiency to drop.

Isentropic Efficiencies of Steady-Flow Devices

7-92C The ideal process for all three devices is the reversible adiabatic (i.e., isentropic) process. The adiabatic efficiencies of these devices are defined as

$$\eta_r = \frac{\text{actual work output}}{\text{isentropic work output}}, \eta_c = \frac{\text{isentropic work input}}{\text{actual work input}}, \text{ and } \eta_N = \frac{\text{actual exit kinetic energy}}{\text{isentropic exit kinetic energy}}$$

7-93C No, because the isentropic process is not the model or ideal process for compressors that are cooled intentionally.

7-94C Yes. Because the entropy of the fluid must increase during an actual adiabatic process as a result of irreversibilities. Therefore, the actual exit state has to be on the right-hand side of the isentropic exit state

7-95 Steam enters an adiabatic turbine with an isentropic efficiency of 0.90 at a specified state with a specified mass flow rate, and leaves at a specified pressure. The turbine exit temperature and power output of the turbine 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.

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

$$\left. \begin{aligned} P_1 &= 8 \text{ MPa} \\ T_1 &= 500^\circ \text{C} \end{aligned} \right\} \begin{aligned} h_1 &= 3398.3 \text{ kJ/kg} \\ s_1 &= 6.7240 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

$$\left. \begin{aligned} P_{2s} &= 30 \text{ kPa} \\ s_{2s} &= s_1 \end{aligned} \right\} \begin{aligned} x_{2s} &= \frac{s_{2s} - s_f}{s_{fg}} = \frac{6.7240 - 0.9439}{6.8247} = 0.847 \\ h_{2s} &= h_f + x_{2s} h_{fg} = 289.23 + (0.847)(2336.1) = 2267.9 \text{ kJ/kg} \end{aligned}$$

From the isentropic efficiency relation,

$$\eta_r = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \longrightarrow h_{2a} = h_1 - \eta_r (h_1 - h_{2s}) = 3398.3 - (0.9)(3398.3 - 2267.9) = 2380.9 \text{ kJ/kg}$$

Thus,

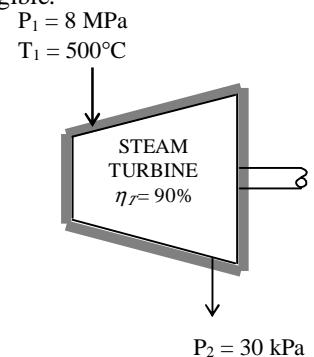
$$\left. \begin{aligned} P_{2a} &= 30 \text{ kPa} \\ h_{2a} &= 2380.9 \text{ kJ/kg} \end{aligned} \right\} T_{2a} = T_{sat@30 \text{ kPa}} = \mathbf{69.10^\circ \text{C}}$$

(b) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. 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

$$\begin{aligned} \underbrace{\dot{Q}_{in} - \dot{Q}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} &= \underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0 \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{m}h_1 &= \dot{m}h_{2a} + \dot{W}_{a,out} \quad (\text{since } \dot{Q} \equiv \Delta ke \equiv \Delta pe \equiv 0) \\ \dot{W}_{a,out} &= \dot{m}(h_1 - h_{2a}) \end{aligned}$$

Substituting,

$$\dot{W}_{a,out} = (3 \text{ kg/s})(3398.3 - 2380.9) \text{ kJ/kg} = \mathbf{3052 \text{ kW}}$$



7-96 Problem 7-95 is reconsidered. The effect of varying the turbine isentropic efficiency from 0.75 to 1.0 on both the work done and the exit temperature of the steam is to be investigated, and the results are to be plotted.

"System: control volume for turbine"

"Property relation: Steam functions"

"Process: Turbine: Steady state, steady flow, adiabatic, reversible or isentropic"

"Since we don't know the mass, we write the conservation of energy per unit mass."

"Conservation of mass: $m_{\dot{1}} = m_{\dot{2}} = m_{\dot{}}$ "

"Knowns:"

WorkFluid\$ = 'Steam'

$m_{\dot{}} = 3$ "[kg/s]"

$P[1] = 8000$ "[kPa]"

$T[1] = 500$ "[C]"

$P[2] = 30$ "[kPa]"

$\eta_{\text{turb}} = 0.9$

"Conservation of Energy - SSSF energy balance for turbine -- neglecting the change in potential energy, no heat transfer:"

$h[1] = \text{enthalpy}(\text{WorkFluid}\$, P=P[1], T=T[1])$ "[kJ/kg]"

$s[1] = \text{entropy}(\text{WorkFluid}\$, P=P[1], T=T[1])$ "[kJ/kg-K]"

$T_{s[1]} = T[1]$

$s[2] = s[1]$ "[kJ/kg-K]"

$s_{s[2]} = s[1]$ "[kJ/kg-K]"

$h_{s[2]} = \text{enthalpy}(\text{WorkFluid}\$, P=P[2], s=s_{s[2]})$ "[kJ/kg]"

$T_{s[2]} = \text{temperature}(\text{WorkFluid}\$, P=P[2], s=s_{s[2]})$ "[C]"

$\eta_{\text{turb}} = w_{\text{turb}}/w_{\text{turb}_s}$

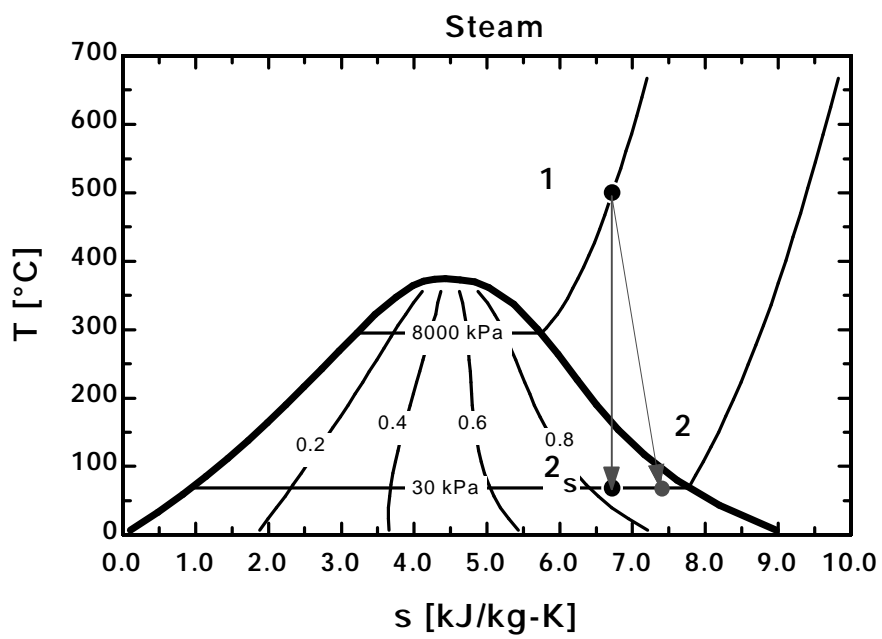
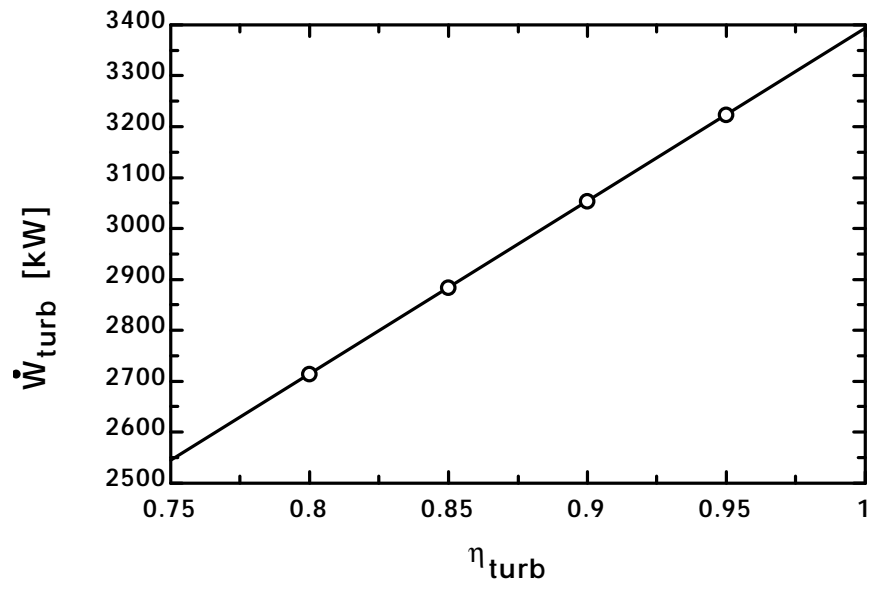
$h[1] = h[2] + w_{\text{turb}}$

$h[1] = h_{s[2]} + w_{\text{turb}_s}$

$T[2] = \text{temperature}(\text{WorkFluid}\$, P=P[2], h=h[2])$ "[C]"

$W_{\dot{\text{turb}}} = m_{\dot{}} w_{\text{turb}}$ "[kW]"

η_{turb}	W_{turb} [kW]
0.75	2545
0.8	2714
0.85	2884
0.9	3054
0.95	3223
1	3393



7-97 Steam enters an adiabatic turbine at a specified state, and leaves at a specified state. The mass flow rate of the steam and the isentropic efficiency 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.

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

$$\begin{aligned} P_1 = 6 \text{ MPa} & \left\{ \begin{aligned} h_1 &= 3658.4 \text{ kJ/kg} \\ s_1 &= 7.1677 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \\ T_1 = 600^\circ \text{C} & \\ P_2 = 50 \text{ kPa} & \left\{ \begin{aligned} h_{2,s} &= 2682.5 \text{ kJ/kg} \\ T_2 = 100^\circ \text{C} & \end{aligned} \right. \end{aligned}$$

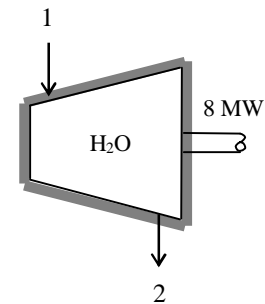
There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

$$\dot{m}_{a,out} = -\dot{m} \left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} \right)$$



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

$$\begin{aligned} 8000 \text{ kJ/s} &= -\dot{m} \left(2682.5 - 3658.4 + \frac{(140 \text{ m/s})^2 - (80 \text{ m/s})^2}{2} \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \right) \\ \dot{m} &= \mathbf{8.25 \text{ kg/s}} \end{aligned}$$

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

$$\begin{aligned} P_{2,s} = 50 \text{ kPa} & \left\{ \begin{aligned} x_{2,s} &= \frac{s_{2,s} - s_f}{s_{fg}} = \frac{7.1677 - 1.0910}{6.5029} = 0.934 \\ s_{2,s} = s_1 & \end{aligned} \right. \\ h_{2,s} &= h_f + x_{2,s} h_{fg} = 340.49 + (0.934)(2305.4) = 2493.7 \text{ kJ/kg} \end{aligned}$$

and

$$\begin{aligned} \dot{m}_{s,out} &= -\dot{m} \left(h_{2,s} - h_1 + \frac{V_2^2 - V_1^2}{2} \right) \\ \dot{m}_{s,out} &= -(8.25 \text{ kg/s}) \left(2493.7 - 3658.4 + \frac{(140 \text{ m/s})^2 - (80 \text{ m/s})^2}{2} \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \right) \\ &= 9554 \text{ kW} \end{aligned}$$

Then the isentropic efficiency of the turbine becomes

$$\eta_T = \frac{\dot{W}_a}{\dot{W}_s} = \frac{8000 \text{ kW}}{9554 \text{ kW}} = 0.837 = \mathbf{83.7\%}$$

7-98 Argon enters an adiabatic turbine at a specified state with a specified mass flow rate, and leaves at a specified pressure. The isentropic efficiency of the turbine 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** The device is adiabatic and thus heat transfer is negligible. **4** Argon is an ideal gas with constant specific heats.

Properties The specific heat ratio of argon is $k = 1.667$. The constant pressure specific heat of argon is $C_p = 0.5203 \text{ kJ/kg} \cdot \text{K}$ (Table A-2).

Analysis There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the isentropic 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

$$\underbrace{\dot{Q}_{in} - \dot{Q}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0$$

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

$$\dot{m}h_1 = \dot{m}h_{2s} + \dot{W}_{s,out} \quad (\text{since } \dot{Q} \equiv \Delta ke \equiv \Delta pe \equiv 0)$$

$$\dot{W}_{s,out} = \dot{m}(h_1 - h_{2s})$$

From the isentropic relations,

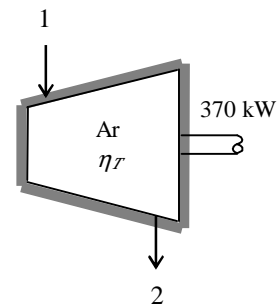
$$T_{2s} = T_1 \left(\frac{P_{2s}}{P_1} \right)^{(k-1)/k} = (1073 \text{ K}) \left(\frac{200 \text{ kPa}}{1500 \text{ kPa}} \right)^{0.667/1.667} = 479 \text{ K}$$

Then the power output of the isentropic turbine becomes

$$\dot{W}_{s,out} = \dot{m}C_p(T_1 - T_{2s}) = (80/60 \text{ kg/min})(0.5203 \text{ kJ/kg} \cdot \text{K})(1073 - 479) = 412.1 \text{ kW}$$

Then the isentropic efficiency of the turbine is determined from

$$\eta_r = \frac{\dot{W}_a}{\dot{W}_s} = \frac{370 \text{ kW}}{412.1 \text{ kW}} = 0.898 = \mathbf{89.8\%}$$



7-99E Combustion gases enter an adiabatic gas turbine with an isentropic efficiency of 86% at a specified state, and leave at a specified pressure. The work output of the turbine 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** The device is adiabatic and thus heat transfer is negligible. **4** Combustion gases can be treated as air that is an ideal gas with variable specific heats.

Analysis From the air table and isentropic relations,

$$T_1 = 2000 \text{ R} \longrightarrow \begin{aligned} h_1 &= 504.71 \text{ Btu/lbm} \\ P_{r1} &= 174.0 \end{aligned}$$

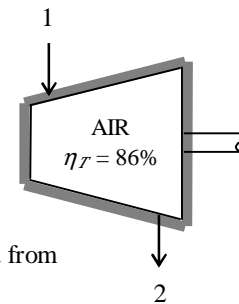
$$P_{r2} = \left(\frac{P_2}{P_1} \right) P_{r1} = \left(\frac{60 \text{ psia}}{120 \text{ psia}} \right) (174.0) = 87.0 \longrightarrow h_{2s} = 417.3 \text{ Btu/lbm}$$

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. 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 as

$$\begin{aligned} \dot{E}_{\text{in}} - \dot{E}_{\text{out}} &= \dot{E}_{\text{system}} \quad \dot{E}_{\text{system}} = 0 \quad (\text{steady}) \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\ \dot{m}h_1 &= \dot{m}h_{2s} + \dot{W}_{a,\text{out}} \quad (\text{since } \dot{Q} \cong \Delta ke \cong \Delta pe \cong 0) \\ \dot{W}_{a,\text{out}} &= \dot{m}(h_1 - h_{2s}) \end{aligned}$$

Noting that $w_a = \eta_T w_s$, the work output of the turbine per unit mass is determined from

$$w_a = (0.86)(504.71 - 417.3) \text{ Btu/lbm} = \mathbf{75.2 \text{ Btu/lbm}}$$



7-100 [Also solved by EES on enclosed CD] Refrigerant-134a enters an adiabatic compressor with an isentropic efficiency of 0.80 at a specified state with a specified volume flow rate, and leaves at a specified pressure. The compressor exit temperature and power input to the compressor 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.

Analysis (a) From the refrigerant tables,

$$\left. \begin{array}{l} P_1 = 120 \text{ kPa} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} h_1 = h_{g@120 \text{ kPa}} = 233.86 \text{ kJ/kg} \\ s_1 = s_{g@120 \text{ kPa}} = 0.9354 \text{ kJ/kg} \cdot \text{K} \\ v_1 = v_{g@120 \text{ kPa}} = 0.1614 \text{ m}^3/\text{kg} \end{array}$$

$$\left. \begin{array}{l} P_2 = 1 \text{ MPa} \\ s_{2s} = s_1 \end{array} \right\} h_{2s} = 277.84 \text{ kJ/kg}$$

From the isentropic efficiency relation,

$$\eta_c = \frac{h_{2s} - h_1}{h_{2a} - h_1} \rightarrow h_{2a} = h_1 + (h_{2s} - h_1) / \eta_c = 233.86 + (277.84 - 233.86) / 0.80 = 288.84 \text{ kJ/kg}$$

Thus,

$$\left. \begin{array}{l} P_{2a} = 1 \text{ MPa} \\ h_{2a} = 288.84 \text{ kJ/kg} \end{array} \right\} T_{2a} = 57.7^\circ \text{C}$$

(b) The mass flow rate of the refrigerant is determined from

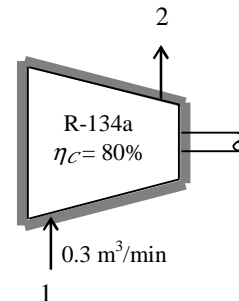
$$\dot{m} = \frac{\dot{V}}{v_1} = \frac{0.3 / 60 \text{ m}^3 / \text{s}}{0.1614 \text{ m}^3 / \text{kg}} = 0.031 \text{ kg/s}$$

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual 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 as

$$\begin{aligned} \underbrace{\dot{Q} - \dot{W}}_{\text{Rate of net energy transfer by heat, work, and mass}} &= \underbrace{\Delta \dot{E}_{\text{system}}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0 \quad \dot{Q} = 0 \quad \dot{W} = \dot{W}_{\text{in}} \quad \dot{E}_{\text{system}} = \dot{E}_{\text{out}} \quad \dot{E}_{\text{in}} = \dot{E}_{\text{out}} \\ \dot{W}_{a,\text{in}} + \dot{m}h_1 &= \dot{m}h_2 \quad (\text{since } \dot{Q} \equiv \Delta ke \equiv \Delta pe \equiv 0) \\ \dot{W}_{a,\text{in}} &= \dot{m}(h_2 - h_1) \end{aligned}$$

Substituting, the power input to the compressor becomes,

$$\dot{W}_{a,\text{in}} = (0.031 \text{ kg/s})(288.84 - 233.86) \text{ kJ/kg} = 1.70 \text{ kW}$$



7-101 Problem 7-100 is reconsidered. The problem is to be solved by considering the kinetic energy and by assuming an inlet-to-exit area ratio of 1.5 for the compressor when the compressor exit pipe inside diameter is 2 cm.

"Input Data from diagram window"

```
{P[1] = 120 "kPa"
P[2] = 1000 "kPa"
Vol_dot_1 = 0.3 "m^3/min"
Eta_c = 0.80 "Compressor adiabatic efficiency"
A_ratio = 1.5
d_2 = 2/100 "m"}
```

"System: Control volume containing the compressor, see the diagram window.

Property Relation: Use the real fluid properties for R134a.

Process: Steady-state, steady-flow, adiabatic process."

Fluid\$='R134a'

"Property Data for state 1"

T[1]=temperature(Fluid\$,P=P[1],x=1)"Real fluid equ. at the sat. vapor state"

h[1]=enthalpy(Fluid\$, P=P[1], x=1)"Real fluid equ. at the sat. vapor state"

s[1]=entropy(Fluid\$, P=P[1], x=1)"Real fluid equ. at the sat. vapor state"

v[1]=volume(Fluid\$, P=P[1], x=1)"Real fluid equ. at the sat. vapor state"

"Property Data for state 2"

s_s[1]=s[1]; T_s[1]=T[1] "needed for plot"

s_s[2]=s[1] "for the ideal, isentropic process across the compressor"

h_s[2]=ENTHALPY(Fluid\$, P=P[2], s=s_s[2])"Enthalpy 2 at the isentropic state 2s and pressure P[2]"

T_s[2]=Temperature(Fluid\$, P=P[2], s=s_s[2])"Temperature of ideal state - needed only for plot."

"Steady-state, steady-flow conservation of mass"

m_dot_1 = m_dot_2

m_dot_1 = Vol_dot_1/(v[1]*60)

Vol_dot_1/v[1]=Vol_dot_2/v[2]

Vel[2]=Vol_dot_2/(A[2]*60)

A[2] = pi*(d_2)^2/4

A_ratio*Vel[1]/v[1] = Vel[2]/v[2] "Mass flow rate: = A*Vel/v, A_ratio = A[1]/A[2]"

A_ratio=A[1]/A[2]

"Steady-state, steady-flow conservation of energy, adiabatic compressor, see diagram window"

m_dot_1*(h[1]+(Vel[1])^2/(2*1000)) + W_dot_c= m_dot_2*(h[2]+(Vel[2])^2/(2*1000))

"Definition of the compressor adiabatic efficiency, Eta_c=W_isen/W_act"

Eta_c = (h_s[2]-h[1])/(h[2]-h[1])

"Knowing h[2], the other properties at state 2 can be found."

v[2]=volume(Fluid\$, P=P[2], h=h[2])"v[2] is found at the actual state 2, knowing P and h."

T[2]=temperature(Fluid\$, P=P[2],h=h[2])"Real fluid equ. for T at the known outlet h and P."

s[2]=entropy(Fluid\$, P=P[2], h=h[2]) "Real fluid equ. at the known outlet h and P."

T_exit=T[2]

"Neglecting the kinetic energies, the work is:"

m_dot_1*h[1] + W_dot_c_noke= m_dot_2*h[2]

ARRAYS TABLE

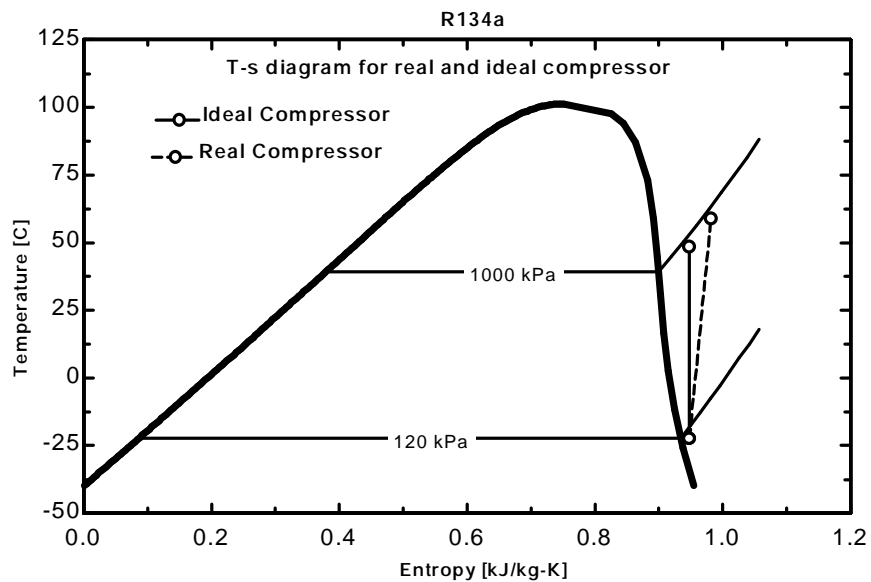
A _i	h _i	h _{si}	P _i	s _i	s _{si}	T _{si}	v _i	Vel _i		
[kJ/kg-K]	[kJ/kg]	[kJ/kg]	kPa]		[kJ/kg-K]		C]	[C]	[m ³ /kg]	[m/s]
0.0004712	233.5		120	0.934		0.934	-22.36	-22.36	0.1613	10.61
0.0003142	288.7	277.6	000.0	.9677		0.934	59.13	49.08	0.0229	2.259

SOLUTION

Variables in Main

 $A[1]=0.0004712 \text{ [m}^2\text{]}$ $A[2]=0.0003142 \text{ [m}^2\text{]}$ $A_ratio=1.5 \text{ []}$ $d_2=0.02 \text{ [m]}$ $Eta_c=0.8 \text{ []}$

Fluid\$='R134a'

 $h[1]=237 \text{ [kJ/kg]}$ $h[2]=292.3 \text{ [kJ/kg]}$ $h_s[2]=281.2 \text{ [kJ/kg]}$ $m_dot_1=0.03083 \text{ [kg/s]}$ $m_dot_2=0.03083 \text{ [kg/s]}$ $P[1]=120.0 \text{ [kPa]}$ $P[2]=1000.0 \text{ [kPa]}$ $s[1]=0.9479 \text{ [kJ/kg-K]}$ $s[2]=0.9817 \text{ [kJ/kg-K]}$ $s_s[1]=0.9479 \text{ [kJ/kg-K]}$ $s_s[2]=0.9479 \text{ [kJ/kg-K]}$ $T[1]=-22.32 \text{ [C]}$ $T[2]=58.95 \text{ [C]}$ $T_exit=58.95 \text{ [C]}$ $T_s[1]=-22.32 \text{ [C]}$ $T_s[2]=48.59 \text{ [C]}$ $Vol_dot_1=0.3 \text{ [m}^3\text{/min]}$ $Vol_dot_2=0.04243 \text{ [m}^3\text{/min]}$ $v[1]=0.1622 \text{ [m}^3\text{/kg]}$ $v[2]=0.02294 \text{ [m}^3\text{/kg]}$ $Vel[1]=10.61 \text{ [m/s]}$ $Vel[2]=2.251 \text{ [m/s]}$ $W_dot_c=1.703 \text{ [kW]}$ $W_dot_c_noke=1.705 \text{ [W]}$ 

7-102 Air enters an adiabatic compressor with an isentropic efficiency of 84% at a specified state, and leaves at a specified temperature. The exit pressure of air and the power input to the compressor 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. **4** Air is an ideal gas with variable specific heats.

Properties The gas constant of air is $R = 0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$ (Table A-1)

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

$$T_1 = 290 \text{ K} \longrightarrow h_1 = 290.16 \text{ kJ/kg}, \quad P_{r1} = 1.2311$$

$$T_2 = 530 \text{ K} \longrightarrow h_{2a} = 533.98 \text{ kJ/kg}$$

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

$$\begin{aligned} h_{2s} &= h_1 + \eta_c (h_{2a} - h_1) \\ &= 290.16 + (0.84)(533.98 - 290.16) = 495.0 \text{ kJ/kg} \longrightarrow P_{r2} = 7.951 \end{aligned}$$

Then from the isentropic relation ,

$$\frac{P_2}{P_1} = \frac{P_{r2}}{P_{r1}} \longrightarrow P_2 = \left(\frac{P_{r2}}{P_{r1}} \right) P_1 = \left(\frac{7.951}{1.2311} \right) (100 \text{ kPa}) = \mathbf{646 \text{ kPa}}$$

(b) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual 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 as

$$\underbrace{\dot{Q} - \dot{W}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\Delta \dot{E}_{\text{system}}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0$$

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

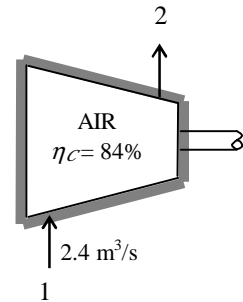
$$\dot{W}_{a,\text{in}} + \dot{m}h_1 = \dot{m}h_2 \quad (\text{since } \dot{Q} \equiv \Delta ke \equiv \Delta pe \equiv 0)$$

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

where $\dot{m} = \frac{P_1 \dot{V}}{RT_1} = \frac{(100 \text{ kPa})(2.4 \text{ m}^3/\text{s})}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(290 \text{ K})} = 2.884 \text{ kg/s}$

Then the power input to the compressor is determined to be

$$\dot{W}_{a,\text{out}} = (2.884 \text{ kg/s})(533.98 - 290.16) \text{ kJ/kg} = \mathbf{703 \text{ kW}}$$



7-103 Air is compressed by an adiabatic compressor from a specified state to another specified state. The isentropic efficiency of the compressor and the exit temperature of air for the isentropic case 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. **4** Air is an ideal gas with variable specific heats.

Analysis 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,

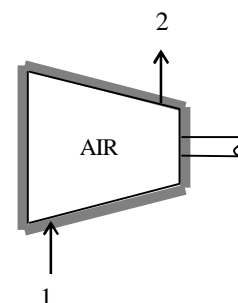
$$P_{r2} = \left(\frac{P_2}{P_1} \right) P_{r1} = \left(\frac{600 \text{ kPa}}{95 \text{ kPa}} \right) (1.386) = 8.754 \longrightarrow h_{2s} = 508.72 \text{ kJ/kg}$$

Then the isentropic efficiency becomes

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

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

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



7-104E Argon enters an adiabatic compressor with an isentropic efficiency of 80% at a specified state, and leaves at a specified pressure. The exit temperature of argon and the work input to the compressor 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. **4** Argon is an ideal gas with constant specific heats.

Properties The specific heat ratio of argon is $k = 1.667$. The constant pressure specific heat of argon is $C_p = 0.1253 \text{ Btu/lbm} \cdot \text{R}$ (Table A-2E).

Analysis (a) The isentropic exit temperature T_{2s} is determined from

$$T_{2s} = T_1 \left(\frac{P_2}{P_1} \right)^{(k-1)/k} = (550 \text{ R}) \left(\frac{200 \text{ psia}}{20 \text{ psia}} \right)^{0.667/1.667} = 1381.9 \text{ R}$$

The actual kinetic energy change during this process is

$$\Delta ke_a = \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} = \frac{(240 \text{ ft/s})^2 - (60 \text{ ft/s})^2}{2} \left(\frac{1 \text{ Btu/lbm}}{25,037 \text{ ft}^2/\text{s}^2} \right) = 1.08 \text{ Btu/lbm}$$

The effect of kinetic energy on isentropic efficiency is very small. Therefore, we can take the kinetic energy changes for the actual and isentropic cases to be same in efficiency calculations. From the isentropic efficiency relation, including the effect of kinetic energy,

$$\eta_c = \frac{w_s}{w_a} = \frac{(h_2 - h_1) + \Delta ke}{(h_{2a} - h_1) + \Delta ke} = \frac{C_p(T_{2s} - T_1) + \Delta ke_s}{C_p(T_{2a} - T_1) + \Delta ke_a} \longrightarrow 0.8 = \frac{0.1253(1381.9 - 550) + 1.08}{0.1253(T_{2a} - 550) + 1.08}$$

It yields

$$T_{2a} = 1592 \text{ R}$$

(b) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual 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 as

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

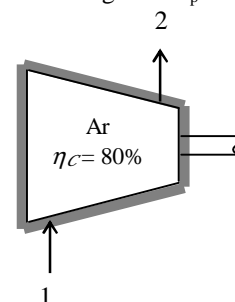
$$\dot{E}_{in} = \dot{E}_{out}$$

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

$$\dot{W}_{a,in} = \dot{m} \left(h_2 - h_1 + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} \right) \rightarrow w_{a,in} = h_2 - h_1 + \Delta ke$$

Substituting, the work input to the compressor is determined to be

$$w_{a,in} = (0.1253 \text{ Btu/lbm} \cdot \text{R})(1592 - 550) \text{ R} + 1.08 \text{ Btu/lbm} = 131.6 \text{ Btu/lbm}$$



7-105 CO₂ gas is compressed by an adiabatic compressor from a specified state to another specified state. The isentropic efficiency of the compressor 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** The device is adiabatic and thus heat transfer is negligible. **4** CO₂ is an ideal gas with constant specific heats.

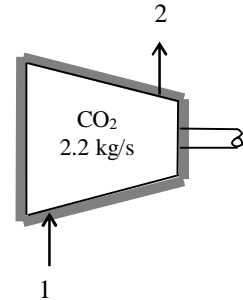
Properties At the average temperature of $(300 + 450)/2 = 375$ K, the constant pressure specific heat and the specific heat ratio of CO₂ are $k = 1.260$ and $C_p = 0.917$ kJ/kg.K (Table A-2).

Analysis The isentropic exit temperature T_{2s} is

$$T_{2s} = T_1 \left(\frac{P_{2s}}{P_1} \right)^{(k-1)/k} = (300 \text{ K}) \left(\frac{600 \text{ kPa}}{100 \text{ kPa}} \right)^{0.260/1.260} = 434.2 \text{ K}$$

From the isentropic efficiency relation,

$$\eta_c = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} = \frac{C_p(T_{2s} - T_1)}{C_p(T_{2a} - T_1)} = \frac{T_{2s} - T_1}{T_{2a} - T_1} = \frac{434.2 - 300}{450 - 300} = 0.895 = \mathbf{89.5\%}$$



7-107E Problem 7-106E is reconsidered. The effect of varying the nozzle isentropic efficiency from 0.8 to 1.0 on the exit temperature and pressure of the air is to be investigated, and the results are to be plotted.

"Knowns:"

WorkFluid\$ = 'Air'

P[1] = 60 "[psia]"

T[1] = 1020 "[F]"

Vel[2] = 800 "[ft/s]"

Vel[1] = 0 "[ft/s]"

eta_nozzle = 0.9

"Conservation of Energy - SSSF energy balance for turbine -- neglecting the change in potential energy, no heat transfer:"

h[1]=enthalpy(WorkFluid\$,T=T[1])"[Btu/lbm]"

s[1]=entropy(WorkFluid\$,P=P[1],T=T[1])"[Btu/lbm-R]"

T_s[1] = T[1]"[F]"

s[2] = s[1]"[Btu/lbm-R]"

s_s[2] = s[1]"[Btu/lbm-R]"

h_s[2]=enthalpy(WorkFluid\$,T=T_s[2])"[Btu/lbm]"

T_s[2]=temperature(WorkFluid\$,P=P[2],s=s_s[2])"[F]"

eta_nozzle = ke[2]/ke_s[2]

ke[1] = Vel[1]^2/2"[ft^2/s^2]"

ke[2]=Vel[2]^2/2

h[1]+ke[1]*convert(ft^2/s^2,Btu/lbm) = h[2] + ke[2]*convert(ft^2/s^2,Btu/lbm)

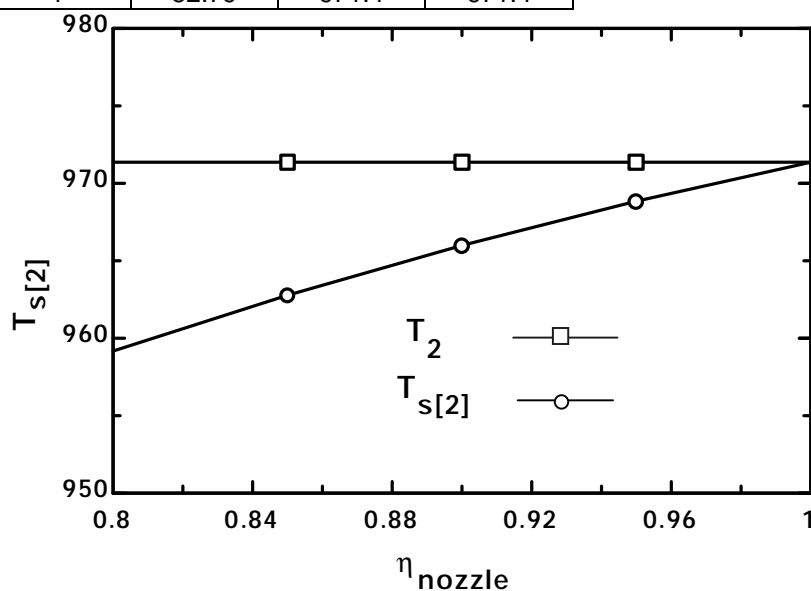
h[1] + ke[1]*convert(ft^2/s^2,Btu/lbm) = h_s[2] + ke_s[2]*convert(ft^2/s^2,Btu/lbm)

T[2]=temperature(WorkFluid\$,h=h[2])"[F]"

P_2_answer = P[2]

T_2_answer = T[2]

η_{nozzle}	P_2 [psia]	T_2 [F]	$T_{s,2}$ [F]
0.8	51.09	971.4	959.2
0.85	51.58	971.4	962.8
0.9	52.03	971.4	966
0.95	52.42	971.4	968.8
1	52.79	971.4	971.4



7-108 Hot combustion gases are accelerated in a 92% efficient adiabatic nozzle from low velocity to a specified velocity. The exit velocity and the exit temperature are to be determined.

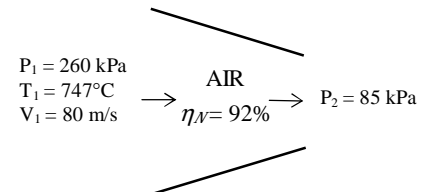
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Potential energy changes are negligible. **3** The device is adiabatic and thus heat transfer is negligible. **4** Combustion gases can be treated as air that is an ideal gas with variable specific heats.

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

$$T_1 = 1020 \text{ K} \longrightarrow h_1 = 1068.89 \text{ kJ/kg}, \quad P_r = 123.4$$

From the isentropic relation ,

$$P_r = \left(\frac{P_2}{P_1} \right) P_{r1} = \left(\frac{85 \text{ kPa}}{260 \text{ kPa}} \right) (123.4) = 40.34 \longrightarrow h_{2s} = 783.92 \text{ kJ/kg}$$



There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. 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 for the isentropic process can be expressed as

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

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

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} \right) = \dot{m} \left(h_{2s} + \frac{V_{2s}^2}{2} \right) \quad (\text{since } \dot{Q} = \dot{W} = \Delta pe \cong 0)$$

$$h_{2s} = h_1 - \frac{V_{2s}^2 - V_1^2}{2}$$

Then the isentropic exit velocity becomes

$$V_{2s} = \sqrt{V_1^2 + 2(h_1 - h_{2s})} = \sqrt{(80 \text{ m/s})^2 + 2(1068.89 - 783.92) \text{ kJ/kg} \left(\frac{1000 \text{ m}^2/\text{s}^2}{1 \text{ kJ/kg}} \right)} = 759.2 \text{ m/s}$$

Therefore,

$$V_{2a} = \sqrt{\eta_N} V_{2s} = \sqrt{0.92} (759.2 \text{ m/s}) = 728.2 \text{ m/s}$$

The exit temperature of air is determined from the steady-flow energy equation,

$$h_{2a} = 1068.89 \text{ kJ/kg} - \frac{(728.2 \text{ m/s})^2 - (80 \text{ m/s})^2}{2} \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) = 806.95 \text{ kJ/kg}$$

From the air table we read

$$T_{2a} = 786.3 \text{ K}$$

Entropy Balance

7-109 Each member of a family of four take a 5-min shower every day. The amount of entropy generated by this family per year is to be determined.

Assumptions **1** Steady operating conditions exist. **2** The kinetic and potential energies are negligible. **3** Heat losses from the pipes and the mixing section are negligible and thus $\dot{Q} \approx 0$. **4** Showers operate at maximum flow conditions during the entire shower. **5** Each member of the household takes a 5-min shower every day. **6** Water is an incompressible substance with constant properties at room temperature. **7** The efficiency of the electric water heater is 100%.

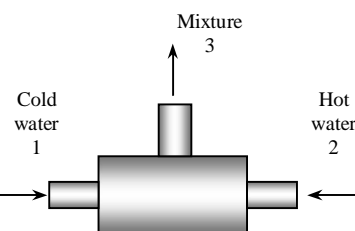
Properties The density and specific heat of water at room temperature are $\rho = 1 \text{ kg/L} = 1000 \text{ kg/m}^3$ and $C = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3).

Analysis The mass flow rate of water at the shower head is

$$\dot{m} = \rho \dot{V} = (1 \text{ kg/L})(12 \text{ L/min}) = 12 \text{ kg/min}$$

The mass balance for the mixing chamber can be expressed in the rate form as

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{system} \xrightarrow{\dot{m}_0 \text{ (steady)}} 0 \rightarrow \dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$



where the subscript 1 denotes the cold water stream, 2 the hot water stream, and 3 the mixture.

The rate of entropy generation during this process can be determined by applying the rate form of the entropy balance on a system that includes the electric water heater and the mixing chamber (the T-elbow). Noting that there is no entropy transfer associated with work transfer (electricity) and there is no heat transfer, the entropy balance for this steady-flow system can be expressed as

$$\begin{aligned} \underbrace{\dot{Q}_1 s_1 + \dot{Q}_2 s_2}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{gen}}_{\text{Rate of entropy generation}} &= \underbrace{\Delta \dot{S}_{system}}_{\text{Rate of change of entropy}} \xrightarrow{\dot{S}_0 \text{ (steady)}} 0 \\ \dot{m}_1 s_1 + \dot{m}_2 s_2 - \dot{m}_3 s_3 + \dot{S}_{gen} &= 0 \quad (\text{since } \dot{Q} = 0 \text{ and work is entropy free}) \\ \dot{S}_{gen} &= \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2 \end{aligned}$$

Noting from mass balance that $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$ and $s_2 = s_1$ since hot water enters the system at the same temperature as the cold water, the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_3 s_3 - (\dot{m}_1 + \dot{m}_2) s_1 = \dot{m}_3 (s_3 - s_1) = \dot{m}_3 C_p \ln \frac{T_3}{T_1} \\ &= (12 \text{ kg/min})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{42 + 273}{15 + 273} = 4.495 \text{ kJ/min} \cdot \text{K} \end{aligned}$$

Noting that 4 people take a 5-min shower every day, the amount of entropy generated per year is

$$\begin{aligned} S_{gen} &= (\dot{S}_{gen}) \Delta t (\text{No. of people})(\text{No. of days}) \\ &= (4.495 \text{ kJ/min} \cdot \text{K})(5 \text{ min/person} \cdot \text{day})(4 \text{ persons})(365 \text{ days/year}) \\ &= \mathbf{32,814 \text{ kJ/K}} \quad (\text{per year}) \end{aligned}$$

Discussion The value above represents the entropy generated within the water heater and the T-elbow in the absence of any heat losses. It does not include the entropy generated as the shower water at 42°C is discarded or cooled to the outdoor temperature. Also, an entropy balance on the mixing chamber alone (hot water entering at 55°C instead of 15°C) will exclude the entropy generated within the water heater.

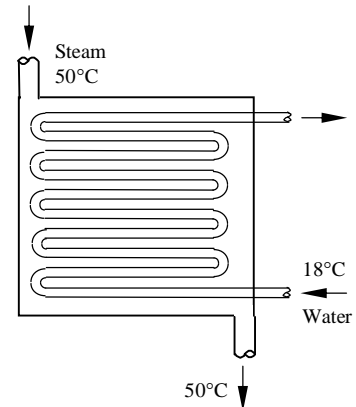
7-110 Steam is condensed by cooling water in the condenser of a power plant. The rate of condensation of steam and the rate of entropy generation are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. 3 Changes in the kinetic and potential energies of fluid streams are negligible. 4 Fluid properties are constant.

Properties The enthalpy and entropy of vaporization of water at 50°C are $h_g = 2382.7$ kJ/kg and $s_g = 7.3725$ kJ/kg.K (Table A-4). The specific heat of water at room temperature is $C_p = 4.18$ kJ/kg.°C (Table A-3).

Analysis (a) We take the cold water tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

$$\begin{aligned} \dot{Q}_{in} - \dot{Q}_{out} &= \dot{\Delta E}_{system} \quad \dot{\Delta E}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{Q}_{in} &= \dot{Q}_{out} \\ \dot{Q}_{in} + \dot{m}h_1 &= \dot{m}h_2 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0) \\ \dot{Q}_{in} &= \dot{m}C_p(T_2 - T_1) \end{aligned}$$



Then the heat transfer rate to the cooling water in the condenser becomes

$$\begin{aligned} \dot{Q} &= [\dot{m}C_p(T_{out} - T_{in})]_{\text{cooling water}} \\ &= (101 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(27^\circ\text{C} - 18^\circ\text{C}) = 3800 \text{ kJ/s} \end{aligned}$$

The rate of condensation of steam is determined to be

$$\dot{Q} = (\dot{m}h_{fg})_{\text{steam}} \longrightarrow \dot{m}_{\text{steam}} = \frac{\dot{Q}}{h_{fg}} = \frac{3800 \text{ kJ/s}}{2382.7 \text{ kJ/kg}} = 1.595 \text{ kg/s}$$

(b) The rate of entropy generation within the condenser during this process can be determined by applying the rate form of the entropy balance on the entire condenser. Noting that the condenser is well-insulated and thus heat transfer is negligible, the entropy balance for this steady-flow system can be expressed as

$$\begin{aligned} \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} &= \dot{\Delta S}_{system} \quad \dot{\Delta S}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net entropy transfer} & \quad \text{Rate of entropy} & \quad \text{Rate of change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{of entropy} \\ \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} &= 0 \quad (\text{since } \dot{Q} = 0) \\ \dot{m}_{\text{water}} s_1 + \dot{m}_{\text{steam}} s_3 - \dot{m}_{\text{water}} s_2 - \dot{m}_{\text{steam}} s_4 + \dot{S}_{gen} &= 0 \\ \dot{S}_{gen} &= \dot{m}_{\text{water}} (s_2 - s_1) + \dot{m}_{\text{steam}} (s_4 - s_3) \end{aligned}$$

Noting that water is an incompressible substance and steam changes from saturated vapor to saturated liquid, the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_{\text{water}} C_p \ln \frac{T_2}{T_1} + \dot{m}_{\text{steam}} (s_f - s_g) = \dot{m}_{\text{water}} C_p \ln \frac{T_2}{T_1} - \dot{m}_{\text{steam}} s_{fg} \\ &= (101 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{27 + 273}{18 + 273} - (1.595 \text{ kg/s})(7.3725 \text{ kJ/kg} \cdot \text{K}) = 1.100 \text{ kW/K} \end{aligned}$$

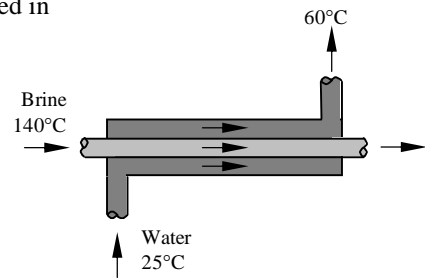
7-111 Water is heated in a heat exchanger by geothermal water. The rate of heat transfer to the water and the rate of entropy generation within the heat exchanger are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. **3** Changes in the kinetic and potential energies of fluid streams are negligible. **4** Fluid properties are constant.

Properties The specific heats of water and geothermal fluid are given to be 4.18 and 4.31 kJ/kg·°C, respectively.

Analysis (a) We take the cold water tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

$$\begin{aligned} \dot{E}_{in} &= \dot{E}_{out} \quad \dot{E}_{in} - \dot{E}_{out} = \dot{E}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{m}_1 h_1 &= \dot{m}_2 h_2 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0) \\ \dot{E}_{in} &= \dot{m} C_p (T_2 - T_1) \end{aligned}$$



Then the rate of heat transfer to the cold water in the heat exchanger becomes

$$\dot{Q}_{in, water} = [\dot{m} C_p (T_{out} - T_{in})]_{water} = (0.50 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(60^\circ\text{C} - 25^\circ\text{C}) = \mathbf{73.15 \text{ kW}}$$

Noting that heat transfer to the cold water is equal to the heat loss from the geothermal water, the outlet temperature of the geothermal water is determined from

$$\begin{aligned} \dot{Q}_{out} &= [\dot{m} C_p (T_{in} - T_{out})]_{geot. water} \longrightarrow T_{out} = T_{in} - \frac{\dot{Q}_{out}}{\dot{m} C_p} \\ &= 140^\circ\text{C} - \frac{73.15 \text{ kW}}{(0.75 \text{ kg/s})(4.31 \text{ kJ/kg} \cdot ^\circ\text{C})} = \mathbf{117.4^\circ\text{C}} \end{aligned}$$

(b) The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:

$$\begin{aligned} \dot{S}_{in} + \dot{S}_{gen} &= \dot{S}_{out} \quad \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = 0 \quad (\text{steady}) \\ \text{Rate of net entropy transfer} & \quad \text{Rate of entropy} & \quad \text{Rate of change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{of entropy} \\ \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} &= 0 \quad (\text{since } \dot{Q} = 0) \\ \dot{m}_{water} s_1 + \dot{m}_{geo} s_3 - \dot{m}_{water} s_2 - \dot{m}_{geo} s_4 + \dot{S}_{gen} &= 0 \\ \dot{S}_{gen} &= \dot{m}_{water} (s_2 - s_1) + \dot{m}_{geo} (s_4 - s_3) \end{aligned}$$

Noting that both fresh and geothermal water are incompressible substances, the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_{water} C_p \ln \frac{T_2}{T_1} + \dot{m}_{geo} C_p \ln \frac{T_4}{T_3} \\ &= (0.50 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{60 + 273}{25 + 273} + (0.75 \text{ kg/s})(4.31 \text{ kJ/kg} \cdot \text{K}) \ln \frac{117.4 + 273}{140 + 273} = \mathbf{0.050 \text{ kW/K}} \end{aligned}$$

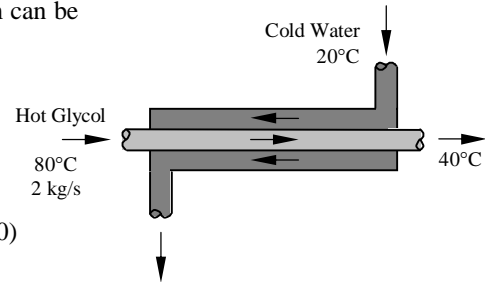
7-112 Ethylene glycol is cooled by water in a heat exchanger. The rate of heat transfer and the rate of entropy generation within the heat exchanger are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. 3 Changes in the kinetic and potential energies of fluid streams are negligible. 4 Fluid properties are constant.

Properties The specific heats of water and ethylene glycol are given to be 4.18 and 2.56 kJ/kg·°C, respectively.

Analysis (a) We take the ethylene glycol tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

$$\begin{aligned} \dot{Q}_{in} - \dot{Q}_{out} &= \dot{E}_{system} \quad \dot{E}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} &\quad \text{potential, etc. energies} \\ \dot{Q}_{in} &= \dot{Q}_{out} \\ \dot{m}h_1 &= \dot{Q}_{out} + \dot{m}h_2 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0) \\ \dot{Q}_{out} &= \dot{m}C_p(T_1 - T_2) \end{aligned}$$



Then the rate of heat transfer becomes

$$\dot{Q}_{out} = [\dot{m}C_p(T_{in} - T_{out})]_{\text{glycol}} = (2 \text{ kg/s})(2.56 \text{ kJ/kg} \cdot ^\circ\text{C})(80^\circ\text{C} - 40^\circ\text{C}) = \mathbf{204.8 \text{ kW}}$$

The rate of heat transfer from water must be equal to the rate of heat transfer to the glycol. Then,

$$\begin{aligned} \dot{Q}_{in} &= [\dot{m}C_p(T_{out} - T_{in})]_{\text{water}} \longrightarrow \dot{m}_{\text{water}} = \frac{\dot{Q}_{in}}{C_p(T_{out} - T_{in})} \\ &= \frac{204.8 \text{ kJ/s}}{(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(55^\circ\text{C} - 20^\circ\text{C})} = \mathbf{1.4 \text{ kg/s}} \end{aligned}$$

(b) The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:

$$\begin{aligned} \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} &= \dot{S}_{system} \quad \dot{S}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net entropy transfer} &= \text{Rate of entropy} \\ \text{by heat and mass} &\quad \text{generation} \\ \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} &= 0 \quad (\text{since } \dot{Q} = 0) \\ \dot{m}_{\text{glycol}} s_1 + \dot{m}_{\text{water}} s_3 - \dot{m}_{\text{glycol}} s_2 - \dot{m}_{\text{water}} s_4 + \dot{S}_{gen} &= 0 \\ \dot{S}_{gen} &= \dot{m}_{\text{glycol}} (s_2 - s_1) + \dot{m}_{\text{water}} (s_4 - s_3) \end{aligned}$$

Noting that both fluid streams are liquids (incompressible substances), the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_{\text{glycol}} C_p \ln \frac{T_2}{T_1} + \dot{m}_{\text{water}} C_p \ln \frac{T_4}{T_3} \\ &= (2 \text{ kg/s})(2.56 \text{ kJ/kg} \cdot \text{K}) \ln \frac{40 + 273}{80 + 273} + (1.4 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{55 + 273}{20 + 273} = \mathbf{0.0446 \text{ kW/K}} \end{aligned}$$

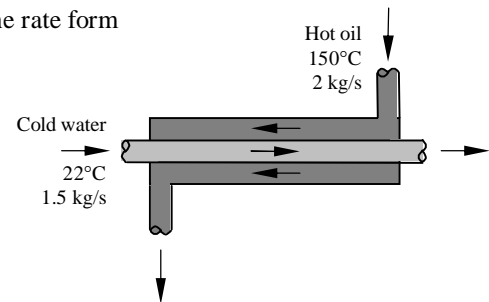
7-113 Oil is to be cooled by water in a thin-walled heat exchanger. The rate of heat transfer and the rate of entropy generation within the heat exchanger are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. 3 Changes in the kinetic and potential energies of fluid streams are negligible. 4 Fluid properties are constant.

Properties The specific heats of water and oil are given to be 4.18 and 2.20 kJ/kg·°C, respectively.

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

$$\begin{aligned} \dot{E}_{in} &= \dot{E}_{out} \\ \dot{E}_{in} &= \dot{E}_{out} \quad (\text{since } \Delta ke \cong \Delta pe \cong 0) \\ \dot{Q}_{out} &= \dot{m} C_p (T_1 - T_2) \end{aligned}$$



Then the rate of heat transfer from the oil becomes

$$\dot{Q}_{out} = [\dot{m} C_p (T_{in} - T_{out})]_{oil} = (2 \text{ kg/s})(2.2 \text{ kJ/kg} \cdot ^\circ\text{C})(150^\circ\text{C} - 40^\circ\text{C}) = \mathbf{484 \text{ kW}}$$

Noting that the heat lost by the oil is gained by the water, the outlet temperature of the water is determined from

$$\begin{aligned} \dot{Q} &= [\dot{m} C_p (T_{out} - T_{in})]_{water} \longrightarrow T_{out} = T_{in} + \frac{\dot{Q}}{\dot{m} C_p} \\ &= 22^\circ\text{C} + \frac{484 \text{ kW}}{(1.5 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})} = 99.2^\circ\text{C} \end{aligned}$$

(b) The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:

$$\begin{aligned} \dot{S}_{in} + \dot{S}_{gen} &= \dot{S}_{out} \\ \dot{S}_{in} + \dot{S}_{gen} &= \dot{S}_{out} \quad (\text{since } \dot{Q} = 0) \\ \dot{m}_{oil} s_1 + \dot{m}_{water} s_3 - \dot{m}_{oil} s_2 - \dot{m}_{water} s_4 + \dot{S}_{gen} &= 0 \\ \dot{S}_{gen} &= \dot{m}_{oil} (s_2 - s_1) + \dot{m}_{water} (s_4 - s_3) \end{aligned}$$

Noting that both fluid streams are liquids (incompressible substances), the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_{oil} C_p \ln \frac{T_2}{T_1} + \dot{m}_{water} C_p \ln \frac{T_4}{T_3} \\ &= (2 \text{ kg/s})(2.2 \text{ kJ/kg} \cdot \text{K}) \ln \frac{40 + 273}{150 + 273} + (1.5 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{99.2 + 273}{22 + 273} = \mathbf{0.132 \text{ kW/K}} \end{aligned}$$

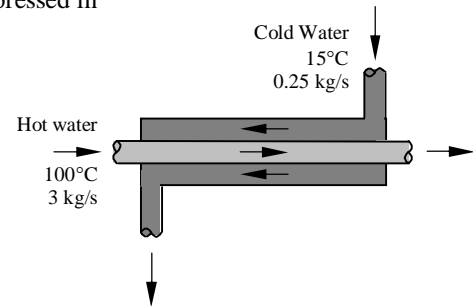
7-114 Cold water is heated by hot water in a heat exchanger. The rate of heat transfer and the rate of entropy generation within the heat exchanger are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. 3 Changes in the kinetic and potential energies of fluid streams are negligible. 4 Fluid properties are constant.

Properties The specific heats of cold and hot water are given to be 4.18 and 4.19 kJ/kg·°C, respectively.

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

$$\begin{aligned} \dot{E}_{in} &= \dot{E}_{out} \quad \dot{E}_{in} - \dot{E}_{out} = \dot{E}_{system} \quad \dot{E}_{in} - \dot{E}_{out} = \dot{E}_{system} \quad \dot{E}_{in} - \dot{E}_{out} = \dot{E}_{system} \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} &\quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{Q}_{in} + \dot{W}_{in} &= \dot{Q}_{out} \quad (\text{since } \Delta ke \cong \Delta pe \cong 0) \\ \dot{Q}_{in} &= \dot{m} C_p (T_2 - T_1) \end{aligned}$$



Then the rate of heat transfer to the cold water in this heat exchanger becomes

$$\dot{Q}_{in} = [\dot{m} C_p (T_{out} - T_{in})]_{\text{cold water}} = (0.25 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(45^\circ\text{C} - 15^\circ\text{C}) = \mathbf{31.35 \text{ kW}}$$

Noting that heat gain by the cold water is equal to the heat loss by the hot water, the outlet temperature of the hot water is determined to be

$$\begin{aligned} \dot{Q} &= [\dot{m} C_p (T_{in} - T_{out})]_{\text{hot water}} \longrightarrow T_{out} = T_{in} - \frac{\dot{Q}}{\dot{m} C_p} \\ &= 100^\circ\text{C} - \frac{31.35 \text{ kW}}{(3 \text{ kg/s})(4.19 \text{ kJ/kg} \cdot ^\circ\text{C})} = \mathbf{97.5^\circ\text{C}} \end{aligned}$$

(b) The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:

$$\begin{aligned} \dot{S}_{in} + \dot{S}_{gen} &= \dot{S}_{out} \quad \dot{S}_{in} - \dot{S}_{out} = -\dot{S}_{gen} \\ \text{Rate of net entropy transfer} &= \text{Rate of entropy} \\ \text{by heat and mass} &\quad \text{generation} \\ \dot{S}_{in} + \dot{S}_{gen} &= \dot{S}_{out} \quad (\text{since } \dot{Q} = 0) \\ \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} &= 0 \\ \dot{m}_{\text{cold}} s_1 + \dot{m}_{\text{hot}} s_3 - \dot{m}_{\text{cold}} s_2 - \dot{m}_{\text{hot}} s_4 + \dot{S}_{gen} &= 0 \\ \dot{S}_{gen} &= \dot{m}_{\text{cold}} (s_2 - s_1) + \dot{m}_{\text{hot}} (s_4 - s_3) \end{aligned}$$

Noting that both fluid streams are liquids (incompressible substances), the rate of entropy generation is determined to be

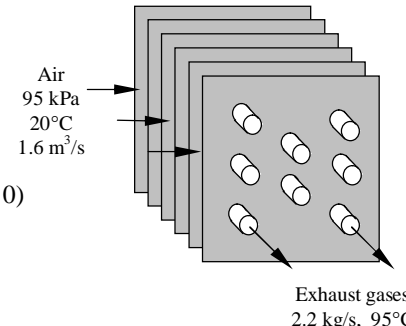
$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_{\text{cold}} C_p \ln \frac{T_2}{T_1} + \dot{m}_{\text{hot}} C_p \ln \frac{T_4}{T_3} \\ &= (0.25 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{45 + 273}{15 + 273} + (3 \text{ kg/s})(4.19 \text{ kJ/kg} \cdot \text{K}) \ln \frac{97.5 + 273}{100 + 273} = \mathbf{0.0190 \text{ kW/K}} \end{aligned}$$

7-115 Air is preheated by hot exhaust gases in a cross-flow heat exchanger. The rate of heat transfer, the outlet temperature of the air, and the rate of entropy generation are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. 3 Changes in the kinetic and potential energies of fluid streams are negligible. 4 Fluid properties are constant.

Properties The specific heats of air and combustion gases are given to be 1.005 and 1.10 kJ/kg·°C, respectively. The gas constant of air is $R = 0.287$ kJ/kg·K (Table A-1).

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

$$\begin{aligned} \dot{E}_{in} &= \dot{E}_{out} \\ \dot{E}_{in} &= \dot{E}_{out} \quad (\text{since } \Delta ke \cong \Delta pe \cong 0) \\ \dot{E}_{out} &= \dot{m} C_p (T_1 - T_2) \end{aligned}$$


Air
95 kPa
20°C
1.6 m³/s

Exhaust gases
2.2 kg/s, 95°C

Then the rate of heat transfer from the exhaust gases becomes

$$\dot{Q} = [\dot{m} C_p (T_{in} - T_{out})]_{\text{gas}} = (2.2 \text{ kg/s})(1.1 \text{ kJ/kg} \cdot ^\circ\text{C})(180^\circ\text{C} - 95^\circ\text{C}) = \mathbf{205.7 \text{ kW}}$$

The mass flow rate of air is

$$\dot{m} = \frac{P\dot{V}}{RT} = \frac{(95 \text{ kPa})(1.6 \text{ m}^3/\text{s})}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}) \times (293 \text{ K})} = 1.808 \text{ kg/s}$$

Noting that heat loss by the exhaust gases is equal to the heat gain by the air, the outlet temperature of the air becomes

$$\dot{Q} = \dot{m} C_p (T_{c,out} - T_{c,in}) \rightarrow T_{c,out} = T_{c,in} + \frac{\dot{Q}}{\dot{m} C_p} = 20^\circ\text{C} + \frac{205.7 \text{ kW}}{(1.808 \text{ kg/s})(1.005 \text{ kJ/kg} \cdot ^\circ\text{C})} = \mathbf{133.2^\circ\text{C}}$$

The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:

$$\begin{aligned} \dot{S}_{in} + \dot{S}_{gen} &= \dot{S}_{out} \\ \dot{S}_{in} + \dot{S}_{gen} &= \dot{S}_{out} \quad (\text{since } \dot{Q} = 0) \\ \dot{S}_{\text{exhaust}} + \dot{S}_{\text{air}} - \dot{S}_{\text{exhaust}} - \dot{S}_{\text{air}} + \dot{S}_{gen} &= 0 \\ \dot{S}_{gen} &= \dot{S}_{\text{exhaust}} (s_2 - s_1) + \dot{S}_{\text{air}} (s_4 - s_3) \end{aligned}$$

Then the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_{\text{exhaust}} C_p \ln \frac{T_2}{T_1} + \dot{m}_{\text{air}} C_p \ln \frac{T_4}{T_3} \\ &= (2.2 \text{ kg/s})(1.1 \text{ kJ/kg} \cdot \text{K}) \ln \frac{95 + 273}{180 + 273} + (1.808 \text{ kg/s})(1.005 \text{ kJ/kg} \cdot \text{K}) \ln \frac{133.2 + 273}{20 + 273} = \mathbf{0.091 \text{ kW/K}} \end{aligned}$$

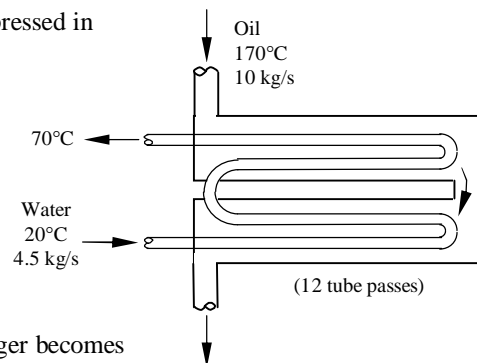
7-116 Water is heated by hot oil in a heat exchanger. The outlet temperature of the oil and the rate of entropy generation within the heat exchanger are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. **3** Changes in the kinetic and potential energies of fluid streams are negligible. **4** Fluid properties are constant.

Properties The specific heats of water and oil are given to be 4.18 and 2.3 kJ/kg·°C, respectively.

Analysis (a) We take the cold water tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

$$\begin{aligned} \dot{E}_{in} &= \dot{E}_{out} \quad \dot{E}_{system} = 0 \text{ (steady)} \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} &\quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{Q}_{in} + \dot{W}_1 &= \dot{W}_2 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0) \\ \dot{Q}_{in} &= \dot{m} C_p (T_2 - T_1) \end{aligned}$$



Then the rate of heat transfer to the cold water in this heat exchanger becomes

$$\dot{Q} = [\dot{m} C_p (T_{out} - T_{in})]_{\text{water}} = (4.5 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(70^\circ\text{C} - 20^\circ\text{C}) = 940.5 \text{ kW}$$

Noting that heat gain by the water is equal to the heat loss by the oil, the outlet temperature of the hot oil is determined from

$$\dot{Q} = [\dot{m} C_p (T_{in} - T_{out})]_{\text{oil}} \rightarrow T_{out} = T_{in} - \frac{\dot{Q}}{\dot{m} C_p} = 170^\circ\text{C} - \frac{940.5 \text{ kW}}{(10 \text{ kg/s})(2.3 \text{ kJ/kg} \cdot ^\circ\text{C})} = 129.1^\circ\text{C}$$

(b) The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:

$$\begin{aligned} \dot{S}_{in} + \dot{S}_{gen} &= \dot{S}_{out} \quad \dot{S}_{system} = 0 \text{ (steady)} \\ \text{Rate of net entropy transfer} &= \text{Rate of entropy} \\ \text{by heat and mass} &\quad \text{generation} \\ \dot{S}_{in} &= \dot{S}_{out} \\ \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} &= 0 \quad (\text{since } \dot{Q} = 0) \\ \dot{m}_{\text{water}} s_1 + \dot{m}_{\text{oil}} s_3 - \dot{m}_{\text{water}} s_2 - \dot{m}_{\text{oil}} s_4 + \dot{S}_{gen} &= 0 \\ \dot{S}_{gen} &= \dot{m}_{\text{water}} (s_2 - s_1) + \dot{m}_{\text{oil}} (s_4 - s_3) \end{aligned}$$

Noting that both fluid streams are liquids (incompressible substances), the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_{\text{water}} C_p \ln \frac{T_2}{T_1} + \dot{m}_{\text{oil}} C_p \ln \frac{T_4}{T_3} \\ &= (4.5 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{70 + 273}{20 + 273} + (10 \text{ kg/s})(2.3 \text{ kJ/kg} \cdot \text{K}) \ln \frac{129.1 + 273}{170 + 273} = 0.736 \text{ kW/K} \end{aligned}$$

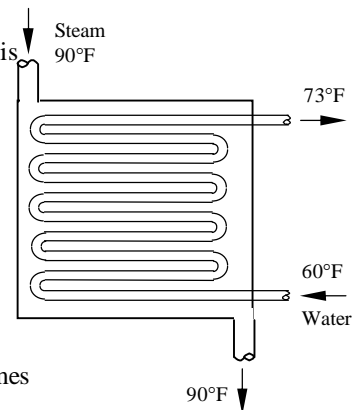
7-117E Steam is condensed by cooling water in a condenser. The rate of heat transfer and the rate of entropy generation within the heat exchanger are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. 3 Changes in the kinetic and potential energies of fluid streams are negligible. 4 Fluid properties are constant.

Properties The specific heat of water is 1.0 Btu/lbm.°F (Table A-3E). The enthalpy and entropy of vaporization of water at 90°F are 1040.2 Btu/lbm and $s_{fg} = 1.8966$ Btu/lbm.R (Table A-4E).

Analysis We take the tube-side of the heat exchanger where cold water is flowing as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \dot{E}_{system} \quad \dot{E}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} &\quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{Q}_{in} + \dot{m}_1 h_1 &= \dot{m}_2 h_2 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0) \\ \dot{Q}_{in} &= \dot{m} C_p (T_2 - T_1) \end{aligned}$$



Then the rate of heat transfer to the cold water in this heat exchanger becomes

$$\dot{Q} = [\dot{m} C_p (T_{out} - T_{in})]_{\text{water}} = (115.3 \text{ lbm/s})(1.0 \text{ Btu/lbm.°F})(73^\circ\text{F} - 60^\circ\text{F}) = \mathbf{1499 \text{ Btu/s}}$$

Noting that heat gain by the water is equal to the heat loss by the condensing steam, the rate of condensation of the steam in the heat exchanger is determined from

$$\dot{Q} = (\dot{m} h_{fg})_{\text{steam}} \longrightarrow \dot{m}_{\text{steam}} = \frac{\dot{Q}}{h_{fg}} = \frac{1499 \text{ Btu/s}}{1040.2 \text{ Btu/lbm}} = \mathbf{1.44 \text{ lbm/s}}$$

(b) The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:

$$\begin{aligned} \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} &= \dot{S}_{system} \quad \dot{S}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net entropy transfer} &= \text{Rate of entropy} \\ \text{by heat and mass} &\quad \text{generation} \\ \text{Rate of change} &\quad \text{of entropy} \\ \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} &= 0 \quad (\text{since } \dot{Q} = 0) \\ \dot{m}_{\text{water}} s_1 + \dot{m}_{\text{steam}} s_3 - \dot{m}_{\text{water}} s_2 - \dot{m}_{\text{steam}} s_4 + \dot{S}_{gen} &= 0 \\ \dot{S}_{gen} &= \dot{m}_{\text{water}} (s_2 - s_1) + \dot{m}_{\text{steam}} (s_4 - s_3) \end{aligned}$$

Noting that water is an incompressible substance and steam changes from saturated vapor to saturated liquid, the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_{\text{water}} C_p \ln \frac{T_2}{T_1} + \dot{m}_{\text{steam}} (s_f - s_g) = \dot{m}_{\text{water}} C_p \ln \frac{T_2}{T_1} - \dot{m}_{\text{steam}} s_{fg} \\ &= (115.3 \text{ lbm/s})(1.0 \text{ Btu/lbm.R}) \ln \frac{73 + 460}{60 + 460} - (1.44 \text{ lbm/s})(1.8966 \text{ Btu/lbm.R}) = \mathbf{0.116 \text{ Btu/s.R}} \end{aligned}$$

7-118 Chickens are to be cooled by chilled water in an immersion chiller that is also gaining heat from the surroundings. The rate of heat removal from the chicken and the rate of entropy generation during this process are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Thermal properties of chickens and water are constant. 3 The temperature of the surrounding medium is given to be 25°C.

Properties The specific heat of chicken is given to be 3.54 kJ/kg·°C. The specific heat of water at room temperature is 4.18 kJ/kg·°C (Table A-3).

Analysis (a) Chickens can be considered to flow steadily through the chiller at a mass flow rate of

$$\dot{m}_{\text{chicken}} = (250 \text{ chicken/h})(2.2 \text{ kg/chicken}) = 550 \text{ kg/h} = 0.1528 \text{ kg/s}$$

Taking the chicken flow stream in the chiller as the system, the energy balance for steadily flowing chickens can be expressed in the rate form as

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta \dot{E}_{\text{system}} \quad \dot{E}_{\text{in}} = \dot{E}_{\text{out}} \quad \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

Rate of net energy transfer by heat, work, and mass Rate of change in internal, kinetic, potential, etc. energies

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

$$\dot{Q}_{\text{out}} = \dot{Q}_{\text{chicken}} = \dot{m}_{\text{chicken}} C_p (T_1 - T_2)$$

Then the rate of heat removal from the chickens as they are cooled from 15°C to 3°C becomes

$$\dot{Q}_{\text{chicken}} = (\dot{m}_{\text{chicken}} C_p \Delta T)_{\text{chicken}} = (0.1528 \text{ kg/s})(3.54 \text{ kJ/kg} \cdot ^\circ\text{C})(15 - 3)^\circ\text{C} = \mathbf{6.49 \text{ kW}}$$

The chiller gains heat from the surroundings as a rate of 150 kJ/h = 0.0417 kJ/s.

Then the total rate of heat gain by the water is

$$\dot{Q}_{\text{water}} = \dot{Q}_{\text{chicken}} + \dot{Q}_{\text{heat gain}} = 6.49 + 0.0417 = 6.532 \text{ kW}$$

Noting that the temperature rise of water is not to exceed 2°C as it flows through the chiller, the mass flow rate of water must be at least

$$\dot{m}_{\text{water}} = \frac{\dot{Q}_{\text{water}}}{(C_p \Delta T)_{\text{water}}} = \frac{6.532 \text{ kW}}{(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(2^\circ\text{C})} = \mathbf{0.781 \text{ kg/s}}$$

(b) The rate of entropy generation is determined by applying the entropy balance on an *extended system* that includes the chiller and the immediate surroundings so that boundary temperature is the surroundings temperature:

$$\dot{S}_{\text{in}} - \dot{S}_{\text{out}} + \dot{S}_{\text{gen}} = \Delta \dot{S}_{\text{system}} \quad \dot{S}_{\text{in}} = \dot{S}_{\text{out}} \quad \dot{S}_{\text{in}} = \dot{S}_{\text{out}}$$

Rate of net entropy transfer by heat and mass Rate of entropy generation Rate of change of entropy

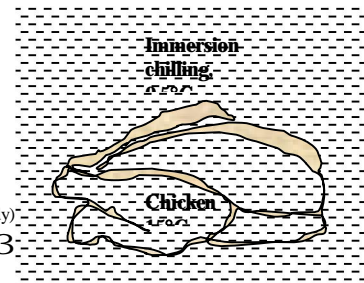
$$\dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \frac{\dot{Q}_{\text{in}}}{T_{\text{surr}}} + \dot{S}_{\text{gen}} = 0$$

$$\dot{m}_{\text{chicken}} s_1 + \dot{m}_{\text{water}} s_3 - \dot{m}_{\text{chicken}} s_2 - \dot{m}_{\text{water}} s_4 + \frac{\dot{Q}_{\text{in}}}{T_{\text{surr}}} + \dot{S}_{\text{gen}} = 0$$

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{chicken}} (s_2 - s_1) + \dot{m}_{\text{water}} (s_4 - s_3) - \frac{\dot{Q}_{\text{in}}}{T_{\text{surr}}}$$

Noting that both streams are incompressible substances, the rate of entropy generation is determined to be

$$\begin{aligned} \dot{S}_{\text{gen}} &= \dot{m}_{\text{chicken}} C_p \ln \frac{T_2}{T_1} + \dot{m}_{\text{water}} C_p \ln \frac{T_4}{T_3} - \frac{\dot{Q}_{\text{in}}}{T_{\text{surr}}} \\ &= (0.1528 \text{ kg/s})(3.54 \text{ kJ/kg} \cdot \text{K}) \ln \frac{276}{288} + (0.781 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{275.5}{273.5} - \frac{0.0417 \text{ kW}}{298 \text{ K}} = \mathbf{0.000625 \text{ kW/K}} \end{aligned}$$



7-119 A regenerator is considered to save heat during the cooling of milk in a dairy plant. The amounts of fuel and money such a generator will save per year and the annual reduction in the rate of entropy generation are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The properties of the milk are constant.

Properties The average density and specific heat of milk can be taken to be $\rho_{\text{milk}} \cong \rho_{\text{water}} = 1 \text{ kg/L}$ and $C_{p, \text{milk}} = 3.79 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3).

Analysis The mass flow rate of the milk is

$$\dot{m}_{\text{milk}} = \rho_{\text{milk}} \dot{V}_{\text{milk}} = (1 \text{ kg/L})(12 \text{ L/s}) = 12 \text{ kg/s} = 43,200 \text{ kg/h}$$

Taking the pasteurizing section as the system, the energy balance for this steady-flow system can be expressed in the rate form as

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \dot{E}_{\text{system}} \quad \dot{E}_{\text{system}} = 0 \quad \rightarrow \quad \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

Rate of net energy transfer by heat, work, and mass Rate of change in internal, kinetic, potential, etc. energies

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

$$\dot{Q}_{\text{in}} = \dot{m}_{\text{milk}} C_p (T_2 - T_1)$$

Therefore, to heat the milk from 4 to 72°C as being done currently, heat must be transferred to the milk at a rate of

$$\dot{Q}_{\text{current}} = [\dot{m}_{\text{milk}} C_p (T_{\text{pasteurization}} - T_{\text{refrigeration}})]_{\text{milk}} = (12 \text{ kg/s})(3.79 \text{ kJ/kg} \cdot ^\circ\text{C})(72 - 4)^\circ\text{C} = 3093 \text{ kJ/s}$$

The proposed regenerator has an effectiveness of $\epsilon = 0.82$, and thus it will save 82 percent of this energy. Therefore,

$$\dot{Q}_{\text{saved}} = \epsilon \dot{Q}_{\text{current}} = (0.82)(3093 \text{ kJ/s}) = 2536 \text{ kJ/s}$$

Noting that the boiler has an efficiency of $\eta_{\text{boiler}} = 0.82$, the energy savings above correspond to fuel savings of

$$\text{Fuel Saved} = \frac{\dot{Q}_{\text{saved}}}{\eta_{\text{boiler}}} = \frac{(2536 \text{ kJ/s}) (1 \text{ therm})}{(0.82) (105,500 \text{ kJ})} = 0.02931 \text{ therm/s}$$

Noting that 1 year = 365×24=8760 h and unit cost of natural gas is \$0.52/therm, the annual fuel and money savings will be

$$\text{Fuel Saved} = (0.02931 \text{ therms/s})(8760 \times 3600 \text{ s}) = \mathbf{924,450 \text{ therms/yr}}$$

$$\text{Money saved} = (\text{Fuel saved})(\text{Unit cost of fuel}) = (924,450 \text{ therm/yr})(\$0.52/\text{therm}) = \mathbf{\$480,700/\text{yr}}$$

The rate of entropy generation during this process is determined by applying the rate form of the entropy balance on an *extended system* that includes the regenerator and the immediate surroundings so that the boundary temperature is the surroundings temperature, which we take to be the cold water temperature of 18°C.:

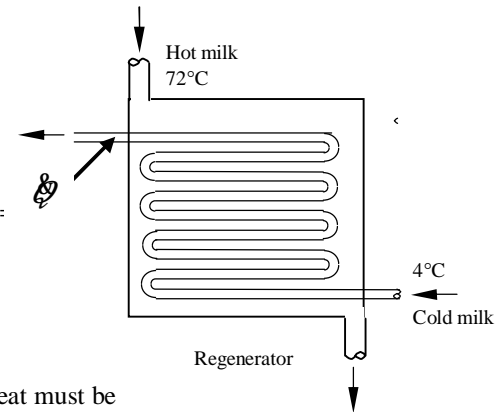
$$\dot{S}_{\text{in}} - \dot{S}_{\text{out}} + \dot{S}_{\text{gen}} = \dot{S}_{\text{system}} \quad \dot{S}_{\text{system}} = 0 \quad \rightarrow \quad \dot{S}_{\text{gen}} = \dot{S}_{\text{out}} - \dot{S}_{\text{in}}$$

Rate of net entropy transfer by heat and mass Rate of entropy generation Rate of change of entropy

Disregarding entropy transfer associated with fuel flow, the only significant difference between the two cases is the reduction in the entropy transfer to water due to the reduction in heat transfer to water, and is determined to be

$$\dot{S}_{\text{gen, reduction}} = \dot{S}_{\text{out, reduction}} = \frac{\dot{Q}_{\text{out, reduction}}}{T_{\text{surr}}} = \frac{\dot{Q}_{\text{saved}}}{T_{\text{surr}}} = \frac{2536 \text{ kJ/s}}{18 + 273} = 8.715 \text{ kW/K}$$

$$\dot{S}_{\text{gen, reduction}} = \dot{S}_{\text{gen, reduction}} \Delta t = (8.715 \text{ kJ/s} \cdot \text{K})(8760 \times 3600 \text{ s/year}) = \mathbf{2.75 \times 10^8 \text{ kJ/K (per year)}}$$



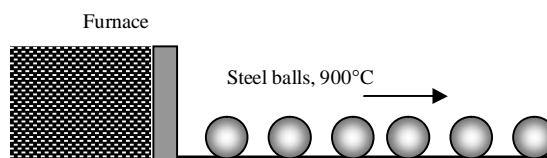
7-120 Stainless steel ball bearings leaving the oven at a uniform temperature of 900°C at a rate of 1400 /min are exposed to air and are cooled to 850°C before they are dropped into the water for quenching. The rate of heat transfer from the ball to the air and the rate of entropy generation due to this heat transfer are to be determined.

Assumptions **1** The thermal properties of the bearing balls are constant. **2** The kinetic and potential energy changes of the balls are negligible. **3** The balls are at a uniform temperature at the end of the process

Properties The density and specific heat of the ball bearings are given to be $\rho = 8085 \text{ kg/m}^3$ and $C_p = 0.480 \text{ kJ/kg}\cdot^\circ\text{C}$.

Analysis (a) We take a single bearing ball as the system. The energy balance for this closed system can be expressed as

$$\begin{aligned} \cancel{E_{in}} - \cancel{E_{out}} &= \Delta E_{\text{system}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ -Q_{out} &= \Delta U_{ball} = m(u_2 - u_1) \\ Q_{out} &= mC(T_1 - T_2) \end{aligned}$$



The total amount of heat transfer from a ball is

$$\begin{aligned} m &= \rho V = \rho \frac{\pi D^3}{6} = (8085 \text{ kg/m}^3) \frac{\pi (0.012 \text{ m})^3}{6} = 0.007315 \text{ kg} \\ Q_{out} &= mC(T_1 - T_2) = (0.007315 \text{ kg})(0.480 \text{ kJ/kg}\cdot^\circ\text{C})(900 - 850)^\circ\text{C} = 0.1756 \text{ kJ/ball} \end{aligned}$$

Then the rate of heat transfer from the balls to the air becomes

$$\dot{Q}_{total} = \dot{n}_{ball} Q_{out} \text{ (per ball)} = (1400 \text{ balls/min}) \times (0.1756 \text{ kJ/ball}) = \mathbf{245.8 \text{ kJ/min} = 4.10 \text{ kW}}$$

Therefore, heat is lost to the air at a rate of 4.10 kW.

(b) We again take a single bearing ball as the system. The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the ball and its immediate surroundings so that the boundary temperature of the extended system is at 30°C at all times:

$$\begin{aligned} \cancel{S_{in}} - \cancel{S_{out}} + S_{gen} &= \Delta S_{\text{system}} \\ \text{Net entropy transfer} & \quad \text{Entropy} & \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{in entropy} \\ -\frac{Q_{out}}{T_b} + S_{gen} &= \Delta S_{\text{system}} \rightarrow S_{gen} = \frac{Q_{out}}{T_b} + \Delta S_{\text{system}} \end{aligned}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mC_{av} \ln \frac{T_2}{T_1} = (0.007315 \text{ kg})(0.480 \text{ kJ/kg}\cdot\text{K}) \ln \frac{850 + 273}{900 + 273} = -0.0001530 \text{ kJ/K}$$

Substituting,

$$S_{gen} = \frac{Q_{out}}{T_b} + \Delta S_{\text{system}} = \frac{0.1756 \text{ kJ}}{303 \text{ K}} - 0.0001530 \text{ kJ/K} = 0.0004265 \text{ kJ/K (per ball)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{gen} = S_{gen} \dot{n}_{ball} = (0.0004265 \text{ kJ/K}\cdot\text{ball})(1400 \text{ balls/min}) = 0.597 \text{ kJ/min}\cdot\text{K} = \mathbf{0.00995 \text{ kW/K}}$$

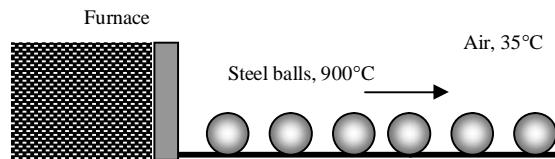
7-121 Carbon steel balls are to be annealed at a rate of 2500/h by heating them first and then allowing them to cool slowly in ambient air at a specified rate. The total rate of heat transfer from the balls to the ambient air and the rate of entropy generation due to this heat transfer are to be determined.

Assumptions **1** The thermal properties of the balls are constant. **2** There are no changes in kinetic and potential energies. **3** The balls are at a uniform temperature at the end of the process

Properties The density and specific heat of the balls are given to be $\rho = 7833 \text{ kg/m}^3$ and $C_p = 0.465 \text{ kJ/kg}\cdot^\circ\text{C}$.

Analysis (a) We take a single ball as the system. The energy balance for this closed system can be expressed as

$$\begin{aligned} \cancel{E_{in}} - \cancel{E_{out}} &= \Delta E_{\text{system}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ -Q_{out} &= \Delta U_{ball} = m(u_2 - u_1) \\ Q_{out} &= mC(T_1 - T_2) \end{aligned}$$



The amount of heat transfer from a single ball is

$$\begin{aligned} m &= \rho V = \rho \frac{\pi D^3}{6} = (7833 \text{ kg/m}^3) \frac{\pi (0.008 \text{ m})^3}{6} = 0.00210 \text{ kg} \\ Q_{out} &= mC_p(T_1 - T_2) = (0.0021 \text{ kg})(0.465 \text{ kJ/kg}\cdot^\circ\text{C})(900 - 100)^\circ\text{C} = 781 \text{ J} = 0.781 \text{ kJ (per ball)} \end{aligned}$$

Then the total rate of heat transfer from the balls to the ambient air becomes

$$\dot{Q}_{out} = \dot{N}_{ball} Q_{out} = (2500 \text{ balls/h}) \times (0.781 \text{ kJ/ball}) = 1,953 \text{ kJ/h} = \mathbf{542 \text{ W}}$$

(b) We again take a single ball as the system. The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the ball and its immediate surroundings so that the boundary temperature of the extended system is at 35°C at all times:

$$\begin{aligned} \cancel{S_{in}} - \cancel{S_{out}} + \dot{S}_{gen} &= \Delta S_{\text{system}} \\ \text{Net entropy transfer} & \quad \text{Entropy} & \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{in entropy} \\ -\frac{Q_{out}}{T_b} + \dot{S}_{gen} &= \Delta S_{\text{system}} \rightarrow \dot{S}_{gen} = \frac{Q_{out}}{T_b} + \Delta S_{\text{system}} \end{aligned}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mC_{av} \ln \frac{T_2}{T_1} = (0.00210 \text{ kg})(0.465 \text{ kJ/kg}\cdot\text{K}) \ln \frac{100 + 273}{900 + 273} = -0.00112 \text{ kJ/K}$$

Substituting,

$$\dot{S}_{gen} = \frac{Q_{out}}{T_b} + \Delta S_{\text{system}} = \frac{0.781 \text{ kJ}}{308 \text{ K}} - 0.00112 \text{ kJ/K} = 0.00142 \text{ kJ/K (per ball)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{gen} = \dot{S}_{gen,ball} = (0.00142 \text{ kJ/K} \cdot \text{ball})(2500 \text{ balls/h}) = 3.55 \text{ kJ/h}\cdot\text{K} = \mathbf{0.986 \text{ W/K}}$$

7-122 An egg is dropped into boiling water. The amount of heat transfer to the egg by the time it is cooked and the amount of entropy generation associated with this heat transfer process are to be determined.

Assumptions **1** The egg is spherical in shape with a radius of $r_0 = 2.75$ cm. **2** The thermal properties of the egg are constant. **3** Energy absorption or release associated with any chemical and/or phase changes within the egg is negligible. **4** There are no changes in kinetic and potential energies.

Properties The density and specific heat of the egg are given to be $\rho = 1020$ kg/m³ and $C_p = 3.32$ kJ/kg·°C.

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

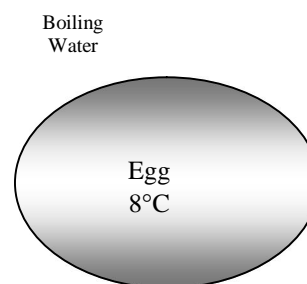
$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc. energies}}$$

$$Q_{in} = \Delta U_{\text{egg}} = m(u_2 - u_1) = mC_p(T_2 - T_1)$$

Then the mass of the egg and the amount of heat transfer become

$$m = \rho V = \rho \frac{\pi D^3}{6} = (1020 \text{ kg/m}^3) \frac{\pi (0.055 \text{ m})^3}{6} = 0.0889 \text{ kg}$$

$$Q_{in} = mC_p(T_2 - T_1) = (0.0889 \text{ kg})(3.32 \text{ kJ/kg} \cdot ^\circ\text{C})(70 - 8)^\circ\text{C} = \mathbf{18.3 \text{ kJ}}$$



We again take a single egg as the system. The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the egg and its immediate surroundings so that the boundary temperature of the extended system is at 97°C at all times:

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta S_{\text{system}}}_{\text{Change in entropy}}$$

$$\frac{Q_{in}}{T_b} + S_{gen} = \Delta S_{\text{system}} \rightarrow S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{\text{system}}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mC_{av} \ln \frac{T_2}{T_1} = (0.0889 \text{ kg})(3.32 \text{ kJ/kg} \cdot \text{K}) \ln \frac{70 + 273}{8 + 273} = 0.0588 \text{ kJ/K}$$

Substituting,

$$S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{\text{system}} = -\frac{18.3 \text{ kJ}}{370 \text{ K}} + 0.0588 \text{ kJ/K} = \mathbf{0.00961 \text{ kJ/K}} \quad (\text{per egg})$$

7-123E Large brass plates are heated in an oven at a specified rate. The rate of heat transfer to the plates in the oven and the rate of entropy generation associated with this heat transfer process are to be determined.

Assumptions **1** The thermal properties of the plates are constant. **2** The changes in kinetic and potential energies are negligible.

Properties The density and specific heat of the brass are given to be $\rho = 532.5 \text{ lbm/ft}^3$ and $C_p = 0.091 \text{ Btu/lbm} \cdot ^\circ\text{F}$.

Analysis We take the plate to be the system. The energy balance for this closed system can be expressed as

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

$$Q_{in} = \Delta U_{plate} = m(u_2 - u_1) = mC(T_2 - T_1)$$

The mass of each plate and the amount of heat transfer to each plate is

$$m = \rho V = \rho LA = (532.5 \text{ lbm/ft}^3)[(1.2/12 \text{ ft})(2 \text{ ft})(2 \text{ ft})] = 213 \text{ lbm}$$

$$Q_{in} = mC(T_2 - T_1) = (213 \text{ lbm/plate})(0.091 \text{ Btu/lbm} \cdot ^\circ\text{F})(1000 - 75)^\circ\text{F} = 17,930 \text{ Btu/plate}$$

Then the total rate of heat transfer to the plates becomes

$$\dot{Q}_{total} = \dot{Q}_{plate} Q_{in, \text{ per plate}} = (450 \text{ plates/min}) \times (17,930 \text{ Btu/plate}) = \mathbf{8,069,000 \text{ Btu/min} = 134,500 \text{ Btu/s}}$$

We again take a single plate as the system. The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the plate and its immediate surroundings so that the boundary temperature of the extended system is at 1300°F at all times:

$$\begin{array}{ccc} \cancel{S_{in}} + \cancel{S_{gen}} & = & \cancel{\Delta S_{system}} \\ \text{Net entropy transfer} & & \text{Entropy} \\ \text{by heat and mass} & & \text{generation} \end{array}$$

$$\frac{Q_{in}}{T_b} + S_{gen} = \Delta S_{system} \rightarrow S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system}$$

where

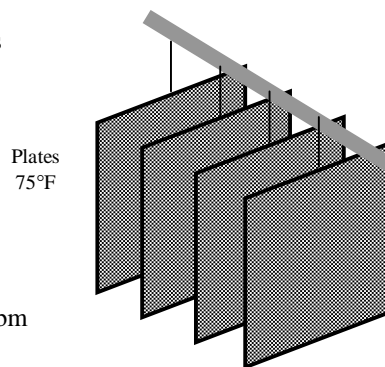
$$\Delta S_{system} = m(s_2 - s_1) = mC_{av} \ln \frac{T_2}{T_1} = (213 \text{ lbm})(0.091 \text{ Btu/lbm} \cdot \text{R}) \ln \frac{1000 + 460}{75 + 460} = 19.46 \text{ Btu/R}$$

Substituting,

$$S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system} = -\frac{17,930 \text{ Btu}}{1300 + 460 \text{ R}} + 19.46 \text{ Btu/R} = 9.272 \text{ Btu/R (per plate)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{gen} = S_{gen} \dot{N}_{plate} = (9.272 \text{ Btu/R} \cdot \text{plate})(450 \text{ plates/min}) = 4172 \text{ Btu/min} \cdot \text{R} = \mathbf{69.5 \text{ Btu/s} \cdot \text{R}}$$



7-124 Long cylindrical steel rods are heat-treated in an oven. The rate of heat transfer to the rods in the oven and the rate of entropy generation associated with this heat transfer process are to be determined.

Assumptions **1** The thermal properties of the rods are constant. **2** The changes in kinetic and potential energies are negligible.

Properties The density and specific heat of the steel rods are given to be $\rho = 7833 \text{ kg/m}^3$ and $C_p = 0.465 \text{ kJ/kg} \cdot ^\circ\text{C}$.

Analysis (a) Noting that the rods enter the oven at a velocity of 3 m/min and exit at the same velocity, we can say that a 3-m long section of the rod is heated in the oven in 1 min. Then the mass of the rod heated in 1 minute is

$$m = \rho V = \rho LA = \rho L(\pi D^2 / 4) = (7833 \text{ kg/m}^3)(3 \text{ m})[\pi(0.1 \text{ m})^2 / 4] = 184.6 \text{ kg}$$

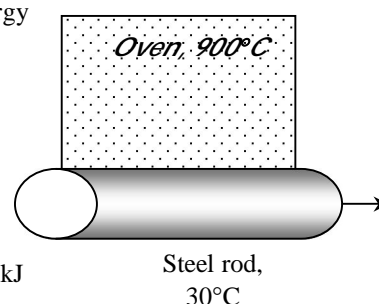
We take the 3-m section of the rod in the oven as the system. The energy balance for this closed system can be expressed as

$$\begin{array}{ccc} \cancel{E_{in}} - \cancel{E_{out}} & = & \cancel{E_{system}} \\ \text{Net energy transfer} & & \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & & \text{potential, etc. energies} \end{array}$$

$$Q_{in} = \Delta U_{rod} = m(u_2 - u_1) = mC(T_2 - T_1)$$

Substituting,

$$Q_{in} = mC(T_2 - T_1) = (184.6 \text{ kg})(0.465 \text{ kJ/kg} \cdot ^\circ\text{C})(700 - 30)^\circ\text{C} = 57,512 \text{ kJ}$$



Noting that this much heat is transferred in 1 min, the rate of heat transfer to the rod becomes

$$\dot{Q}_{in} = Q_{in} / \Delta t = (57,512 \text{ kJ}) / (1 \text{ min}) = 57,512 \text{ kJ/min} = \mathbf{958.5 \text{ kW}}$$

(b) We again take the 3-m long section of the rod as the system. The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the rod and its immediate surroundings so that the boundary temperature of the extended system is at 900°C at all times:

$$\begin{array}{ccc} \cancel{S_{in}} - \cancel{S_{out}} & + & \cancel{S_{gen}} \\ \text{Net entropy transfer} & & \text{Entropy} \\ \text{by heat and mass} & & \text{generation} \end{array} = \begin{array}{c} \cancel{\Delta S_{system}} \\ \text{Change} \\ \text{in entropy} \end{array}$$

$$\frac{Q_{in}}{T_b} + S_{gen} = \Delta S_{system} \rightarrow S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system}$$

where

$$\Delta S_{system} = m(s_2 - s_1) = mC_{av} \ln \frac{T_2}{T_1} = (184.6 \text{ kg})(0.465 \text{ kJ/kg} \cdot \text{K}) \ln \frac{700 + 273}{30 + 273} = 100.1 \text{ kJ/K}$$

Substituting,

$$S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system} = -\frac{57,512 \text{ kJ}}{900 + 273 \text{ K}} + 100.1 \text{ kJ/K} = 51.1 \text{ kJ/K}$$

Noting that this much entropy is generated in 1 min, the rate of entropy generation becomes

$$\dot{S}_{gen} = \frac{S_{gen}}{\Delta t} = \frac{51.1 \text{ kJ/K}}{1 \text{ min}} = 51.1 \text{ kJ/min} \cdot \text{K} = \mathbf{0.85 \text{ kW/K}}$$

7-125 The inner and outer surfaces of a brick wall are maintained at specified temperatures. The rate of entropy generation within the wall is to be determined.

Assumptions Steady operating conditions exist since the surface temperatures of the wall remain constant at the specified values.

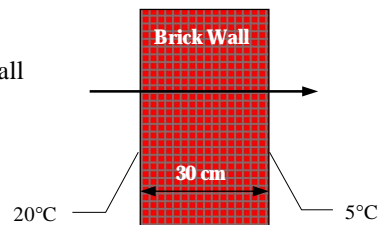
Analysis We take the wall to be the system, which is a closed system.

Under steady conditions, the rate form of the entropy balance for the wall simplifies to

$$\underbrace{\dot{\mathcal{S}}_{in}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{\mathcal{S}}_{gen}}_{\text{Rate of entropy generation}} = \underbrace{\Delta \dot{\mathcal{S}}_{system}}_{\text{Rate of change of entropy}} = 0$$

$$\frac{\dot{Q}_{in}}{T_{b,in}} - \frac{\dot{Q}_{out}}{T_{b,out}} + \dot{\mathcal{S}}_{gen,wall} = 0$$

$$\frac{1035 \text{ W}}{293 \text{ K}} - \frac{1035 \text{ W}}{278 \text{ K}} + \dot{\mathcal{S}}_{gen,wall} = 0 \rightarrow \dot{\mathcal{S}}_{gen,wall} = \mathbf{0.191 \text{ W/K}}$$



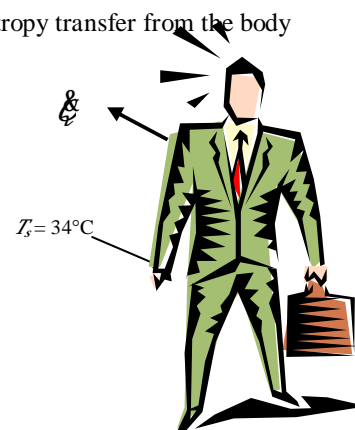
Therefore, the rate of entropy generation in the wall is 0.191 W/K.

7-126 A person is standing in a room at a specified temperature. The rate of entropy transfer from the body with heat is to be determined.

Assumptions Steady operating conditions exist.

Analysis Noting that Q/T represents entropy transfer with heat, the rate of entropy transfer from the body of the person accompanying heat transfer is

$$\dot{\mathcal{S}}_{transfer} = \frac{\dot{Q}}{T} = \frac{336 \text{ W}}{307 \text{ K}} = \mathbf{1.094 \text{ W/K}}$$



7-127 A 1000-W iron is left on the iron board with its base exposed to the air at 20°C. The rate of entropy generation is to be determined in steady operation.

Assumptions Steady operating conditions exist.

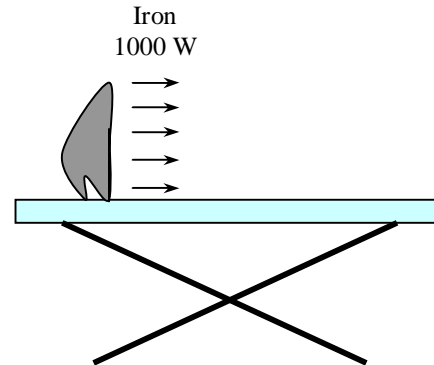
Analysis We take the iron to be the system, which is a closed system. Considering that the iron experiences no change in its properties in steady operation, including its entropy, the rate form of the entropy balance for the iron simplifies to

$$\underbrace{\dot{\mathcal{S}}_{in} - \dot{\mathcal{S}}_{out}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{\mathcal{S}}_{gen}}_{\text{Rate of entropy generation}} = \underbrace{\Delta \dot{\mathcal{S}}_{system}}_{\text{Rate of change of entropy}} = 0$$

$$-\frac{\dot{\mathcal{S}}_{out}}{T_{b,out}} + \dot{\mathcal{S}}_{gen,iron} = 0$$

Therefore,

$$\dot{\mathcal{S}}_{gen,iron} = \frac{\dot{\mathcal{S}}_{out}}{T_{b,out}} = \frac{1000 \text{ W}}{673 \text{ K}} = \mathbf{1.486 \text{ W/K}}$$



The rate of total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes the iron and its immediate surroundings so that the boundary temperature of the extended system is at 20°C at all times. It gives

$$\dot{\mathcal{S}}_{gen,total} = \frac{\dot{\mathcal{S}}_{out}}{T_{b,out}} = \frac{\dot{\mathcal{S}}}{T_{surr}} = \frac{1000 \text{ W}}{293 \text{ K}} = \mathbf{3.413 \text{ W/K}}$$

Discussion Note that only about one-third of the entropy generation occurs within the iron. The rest occurs in the air surrounding the iron as the temperature drops from 400°C to 20°C without serving any useful purpose.

7-128E A cylinder contains saturated liquid water at a specified pressure. Heat is transferred to liquid from a source and some liquid evaporates. The total entropy generation during this process is to be determined.

Assumptions **1** No heat loss occurs from the water to the surroundings during the process. **2** The pressure inside the cylinder and thus the water temperature remains constant during the process. **3** No irreversibilities occur within the cylinder during the process.

Analysis The pressure of the steam is maintained constant. Therefore, the temperature of the steam remains constant also at

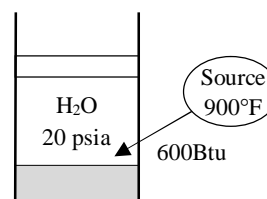
$$T = T_{\text{sat@20 psia}} = 227.96^\circ\text{F} = 688 \text{ R}$$

Taking the contents of the cylinder as the system and noting that the temperature of water remains constant, the entropy change of the system during this isothermal, internally reversible process becomes

$$\Delta S_{\text{system}} = \frac{Q_{\text{sys,in}}}{T_{\text{sys}}} = \frac{600 \text{ Btu}}{688 \text{ R}} = 0.872 \text{ Btu/R}$$

Similarly, the entropy change of the heat source is determined from

$$\Delta S_{\text{source}} = -\frac{Q_{\text{source,out}}}{T_{\text{source}}} = -\frac{600 \text{ Btu}}{900 + 460 \text{ R}} = -0.441 \text{ Btu/R}$$



Now consider a combined system that includes the cylinder and the source. Noting that no heat or mass crosses the boundaries of this combined system, the entropy balance for it can be expressed as

$$\underbrace{142.43}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{\text{gen}}}_{\text{Entropy generation}} = \underbrace{142.43}_{\text{Change in entropy}}$$

$$0 + S_{\text{gen,total}} = \Delta S_{\text{water}} + \Delta S_{\text{source}}$$

Therefore, the total entropy generated during this process is

$$S_{\text{gen,total}} = \Delta S_{\text{water}} + \Delta S_{\text{source}} = 0.872 - 0.441 = \mathbf{0.431 \text{ Btu/R}}$$

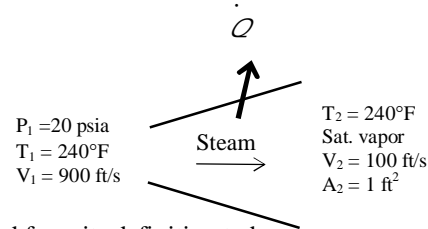
Discussion The entropy generation in this case is entirely due to the irreversible heat transfer through a finite temperature difference. We could also determine the total entropy generation by writing an energy balance on an extended system that includes the system and its immediate surroundings so that part of the boundary of the extended system, where heat transfer occurs, is at the source temperature.

7-129E Steam is decelerated in a diffuser from a velocity of 900 ft/s to 100 ft/s. The mass flow rate of steam and the rate of entropy generation 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** There are no work interactions.

Properties The properties of steam at the inlet and the exit of the diffuser are (Tables A-4E through A-6E)

$$\begin{aligned} P_1 = 20 \text{ psia} & \left\{ \begin{aligned} h_1 &= 1162.3 \text{ Btu/lbm} \\ s_1 &= 1.7405 \text{ Btu/lbm} \cdot \text{R} \end{aligned} \right. \\ T_1 = 240^\circ \text{F} & \\ T_2 = 240^\circ \text{F} & \left\{ \begin{aligned} h_2 &= 1160.7 \text{ Btu/lbm} \\ s_2 &= 1.7143 \text{ Btu/lbm} \cdot \text{R} \end{aligned} \right. \\ \text{sat. vapor} & \left\{ \begin{aligned} v_2 &= 16.327 \text{ ft}^3/\text{lbm} \end{aligned} \right. \end{aligned}$$



Analysis (a) The mass flow rate of the steam can be determined from its definition to be

$$\dot{m} = \frac{1}{v_2} A_2 V_2 = \frac{1}{16.327 \text{ ft}^3/\text{lbm}} (1 \text{ ft}^2) (100 \text{ ft/s}) = \mathbf{6.125 \text{ lbm/s}}$$

(b) 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

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \dot{E}_{system}^{d0} \text{ (steady)} = 0 \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \end{aligned}$$

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

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

$$\dot{E}_{out} = -\dot{m} \left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} \right)$$

Substituting, the rate of heat loss from the diffuser is determined to be

$$\dot{E}_{out} = -(6.125 \text{ lbm/s}) \left(1160.7 - 1162.3 + \frac{(100 \text{ ft/s})^2 - (900 \text{ ft/s})^2}{2} \left(\frac{1 \text{ Btu/lbm}}{25,037 \text{ ft}^2/\text{s}^2} \right) \right) = 107.66 \text{ Btu/s}$$

The rate of total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes the diffuser and its immediate surroundings so that the boundary temperature of the extended system is 77°F at all times. It gives

$$\begin{aligned} \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} &= \dot{S}_{system}^{d0} = 0 \\ \text{Rate of net entropy transfer} & \quad \text{Rate of entropy} & \quad \text{Rate of change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{of entropy} \end{aligned}$$

$$\dot{m} s_1 - \dot{m} s_2 - \frac{\dot{E}_{out}}{T_{b,surr}} + \dot{S}_{gen} = 0$$

Substituting, the total rate of entropy generation during this process becomes

$$\dot{S}_{gen} = \dot{m} (s_2 - s_1) + \frac{\dot{E}_{out}}{T_{b,surr}} = (6.125 \text{ lbm/s}) (1.7143 - 1.7405) \text{ Btu/lbm} \cdot \text{R} + \frac{107.66 \text{ Btu/s}}{537 \text{ R}} = \mathbf{0.040 \text{ Btu/s} \cdot \text{R}}$$

7-130 Steam expands in a turbine from a specified state to another specified state. The rate of entropy generation during this process is to be determined.

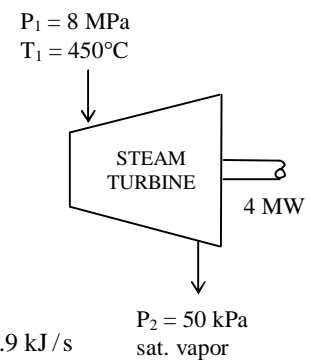
Assumptions 1 This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible.

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

$$\begin{aligned} P_1 = 8 \text{ MPa} & \left\{ \begin{aligned} h_1 &= 3272.0 \text{ kJ/kg} \\ T_1 = 450^\circ \text{C} & \left\{ \begin{aligned} s_1 &= 6.5551 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \\ P_2 = 50 \text{ kPa} & \left\{ \begin{aligned} h_2 &= 2645.9 \text{ kJ/kg} \\ \text{sat. vapor} & \left\{ \begin{aligned} s_2 &= 7.5939 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned} \right. \end{aligned}$$

Analysis 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

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \dot{E}_{system} \quad \dot{E}_{system} = 0 \quad (\text{steady}) \quad \dot{E}_{system} = 0 \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{m}h_1 &= \dot{E}_{out} + \dot{W}_{out} + \dot{m}h_2 \\ \dot{E}_{out} &= \dot{m}(h_1 - h_2) - \dot{W}_{out} \end{aligned}$$



Substituting,

$$\dot{E}_{out} = (25,000 / 3600 \text{ kg/s})(3272 - 2645.9) \text{ kJ/kg} - 4000 \text{ kJ/s} = 347.9 \text{ kJ/s}$$

The rate of total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes the turbine and its immediate surroundings so that the boundary temperature of the extended system is 25°C at all times. It gives

$$\begin{aligned} \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} &= \dot{S}_{system} \quad \dot{S}_{system} = 0 \quad (\text{steady}) \quad \dot{S}_{system} = 0 \\ \text{Rate of net entropy transfer} & \quad \text{Rate of entropy} & \quad \text{Rate of change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{of entropy} \\ \dot{m}s_1 - \dot{m}s_2 - \frac{\dot{E}_{out}}{T_{b,surr}} + \dot{S}_{gen} &= 0 \end{aligned}$$

Substituting, the rate of entropy generation during this process is determined to be

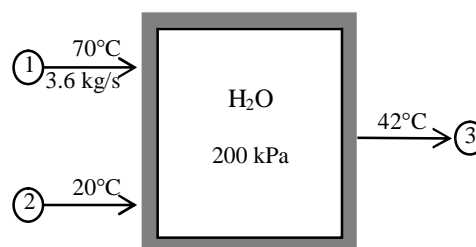
$$\dot{S}_{gen} = \dot{m}(s_2 - s_1) + \frac{\dot{E}_{out}}{T_{b,surr}} = (25,000/3600 \text{ kg/s})(7.5939 - 6.5551) \text{ kJ/kg} \cdot \text{K} + \frac{347.9 \text{ kW}}{298 \text{ K}} = \mathbf{8.38 \text{ kW/K}}$$

7-131 A hot water stream is mixed with a cold water stream. For a specified mixture temperature, the mass flow rate of cold water stream and the rate of entropy generation are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The mixing chamber is well-insulated so that heat loss to the surroundings is negligible. 3 Changes in the kinetic and potential energies of fluid streams are negligible.

Properties Noting that $T < T_{\text{sat}} @ 200 \text{ kPa} = 120.23^\circ\text{C}$, the water in all three streams exists as a compressed liquid, which can be approximated as a saturated liquid at the given temperature. Thus from Table A-4,

$$\begin{aligned} P_1 &= 200 \text{ kPa} \quad \left\{ \begin{aligned} h_1 &\equiv h_{f@70^\circ\text{C}} = 292.88 \text{ kJ/kg} \\ T_1 &= 70^\circ\text{C} \quad \left\{ \begin{aligned} s_1 &\equiv s_{f@70^\circ\text{C}} = 0.9549 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned} \right. \\ P_2 &= 200 \text{ kPa} \quad \left\{ \begin{aligned} h_2 &\equiv h_{f@20^\circ\text{C}} = 83.96 \text{ kJ/kg} \\ T_2 &= 20^\circ\text{C} \quad \left\{ \begin{aligned} s_2 &\equiv s_{f@20^\circ\text{C}} = 0.2966 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned} \right. \\ P_3 &= 200 \text{ kPa} \quad \left\{ \begin{aligned} h_3 &\equiv h_{f@42^\circ\text{C}} = 175.92 \text{ kJ/kg} \\ T_3 &= 42^\circ\text{C} \quad \left\{ \begin{aligned} s_3 &\equiv s_{f@42^\circ\text{C}} = 0.5990 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned} \right. \end{aligned}$$



Analysis (a) We take the mixing chamber 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: $\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{E}_{\text{system}}^{\dot{a}0} (\text{steady}) = 0 \longrightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy balance:

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \Delta \dot{E}_{\text{system}}^{\dot{a}0} (\text{steady}) = 0 \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{m}_1 h_1 + \dot{m}_2 h_2 &= \dot{m}_3 h_3 \quad (\text{since } \dot{Q} = \dot{W} = \Delta \dot{ke} \equiv \Delta \dot{pe} \equiv 0) \end{aligned}$$

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

Solving for \dot{m}_2 and substituting, the mass flow rate of cold water stream is determined to be

$$\dot{m}_2 = \frac{h_1 - h_3}{h_3 - h_2} \dot{m}_1 = \frac{(292.88 - 175.92) \text{ kJ/kg}}{(175.92 - 83.96) \text{ kJ/kg}} (3.6 \text{ kg/s}) = 4.58 \text{ kg/s}$$

Also,

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 3.6 + 4.58 = 8.18 \text{ kg/s}$$

(b) Noting that the mixing chamber is adiabatic and thus there is no heat transfer to the surroundings, the entropy balance of the steady-flow system (the mixing chamber) can be expressed as

$$\begin{aligned} \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} &= \Delta \dot{S}_{\text{system}}^{\dot{A}0} = 0 \\ \text{Rate of net entropy transfer} & \quad \text{Rate of entropy} & \quad \text{Rate of change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{of entropy} \\ \dot{m}_1 s_1 + \dot{m}_2 s_2 - \dot{m}_3 s_3 + \dot{S}_{gen} &= 0 \end{aligned}$$

Substituting, the total rate of entropy generation during this process becomes

$$\begin{aligned} \dot{S}_{gen} &= \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1 \\ &= (4.09 \text{ kg/s})(0.599 \text{ kJ/kg} \cdot \text{K}) - (2.29 \text{ kg/s})(0.2966 \text{ kJ/kg} \cdot \text{K}) \\ &\quad - (1.8 \text{ kg/s})(0.9549 \text{ kJ/kg} \cdot \text{K}) \\ &= 0.0519 \text{ kW/K} \end{aligned}$$

7-132 Liquid water is heated in a chamber by mixing it with superheated steam. For a specified mixing temperature, the mass flow rate of the steam and the rate of entropy generation are to be determined.

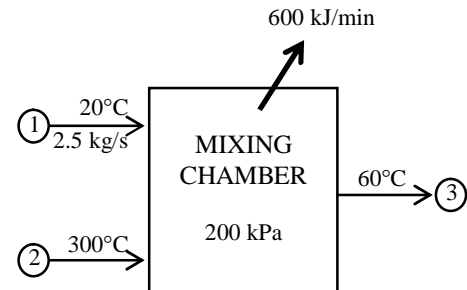
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** There are no work interactions.

Properties Noting that $T < T_{\text{sat}} @ 200 \text{ kPa} = 120.23^\circ\text{C}$, the cold water and the exit mixture streams exist as a compressed liquid, which can be approximated as a saturated liquid at the given temperature. From tables,

$$\left. \begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 20^\circ\text{C} \end{array} \right\} \begin{array}{l} h_1 \equiv h_{f@20^\circ\text{C}} = 83.96 \text{ kJ/kg} \\ s_1 \equiv s_{f@20^\circ\text{C}} = 0.2966 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 200 \text{ kPa} \\ T_2 = 300^\circ\text{C} \end{array} \right\} \begin{array}{l} h_2 = 3071.8 \text{ kJ/kg} \\ s_2 = 7.8926 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_3 = 200 \text{ kPa} \\ T_3 = 60^\circ\text{C} \end{array} \right\} \begin{array}{l} h_3 \equiv h_{f@60^\circ\text{C}} = 251.13 \text{ kJ/kg} \\ s_3 \equiv s_{f@60^\circ\text{C}} = 0.8312 \text{ kJ/kg} \cdot \text{K} \end{array}$$



Analysis (a) We take the mixing chamber 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

$$\text{Mass balance: } \dot{m}_{\text{in}} - \dot{m}_{\text{out}} = \Delta \dot{E}_{\text{system}}^{\dot{A}0} \text{ (steady)} = 0 \longrightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

Energy balance:

$$\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} = \Delta \dot{E}_{\text{system}}^{\dot{A}0} \text{ (steady)} = 0$$

Rate of net energy transfer by heat, work, and mass Rate of change in internal, kinetic, potential, etc. energies

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

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

Combining the two relations gives $\dot{Q}_{\text{out}} = \dot{m}_1 h_1 + \dot{m}_2 h_2 - (\dot{m}_1 + \dot{m}_2) h_3 = \dot{m}_1 (h_1 - h_3) + \dot{m}_2 (h_2 - h_3)$

Solving for \dot{m}_2 and substituting, the mass flow rate of the superheated steam is determined to be

$$\dot{m}_2 = \frac{\dot{Q}_{\text{out}} - \dot{m}_1 (h_1 - h_3)}{h_2 - h_3} = \frac{(600/60 \text{ kJ/s}) - (2.5 \text{ kg/s})(83.96 - 251.13) \text{ kJ/kg}}{(3071.8 - 251.13) \text{ kJ/kg}} = \mathbf{0.152 \text{ kg/s}}$$

Also, $\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 2.5 + 0.152 = 2.652 \text{ kg/s}$

(b) The rate of total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes the mixing chamber and its immediate surroundings so that the boundary temperature of the extended system is 25°C at all times. It gives

$$\dot{S}_{\text{in}} + \dot{S}_{\text{gen}} = \Delta \dot{S}_{\text{system}}^{\dot{A}0} = 0$$

Rate of net entropy transfer by heat and mass Rate of entropy generation Rate of change of entropy

$$\dot{m}_1 s_1 + \dot{m}_2 s_2 - \dot{m}_3 s_3 - \frac{\dot{Q}_{\text{out}}}{T_{b,\text{surr}}} + \dot{S}_{\text{gen}} = 0$$

Substituting, the rate of entropy generation during this process is determined to be

$$\begin{aligned} \dot{S}_{\text{gen}} &= \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1 + \frac{\dot{Q}_{\text{out}}}{T_{b,\text{surr}}} \\ &= (2.652 \text{ kg/s})(0.8312 \text{ kJ/kg} \cdot \text{K}) - (0.152 \text{ kg/s})(7.8926 \text{ kJ/kg} \cdot \text{K}) \\ &\quad - (2.5 \text{ kg/s})(0.2966 \text{ kJ/kg} \cdot \text{K}) + \frac{(600/60 \text{ kJ/s})}{298 \text{ K}} \\ &= \mathbf{0.297 \text{ kW/K}} \end{aligned}$$

7-133 A rigid tank initially contains saturated liquid water. A valve at the bottom of the tank is opened, and half of mass in liquid form is withdrawn from the tank. The temperature in the tank is maintained constant. The amount of heat transfer and the entropy generation during this process are to be determined.

Assumptions **1** This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform-flow process since the state of fluid leaving the device remains constant. **2** Kinetic and potential energies are negligible. **3** There are no work interactions involved. **4** The direction of heat transfer is to the tank (will be verified).

Properties The properties of water are (Tables A-4 through A-6)

$$T_1 = 200^\circ\text{C} \left\{ \begin{array}{l} v_1 = v_{f@200^\circ\text{C}} = 0.001157\text{m}^3/\text{kg} \\ u_1 = u_{f@200^\circ\text{C}} = 850.65\text{kJ/kg} \\ s_1 = s_{f@200^\circ\text{C}} = 2.3309\text{kJ/kg} \cdot \text{K} \end{array} \right. \text{sat.liquid}$$

$$T_e = 200^\circ\text{C} \left\{ \begin{array}{l} h_e = h_{f@200^\circ\text{C}} = 852.45\text{kJ/kg} \\ s_e = s_{f@200^\circ\text{C}} = 2.3309\text{kJ/kg} \cdot \text{K} \end{array} \right. \text{sat.liquid}$$

Analysis (a) We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u , respectively, the mass and energy balances for this uniform-flow system can be expressed as

$$\text{Mass balance: } m_{in} - m_{out} = \Delta m_{\text{system}} \rightarrow m_e = m_1 - m_2$$

$$\text{Energy balance: } \begin{array}{c} \cancel{E_{in}} - \cancel{E_{out}} \\ \text{Net energy transfer} \\ \text{by heat, work, and mass} \end{array} = \begin{array}{c} \cancel{\Delta E_{\text{system}}} \\ \text{Change in internal, kinetic,} \\ \text{potential, etc. energies} \end{array}$$

$$Q_{in} = m_e h_e + m_2 u_2 - m_1 u_1 \quad (\text{since } W \cong ke \cong pe \cong 0)$$

The initial and the final masses in the tank are

$$m_1 = \frac{V}{v_1} = \frac{0.4\text{m}^3}{0.001157\text{m}^3/\text{kg}} = 345.72\text{kg}$$

$$m_2 = \frac{1}{2} m_1 = \frac{1}{2} (345.72\text{kg}) = 172.86\text{kg} = m_e$$

Now we determine the final internal energy and entropy,

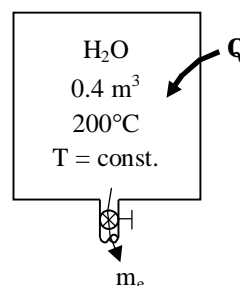
$$v_2 = \frac{V}{m_2} = \frac{0.4\text{m}^3}{172.86\text{kg}} = 0.002314\text{m}^3/\text{kg}$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.002314 - 0.001157}{0.12736 - 0.001157} = 0.00917$$

$$\left. \begin{array}{l} T_2 = 200^\circ\text{C} \\ x_2 = 0.00917 \end{array} \right\} \begin{array}{l} u_2 = u_f + x_2 u_{fg} = 850.65 + (0.00917)(1744.7) = 866.65\text{kJ/kg} \\ s_2 = s_f + x_2 s_{fg} = 2.3309 + (0.00917)(4.1014) = 2.3685\text{kJ/kg} \cdot \text{K} \end{array}$$

The heat transfer during this process is determined by substituting these values into the energy balance equation,

$$\begin{aligned} Q_{in} &= m_e h_e + m_2 u_2 - m_1 u_1 \\ &= (172.86\text{kg})(852.45\text{kJ/kg}) + (172.86\text{kg})(866.65\text{kJ/kg}) \\ &\quad - (345.72\text{kg})(850.65\text{kJ/kg}) \\ &= \mathbf{3077\text{kJ}} \end{aligned}$$



(~~D~~) The total entropy generation is determined by considering a combined system that includes the tank and the heat source. Noting that no heat crosses the boundaries of this combined system and no mass enters, the entropy balance for it can be expressed as

$$\underbrace{\dot{S}_{in}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{gen}}_{\text{Entropy generation}} = \underbrace{\dot{S}_{out}}_{\text{Change in entropy}}$$

$$-m_e s_e + S_{gen} = \Delta S_{\text{tank}} + \Delta S_{\text{source}}$$

Therefore, the total entropy generated during this process is

$$\begin{aligned} S_{gen} &= m_e s_e + \Delta S_{\text{tank}} + \Delta S_{\text{source}} = m_e s_e + (m_2 s_2 - m_1 s_1) - \frac{Q_{\text{source,out}}}{T_{\text{source}}} \\ &= (172.86 \text{ kg})(2.3309 \text{ kJ/kg} \cdot \text{K}) + (172.86 \text{ kg})(2.3685 \text{ kJ/kg} \cdot \text{K}) \\ &\quad - (345.72 \text{ kg})(2.3309 \text{ kJ/kg} \cdot \text{K}) - \frac{3077 \text{ kJ}}{523 \text{ K}} \\ &= \mathbf{0.616 \text{ kJ/K}} \end{aligned}$$

7-134E An unknown mass of iron is dropped into water in an insulated tank while being stirred by a 200-W paddle wheel. Thermal equilibrium is established after 10 min. The mass of the iron block and the entropy generated during this process are to be determined.

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 energy changes are zero. **3** The system is well-insulated and thus there is no heat transfer.

Properties The specific heats of water and the iron block at room temperature are $C_{p, \text{water}} = 1.00 \text{ Btu/lbm} \cdot ^\circ\text{F}$ and $C_{p, \text{iron}} = 0.107 \text{ Btu/lbm} \cdot ^\circ\text{F}$ (Table A-3E). The density of water at room temperature is 62.1 lbm/ft^3 .

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 on the system can be expressed as

$$\begin{aligned} \cancel{E_{\text{in}}} - \cancel{E_{\text{out}}} &= \Delta E_{\text{system}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ W_{\text{pw, in}} &= \Delta U \end{aligned}$$

or,

$$W_{\text{pw, in}} = \Delta U_{\text{iron}} + \Delta U_{\text{water}}$$

$$W_{\text{pw, in}} = [mC(T_2 - T_1)]_{\text{iron}} + [mC(T_2 - T_1)]_{\text{water}}$$

where

$$m_{\text{water}} = \rho V = (62.1 \text{ lbm/ft}^3)(0.8 \text{ ft}^3) = 49.7 \text{ lbm}$$

$$W_{\text{pw}} = \dot{W}_{\text{pw}} \Delta t = (0.2 \text{ kJ/s})(10 \times 60 \text{ s}) \left(\frac{1 \text{ Btu}}{1.055 \text{ kJ}} \right) = 113.7 \text{ Btu}$$

Using specific heat values for iron and liquid water and substituting,

$$113.7 \text{ Btu} = m_{\text{iron}}(0.107 \text{ Btu/lbm} \cdot ^\circ\text{F})(75 - 185)^\circ\text{F} + (49.7 \text{ lbm})(1.00 \text{ Btu/lbm} \cdot ^\circ\text{F})(75 - 70)^\circ\text{F}$$

$$m_{\text{iron}} = \mathbf{11.4 \text{ lbm}}$$

(\cancel{D}) Again we take the iron + water in the tank to be the system. Noting that no heat or mass crosses the boundaries of this combined system, the entropy balance for it can be expressed as

$$\begin{aligned} \cancel{S_{\text{in}}} - \cancel{S_{\text{out}}} + S_{\text{gen}} &= \Delta S_{\text{system}} \\ \text{Net entropy transfer} & \quad \text{Entropy} & \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{in entropy} \\ 0 + S_{\text{gen, total}} &= \Delta S_{\text{iron}} + \Delta S_{\text{water}} \end{aligned}$$

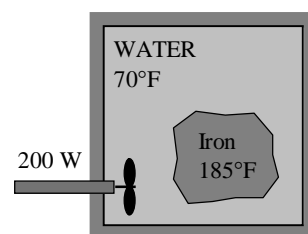
where

$$\Delta S_{\text{iron}} = mC_{\text{ave}} \ln \left(\frac{T_2}{T_1} \right) = (11.4 \text{ lbm})(0.107 \text{ Btu/lbm} \cdot \text{R}) \ln \left(\frac{535 \text{ R}}{645 \text{ R}} \right) = -0.228 \text{ Btu/R}$$

$$\Delta S_{\text{water}} = mC_{\text{ave}} \ln \left(\frac{T_2}{T_1} \right) = (49.6 \text{ lbm})(1.0 \text{ Btu/lbm} \cdot \text{R}) \ln \left(\frac{535 \text{ R}}{530 \text{ R}} \right) = 0.466 \text{ Btu/R}$$

Therefore, the total entropy generated during this process is

$$\Delta S_{\text{total}} = S_{\text{gen, total}} = \Delta S_{\text{iron}} + \Delta S_{\text{water}} = -0.228 + 0.466 = \mathbf{0.238 \text{ Btu/R}}$$



7-135E Air is compressed steadily by a compressor. The mass flow rate of air through the compressor and the rate of entropy generation 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 Air is an ideal gas with variable specific heats.

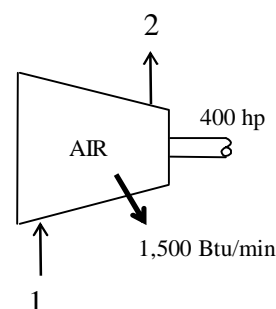
Properties The inlet and exit enthalpies of air are (Table A-17)

$$\left. \begin{aligned} T_1 &= 520 \text{ R} \\ P_1 &= 15 \text{ psia} \end{aligned} \right\} \begin{aligned} h_1 &= 124.27 \text{ Btu/lbm} \\ s_1^0 &= 0.59173 \text{ Btu/lbm} \cdot \text{R} \end{aligned}$$

$$\left. \begin{aligned} T_2 &= 1080 \text{ R} \\ P_2 &= 150 \text{ psia} \end{aligned} \right\} \begin{aligned} h_2 &= 260.97 \text{ Btu/lbm} \\ s_2^0 &= 0.76964 \text{ Btu/lbm} \cdot \text{R} \end{aligned}$$

Analysis (a) 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

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \dot{E}_{system} \quad \dot{E}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} &\quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{m} \left(h_1 + \frac{V_1^2}{2} \right) &= \dot{m} \left(h_2 + \frac{V_2^2}{2} \right) \quad (\text{since } \Delta p_e \cong 0) \\ \dot{m} - \dot{m} &= \dot{m} \left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} \right) \end{aligned}$$



Substituting, the mass flow rate is determined to be

$$\text{Thus,} \quad (400 \text{ hp}) \left(\frac{0.7068 \text{ Btu/s}}{1 \text{ hp}} \right) - \frac{1500 \text{ Btu}}{60 \text{ s}} = \dot{m} \left(260.97 - 124.27 + \frac{(300 \text{ ft/s})^2}{2} \left(\frac{1 \text{ Btu/lbm}}{25,037 \text{ ft}^2/\text{s}^2} \right) \right)$$

It yields $\dot{m} = 1.861 \text{ lbm/s}$

(b) Again we take the compressor to be the system. Noting that no heat or mass crosses the boundaries of this combined system, the entropy balance for it can be expressed as

$$\begin{aligned} \dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} &= \dot{S}_{system} \quad \dot{S}_{system} = 0 \quad (\text{steady}) \\ \text{Rate of net entropy transfer} &= \text{Rate of entropy} \\ \text{by heat and mass} &\quad \text{generation} \\ \text{Rate of change} &\quad \text{of entropy} \\ \dot{m} s_1 - \dot{m} s_2 - \frac{\dot{Q}_{out}}{T_{b,surr}} + \dot{S}_{gen} &= 0 \rightarrow \dot{S}_{gen} = \dot{m} (s_2 - s_1) + \frac{\dot{Q}_{out}}{T_{b,surr}} \end{aligned}$$

where

$$\begin{aligned} \Delta \dot{S}_{air} &= \dot{m} (s_2 - s_1) = \dot{m} \left(s_2^0 - s_1^0 - R \ln \frac{P_2}{P_1} \right) \\ &= (1.861 \text{ lbm/s}) \left(0.76964 - 0.59173 - (0.06855 \text{ Btu/lbm} \cdot \text{R}) \ln \frac{150 \text{ psia}}{15 \text{ psia}} \right) = 0.0373 \text{ Btu/s} \cdot \text{R} \end{aligned}$$

Substituting, the rate of entropy generation during this process is determined to be

$$\dot{S}_{gen} = \dot{m} (s_2 - s_1) + \frac{\dot{Q}_{out}}{T_{b,surr}} = 0.0373 \text{ Btu/s} \cdot \text{R} + \frac{1500/60 \text{ Btu/s}}{520 \text{ R}} = \mathbf{0.0854 \text{ kW/K}}$$

7-136 Steam is accelerated in a nozzle from a velocity of 70 m/s to 320 m/s. The exit temperature and the rate of entropy generation 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** There are no work interactions. **4** The device is adiabatic and thus heat transfer is negligible.

Properties From the steam tables (Table A-6),

$$\left. \begin{aligned} P_1 &= 3 \text{ MPa} \\ T_1 &= 400^\circ \text{C} \end{aligned} \right\} \begin{aligned} h_1 &= 3230.9 \text{ kJ/kg} \\ s_1 &= 6.9212 \text{ kJ/kg} \cdot \text{K} \\ v_1 &= 0.09936 \text{ m}^3/\text{kg} \end{aligned}$$

Analysis (a) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. 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

$$\underbrace{\dot{Q}_{in} - \dot{Q}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\dot{E}_{system}^{A0}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0 \quad \begin{array}{l} P_1 = 3 \text{ MPa} \\ T_1 = 400^\circ \text{C} \\ V_1 = 70 \text{ m/s} \end{array} \quad \begin{array}{l} \text{Steam} \\ \longrightarrow \end{array} \quad \begin{array}{l} P_2 = 2 \text{ MPa} \\ V_2 = 320 \text{ m/s} \end{array}$$

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

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

$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$

Substituting,,

$$\text{or,} \quad h_2 = 3230.9 \text{ kJ/kg} - \frac{(320 \text{ m/s})^2 - (70 \text{ m/s})^2}{2} \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) = 3182.15 \text{ kJ/kg}$$

Thus,

$$\left. \begin{aligned} P_2 &= 2 \text{ MPa} \\ h_{2,s} &= 3182.15 \text{ kJ/kg} \end{aligned} \right\} \quad \begin{aligned} T_2 &= 370.4^\circ \text{C} \\ s_2 &= 7.0260 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

The mass flow rate of steam is

$$\dot{m} = \frac{1}{v_1} A_1 V_1 = \frac{1}{0.09936 \text{ m}^3/\text{kg}} (7 \times 10^{-4} \text{ m}^2) (70 \text{ m/s}) = 0.493 \text{ kg/s}$$

(b) Again we take the nozzle to be the system. Noting that no heat crosses the boundaries of this combined system, the entropy balance for it can be expressed as

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{gen}}_{\text{Rate of entropy generation}} = \underbrace{\dot{S}_{system}^{A0}}_{\text{Rate of change of entropy}} = 0$$

$$\dot{m}s_1 - \dot{m}s_2 + \dot{S}_{gen} = 0 \rightarrow \dot{S}_{gen} = \dot{m}(s_2 - s_1)$$

Substituting, the rate of entropy generation during this process is determined to be

$$\dot{S}_{gen} = \dot{m}(s_2 - s_1) = (0.493 \text{ kg/s})(7.0260 - 6.9212) \text{ kJ/kg} \cdot \text{K} = 0.0517 \text{ kW/K}$$

Review Problems

7-137 It is to be shown that the difference between the steady-flow and boundary works is the flow energy.

Analysis The total differential of flow energy Pv can be expressed as

$$d(Pv) = Pdv + v dP = \delta w_b - \delta w_{flow} = \delta(w_b - w_{flow})$$

Therefore, the difference between the reversible steady-flow work and the reversible boundary work is the flow energy.

7-138E An insulated rigid can initially contains R-134a at a specified state. A crack develops, and refrigerant escapes slowly. The final mass in the can is to be determined when the pressure inside drops to a specified value.

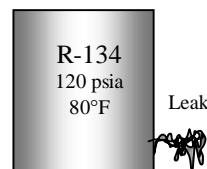
Assumptions **1** The can is well-insulated and thus heat transfer is negligible. **2** The refrigerant that remains in the can underwent a reversible adiabatic process.

Analysis Noting that for a reversible adiabatic (i.e., isentropic) process, $s_1 = s_2$, the properties of the refrigerant in the can are

$$\left. \begin{array}{l} P_1 = 120 \text{ psia} \\ T_1 = 80^\circ \text{F} \end{array} \right\} s_1 \cong s_f @ 80^\circ \text{F} = 0.0774 \text{ Btu/lbm} \cdot \text{R}$$

$$\left. \begin{array}{l} P_2 = 30 \text{ psia} \\ s_2 = s_1 \end{array} \right\} x_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{0.0774 - 0.0364}{0.2209 - 0.0364} = 0.2222$$

$$v_2 = v_f + x_2 v_{fg} = 0.01209 + (0.2222)(1.5408 - 0.01209) = 0.3518 \text{ ft}^3/\text{lbm}$$



Thus the final mass of the refrigerant in the can is

$$m = \frac{V}{v_2} = \frac{1.2 \text{ ft}^3}{0.3518 \text{ ft}^3/\text{lbm}} = \mathbf{3.411 \text{ lbm}}$$

7-139 An insulated rigid tank is connected to a piston-cylinder device with zero clearance that is maintained at constant pressure. A valve is opened, and some steam in the tank is allowed to flow into the cylinder. The final temperatures in the tank and the cylinder are to be determined.

Assumptions **1** Both the tank and cylinder are well-insulated and thus heat transfer is negligible. **2** The water that remains in the tank underwent a reversible adiabatic process. **3** The thermal energy stored in the tank and cylinder themselves is negligible. **4** The system is stationary and thus kinetic and potential energy changes are negligible.

Analysis (a) The steam in tank A undergoes a reversible, adiabatic process, and thus $s_2 = s_1$. From the steam tables,

$$\begin{aligned}
 \left. \begin{array}{l} P_1 = 500 \text{ kPa} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} v_1 = v_{g@500 \text{ kPa}} = 0.3749 \text{ m}^3/\text{kg} \\ u_1 = u_{g@500 \text{ kPa}} = 2561.2 \text{ kJ/kg} \\ s_1 = s_{g@500 \text{ kPa}} = 6.8213 \text{ kJ/kg} \cdot \text{K} \end{array}
 \end{aligned}$$

$$\begin{aligned}
 \left. \begin{array}{l} P_2 = 150 \text{ kPa} \\ s_2 = s_1 \\ (\text{sat. mixture}) \end{array} \right\} \begin{array}{l} T_{2,A} = T_{\text{sat}@150 \text{ kPa}} = \mathbf{111.37^\circ \text{C}} \\ x_{2,A} = \frac{s_{2,A} - s_f}{s_{fg}} = \frac{6.8213 - 1.4336}{5.7897} = 0.9306 \\ v_{2,A} = v_f + x_{2,A} v_{fg} = 0.001053 + (0.9306)(1.1593 - 0.001053) = 1.079 \text{ m}^3/\text{kg} \\ u_{2,A} = u_f + x_{2,A} u_{fg} = 466.94 + (0.9306)(2052.7 \text{ kJ/kg}) = 2377.2 \text{ kJ/kg} \end{array}
 \end{aligned}$$

The initial and the final masses in tank A are

$$m_{1,A} = \frac{V_A}{v_{1,A}} = \frac{0.4 \text{ m}^3}{0.3749 \text{ m}^3/\text{kg}} = 1.067 \text{ kg} \quad \text{and} \quad m_{2,A} = \frac{V_A}{v_{2,A}} = \frac{0.4 \text{ m}^3}{1.079 \text{ m}^3/\text{kg}} = 0.371 \text{ kg}$$

Thus,

$$m_{2,B} = m_{1,A} - m_{2,A} = 1.067 - 0.371 = 0.696 \text{ kg}$$

(b) The boundary work done during this process is

$$W_{b,\text{out}} = \int_1^2 P dV = P_B (V_{2,B} - 0) = P_B m_{2,B} v_{2,B}$$

Taking the contents of both the tank and the cylinder to be the system, the energy balance for this closed system can be expressed as

$$\begin{aligned}
 \cancel{E_{in}} - \cancel{E_{out}} &= \Delta E_{\text{system}} \\
 \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\
 \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\
 -W_{b,\text{out}} &= \Delta U = (\Delta U)_A + (\Delta U)_B
 \end{aligned}$$

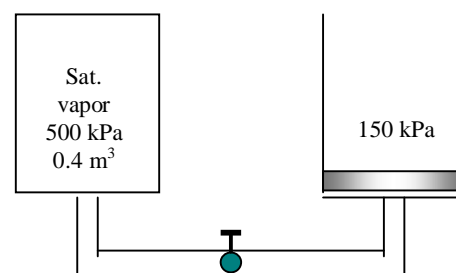
$$\begin{aligned}
 & W_{b,\text{out}} + (\Delta U)_A + (\Delta U)_B = 0 \\
 \text{or,} \quad & P_B m_{2,B} v_{2,B} + (m_2 u_2 - m_1 u_1)_A + (m_2 u_2)_B = 0 \\
 & m_{2,B} h_{2,B} + (m_2 u_2 - m_1 u_1)_A = 0
 \end{aligned}$$

Thus,

$$h_{2,B} = \frac{(m_1 u_1 - m_2 u_2)_A}{m_{2,B}} = \frac{(1.067)(2561.2) - (0.371)(2377.2)}{0.696} = 2659.3 \text{ kJ/kg}$$

At 150 kPa, $h_f = 467.11$ and $h_g = 2693.6$ kJ/kg. Thus at the final state, the cylinder will contain a saturated liquid-vapor mixture since $h_f < h_2 < h_g$. Therefore,

$$T_{2,B} = T_{\text{sat}@150 \text{ kPa}} = \mathbf{111.37^\circ \text{C}}$$



7-140 One ton of liquid water at 80°C is brought into a room. The final equilibrium temperature in the room and the entropy change during this process are to be determined.

Assumptions **1** The room is well insulated and well sealed. **2** The thermal properties of water and air are constant at room temperature. **3** The system is stationary and thus the kinetic and potential energy changes are zero. **4** There are no work interactions involved.

Properties The gas constant of air is $R = 0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$ (Table A-1). The specific heat of water at room temperature is $C = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3). For air is $C_v = 0.718 \text{ kJ/kg} \cdot ^\circ\text{C}$ at room temperature.

Analysis The volume and the mass of the air in the room are

$$V = 4 \times 5 \times 6 = 120 \text{ m}^3$$

$$m_{\text{air}} = \frac{P_1 V_1}{R T_1} = \frac{(100 \text{ kPa})(120 \text{ m}^3)}{(0.2870 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(295 \text{ K})} = 141.7 \text{ kg}$$

Taking the contents of the room, including the water, as our system, the energy balance can be written as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc. energies}} \rightarrow 0 = \Delta U = (\Delta U)_{\text{water}} + (\Delta U)_{\text{air}}$$

$$\text{or} \quad [mC(T_2 - T_1)]_{\text{water}} + [mC_v(T_2 - T_1)]_{\text{air}} = 0$$

Substituting,

$$(1000 \text{ kg})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(T_f - 80)^\circ\text{C} + (141.7 \text{ kg})(0.718 \text{ kJ/kg} \cdot ^\circ\text{C})(T_f - 22)^\circ\text{C} = 0$$

It gives the final equilibrium temperature in the room to be

$$T_f = 78.6^\circ\text{C}$$

(*h*) Considering that the system is well-insulated and no mass is entering and leaving, the total entropy change during this process is the sum of the entropy changes of water and the room air,

$$\Delta S_{\text{total}} = S_{\text{gen}} = \Delta S_{\text{air}} + \Delta S_{\text{water}}$$

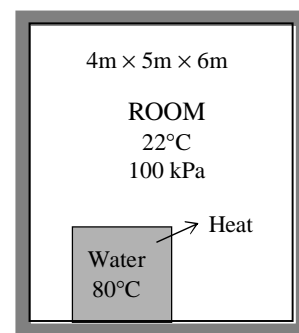
where

$$\Delta S_{\text{air}} = mC_v \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1} = (141.7 \text{ kg})(0.718 \text{ kJ/kg} \cdot \text{K}) \ln \frac{351.6 \text{ K}}{295 \text{ K}} = 17.86 \text{ kJ/K}$$

$$\Delta S_{\text{water}} = mC \ln \frac{T_2}{T_1} = (1000 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{351.6 \text{ K}}{353 \text{ K}} = -16.61 \text{ kJ/K}$$

Substituting, the total entropy change is determined to be

$$\Delta S_{\text{total}} = 17.86 - 16.61 = 1.25 \text{ kJ/K}$$



7-141E A cylinder initially filled with helium gas at a specified state is compressed polytropically to a specified temperature and pressure. The entropy changes of the helium and the surroundings are to be determined, and it is to be assessed if the process is reversible, irreversible, or impossible.

Assumptions **1** Helium is an ideal gas with constant specific heats. **2** The cylinder is stationary and thus the kinetic and potential energy changes are negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

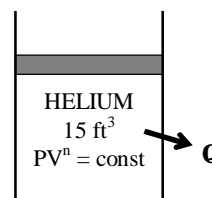
Properties The gas constant of helium is $R = 2.6805 \text{ psia} \cdot \text{ft}^3 / \text{lbm} \cdot \text{R} = 0.4961 \text{ Btu} / \text{lbm} \cdot \text{R}$ (Table A-1E). The specific heats of helium are $C_v = 0.753$ and $C_p = 1.25 \text{ Btu} / \text{lbm} \cdot \text{R}$ (Table A-2E).

Analysis (a) The mass of helium is

$$m = \frac{PV_1}{RT_1} = \frac{(25 \text{ psia})(15 \text{ ft}^3)}{(2.6805 \text{ psia} \cdot \text{ft}^3 / \text{lbm} \cdot \text{R})(530 \text{ R})} = 0.264 \text{ lbm}$$

Then the entropy change of helium becomes

$$\begin{aligned} \Delta S_{\text{sys}} = \Delta S_{\text{helium}} &= m \left[C_{p, \text{ave}} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \right] \\ &= (0.264 \text{ lbm}) \left[(1.25 \text{ Btu} / \text{lbm} \cdot \text{R}) \ln \frac{760 \text{ R}}{530 \text{ R}} - (0.4961 \text{ Btu} / \text{lbm} \cdot \text{R}) \ln \frac{70 \text{ psia}}{25 \text{ psia}} \right] = -0.016 \text{ Btu} / \text{R} \end{aligned}$$



(b) The exponent n and the boundary work for this polytropic process are determined to be

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \longrightarrow V_2 = \frac{T_2}{T_1} \frac{P_1}{P_2} V_1 = \frac{(760 \text{ R})(25 \text{ psia})}{(530 \text{ R})(70 \text{ psia})} (15 \text{ ft}^3) = 7.682 \text{ ft}^3$$

$$P_2 V_2^n = P_1 V_1^n \longrightarrow \left(\frac{P_2}{P_1} \right) = \left(\frac{V_1}{V_2} \right)^n \longrightarrow \left(\frac{70}{25} \right) = \left(\frac{15}{7.682} \right)^n \longrightarrow n = 1.539$$

Then the boundary work for this polytropic process can be determined from

$$\begin{aligned} W_{b, \text{in}} &= - \int_1^2 P dV = - \frac{P_2 V_2 - P_1 V_1}{1 - n} = - \frac{m R (T_2 - T_1)}{1 - n} \\ &= - \frac{(0.264 \text{ lbm})(0.4961 \text{ Btu} / \text{lbm} \cdot \text{R})(760 - 530) \text{ R}}{1 - 1.539} = 55.9 \text{ Btu} \end{aligned}$$

We take the helium in the cylinder as the system, which is a closed system. Taking the direction of heat transfer to be from the cylinder, the energy balance for this stationary closed system can be expressed as

$$\begin{aligned} \cancel{E_{\text{in}}} - \cancel{E_{\text{out}}} &= \cancel{\Delta E_{\text{system}}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ -Q_{\text{out}} + W_{b, \text{in}} &= \Delta U = m(u_2 - u_1) \\ -Q_{\text{out}} &= m(u_2 - u_1) - W_{b, \text{in}} \\ Q_{\text{out}} &= W_{b, \text{in}} - mC_v(T_2 - T_1) \end{aligned}$$

Substituting,

$$Q_{\text{out}} = 55.9 \text{ Btu} - (0.264 \text{ lbm})(0.753 \text{ Btu} / \text{lbm} \cdot \text{R})(760 - 530) \text{ R} = 10.2 \text{ Btu}$$

Noting that the surroundings undergo a reversible isothermal process, its entropy change becomes

$$\Delta S_{\text{surr}} = \frac{Q_{\text{surr, in}}}{T_{\text{surr}}} = \frac{10.2 \text{ Btu}}{530 \text{ R}} = 0.019 \text{ Btu} / \text{R}$$

(c) Noting that the system+surroundings combination can be treated as an isolated system,

$$\Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} = -0.016 + 0.019 = 0.003 \text{ Btu} / \text{R} > 0$$

Therefore, the process is **irreversible**.

7-142 Air is compressed steadily by a compressor from a specified state to a specified pressure. The minimum power input required is to be determined for the cases of adiabatic and isothermal operation.

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 with variable specific heats. **4** The process is reversible since the work input to the compressor will be minimum when the compression process is reversible.

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

Analysis (a) For the adiabatic case, the process will be reversible and adiabatic (i.e., isentropic), thus the isentropic relations are applicable.

$$T_1 = 290 \text{ K} \longrightarrow P_{r1} = 1.2311 \text{ and } h_1 = 290.16 \text{ kJ/kg}$$

and

$$P_{r2} = \frac{P_2}{P_1} P_{r1} = \frac{700 \text{ kPa}}{100 \text{ kPa}} (1.2311) = 8.6177 \longrightarrow \begin{matrix} T_2 = 503.3 \text{ K} \\ h_2 = 506.45 \text{ kJ/kg} \end{matrix}$$

The energy balance for the compressor, which is a steady-flow system, can be expressed in the rate form as

$$\dot{E}_{in} = \dot{E}_{out} \quad \Delta \dot{E}_{system} = 0 \quad \dot{E}_{in} = \dot{E}_{out}$$

Rate of net energy transfer by heat, work, and mass Rate of change in internal, kinetic, potential, etc. energies

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

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

Substituting, the power input to the compressor is determined to be

$$\dot{W}_{in} = (5/60 \text{ kg/s})(506.45 - 290.16) \text{ kJ/kg} = 18.0 \text{ kW}$$

(b) In the case of the reversible isothermal process, the steady-flow energy balance becomes

$$\dot{E}_{in} = \dot{E}_{out} \longrightarrow \dot{W}_{in} + \dot{m}h_1 - \dot{Q}_{out} = \dot{m}h_2 \longrightarrow \dot{W}_{in} = \dot{Q}_{out} + \dot{m}(h_2 - h_1) \stackrel{\Delta 0}{=} \dot{Q}_{out}$$

since $h = h(T)$ for ideal gases, and thus the enthalpy change in this case is zero. Also, for a reversible isothermal process,

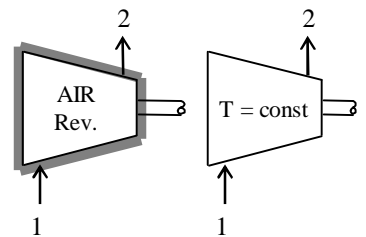
$$\dot{Q}_{out} = \dot{m}T(s_1 - s_2) = -\dot{m}T(s_2 - s_1)$$

where

$$s_2 - s_1 = (s_2^0 - s_1^0) - R \ln \frac{P_2}{P_1} = -R \ln \frac{P_2}{P_1} = -(0.287 \text{ kJ/kg} \cdot \text{K}) \ln \frac{700 \text{ kPa}}{100 \text{ kPa}} = -0.5585 \text{ kJ/kg} \cdot \text{K}$$

Substituting, the power input for the reversible isothermal case becomes

$$\dot{W}_{in} = -(5/60 \text{ kg/s})(290 \text{ K})(-0.5585 \text{ kJ/kg} \cdot \text{K}) = 13.5 \text{ kW}$$



7-143 Air is compressed in a two-stage ideal compressor with intercooling. For a specified mass flow rate of air, the power input to the compressor is to be determined, and it is to be compared to the power input to a single-stage compressor. \checkmark

Assumptions **1** The compressor operates steadily. **2** Kinetic and potential energies are negligible. **3** The compression process is reversible adiabatic, and thus isentropic. **4** Air is an ideal gas with constant specific heats at room temperature.

Properties The gas constant of air is $R=0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$ (Table A-1). The specific heat ratio of air is $k=1.4$ (Table A-2)

Analysis The intermediate pressure between the two stages is

$$P_x = \sqrt{P_1 P_2} = \sqrt{(100 \text{ kPa})(900 \text{ kPa})} = 300 \text{ kPa}$$

The compressor work across each stage is the same, thus total compressor work is twice the compression work for a single stage:

$$\begin{aligned} w_{\text{comp},in} &= (2)(w_{\text{comp},in,I}) = 2 \frac{kRT}{k-1} \left(\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right) \\ &= 2 \frac{(1.4)(0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})}{1.4-1} \left(\left(\frac{300 \text{ kPa}}{100 \text{ kPa}} \right)^{0.4/1.4} - 1 \right) \\ &= 222.2 \text{ kJ/kg} \end{aligned}$$

and

$$\dot{W}_{in} = \dot{m} w_{\text{comp},in} = (0.02 \text{ kg/s})(222.2 \text{ kJ/kg}) = \mathbf{4.44 \text{ kW}}$$

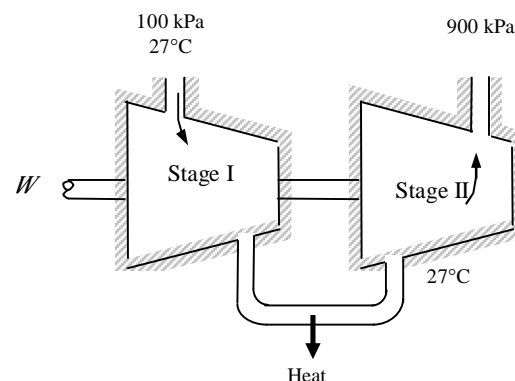
The work input to a single-stage compressor operating between the same pressure limits would be

$$w_{\text{comp},in} = \frac{kRT}{k-1} \left(\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right) = \frac{(1.4)(0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})}{1.4-1} \left(\left(\frac{900 \text{ kPa}}{100 \text{ kPa}} \right)^{0.4/1.4} - 1 \right) = 263.2 \text{ kJ/kg}$$

and

$$\dot{W}_{in} = \dot{m} w_{\text{comp},in} = (0.02 \text{ kg/s})(263.2 \text{ kJ/kg}) = \mathbf{5.26 \text{ kW}}$$

Discussion Note that the power consumption of the compressor decreases significantly by using 2-stage compression with intercooling.



7-144 A three-stage compressor with two stages of intercooling is considered. The two intermediate pressures that will minimize the work input are to be determined in terms of the inlet and exit pressures.

Analysis The work input to this three-stage compressor with intermediate pressures P_x and P_y and two intercoolers can be expressed as

$$\begin{aligned}
 W_{comp} &= W_{comp,I} + W_{comp,II} + W_{comp,III} \\
 &= \frac{nRT_1}{n-1} \left(1 - (P_x/P_1)^{(n-1)/n} \right) + \frac{nRT_1}{n-1} \left(1 - (P_y/P_x)^{(n-1)/n} \right) + \frac{nRT_1}{n-1} \left(1 - (P_2/P_y)^{(n-1)/n} \right) \\
 &= \frac{nRT_1}{n-1} \left(1 - (P_x/P_1)^{(n-1)/n} + 1 - (P_y/P_x)^{(n-1)/n} + 1 - (P_2/P_y)^{(n-1)/n} \right) \\
 &= \frac{nRT_1}{n-1} \left(3 - (P_x/P_1)^{(n-1)/n} - (P_y/P_x)^{(n-1)/n} - (P_2/P_y)^{(n-1)/n} \right)
 \end{aligned}$$

The P_x and P_y values that will minimize the work input are obtained by taking the partial differential of W with respect to P_x and P_y , and setting them equal to zero:

$$\begin{aligned}
 \frac{\partial W}{\partial P_x} = 0 &\longrightarrow -\frac{n-1}{n} \left(\frac{1}{P_1} \right) \left(\frac{P_x}{P_1} \right)^{\frac{n-1}{n}-1} + \frac{n-1}{n} \left(\frac{1}{P_y} \right) \left(\frac{P_x}{P_y} \right)^{-\frac{n-1}{n}-1} = 0 \\
 \frac{\partial W}{\partial P_y} = 0 &\longrightarrow -\frac{n-1}{n} \left(\frac{1}{P_x} \right) \left(\frac{P_y}{P_x} \right)^{\frac{n-1}{n}-1} + \frac{n-1}{n} \left(\frac{1}{P_2} \right) \left(\frac{P_y}{P_2} \right)^{-\frac{n-1}{n}-1} = 0
 \end{aligned}$$

Simplifying,

$$\begin{aligned}
 \frac{1}{P_1} \left(\frac{P_x}{P_1} \right)^{-\frac{1}{n}} &= \frac{1}{P_y} \left(\frac{P_x}{P_y} \right)^{-\frac{2n-1}{n}} \longrightarrow \frac{1}{P_1^n} \left(\frac{P_x}{P_1} \right) = \frac{1}{P_y^n} \left(\frac{P_x}{P_y} \right)^{1-2n} \longrightarrow P_x^{2(1-n)} = (P_1 P_y)^{1-n} \\
 \frac{1}{P_x} \left(\frac{P_y}{P_x} \right)^{-\frac{1}{n}} &= \frac{1}{P_2} \left(\frac{P_y}{P_2} \right)^{-\frac{2n-1}{n}} \longrightarrow \frac{1}{P_x^n} \left(\frac{P_y}{P_x} \right) = \frac{1}{P_2^n} \left(\frac{P_y}{P_2} \right)^{1-2n} \longrightarrow P_y^{2(1-n)} = (P_x P_2)^{1-n}
 \end{aligned}$$

which yield

$$\begin{aligned}
 P_x^2 &= P_1 \sqrt{P_x P_2} \longrightarrow P_x = (P_1^2 P_2)^{1/3} \\
 P_y^2 &= P_2 \sqrt{P_1 P_y} \longrightarrow P_y = (P_1 P_2^2)^{1/3}
 \end{aligned}$$

7-145 Steam expands in a two-stage adiabatic turbine from a specified state to specified pressure. Some steam is extracted at the end of the first stage. The power output of the turbine is to be determined for the cases of 100% and 88% isentropic efficiencies.

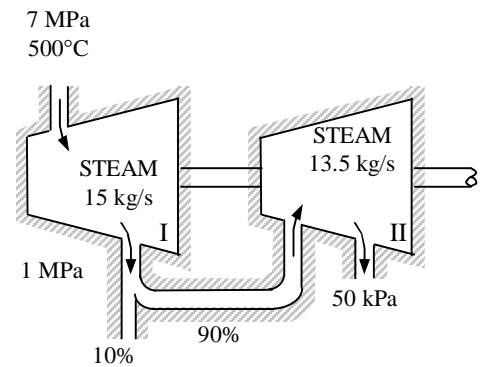
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** The turbine is adiabatic and thus heat transfer is negligible.

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

$$\begin{aligned} P_1 = 7 \text{ MPa} \quad \left\{ \begin{array}{l} h_1 = 3410.3 \text{ kJ/kg} \\ s_1 = 6.7975 \text{ kJ/kg} \cdot \text{K} \end{array} \right. \\ T_1 = 500^\circ \text{C} \end{aligned}$$

$$\begin{aligned} P_2 = 1 \text{ MPa} \quad \left\{ \begin{array}{l} h_2 = 2879.4 \text{ kJ/kg} \\ s_2 = s_1 \end{array} \right. \end{aligned}$$

$$\begin{aligned} P_3 = 50 \text{ kPa} \quad \left\{ \begin{array}{l} x_{3,s} = \frac{s_{3,s} - s_f}{s_{fg}} = \frac{6.7975 - 1.0910}{6.5029} = 0.8775 \\ s_3 = s_1 \end{array} \right. \\ h_{3,s} = h_f + x_{3,s} h_{fg} = 340.49 + (0.8775)(2305.4) = 2363.5 \text{ kJ/kg} \end{aligned}$$



Analysis (a) The mass flow rate through the second stage is

$$\dot{m}_3 = 0.9 \dot{m}_1 = (0.9)(15 \text{ kg/s}) = 13.5 \text{ kg/s}$$

We take the entire turbine, including the connection part between the two stages, as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters the turbine and two fluid streams leave, the energy balance for this steady-flow system can be expressed in the rate form as

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \Delta \dot{E}_{system} \quad \dot{A}0 \text{ (steady)} = 0 \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{m}_1 h_1 &= (\dot{m}_1 - \dot{m}_3) h_2 + \dot{m}_3 h_3 \\ \dot{m}_3 h_3 &= \dot{m}_1 h_1 - (\dot{m}_1 - \dot{m}_3) h_2 + \dot{m}_3 h_3 \\ &= \dot{m}_1 (h_1 - h_2) + \dot{m}_3 (h_2 - h_3) \end{aligned}$$

Substituting, the power output of the turbine is

$$\begin{aligned} \dot{W}_{out} &= (15 \text{ kg/s})(3410.3 - 2879.4) \text{ kJ/kg} + (13.5 \text{ kg/s})(2879.4 - 2363.5) \text{ kJ/kg} \\ &= \mathbf{14,930 \text{ kW}} \end{aligned}$$

(b) If the turbine has an adiabatic efficiency of 88%, then the power output becomes

$$\dot{W}_a = \eta_T \dot{W}_s = (0.88)(14,928 \text{ kW}) = \mathbf{13,140 \text{ kW}}$$

7-146 Steam expands in an 84% efficient two-stage adiabatic turbine from a specified state to a specified pressure. Steam is reheated between the stages. For a given power output, the mass flow rate of steam through the turbine 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** The turbine is adiabatic and thus heat transfer is negligible.

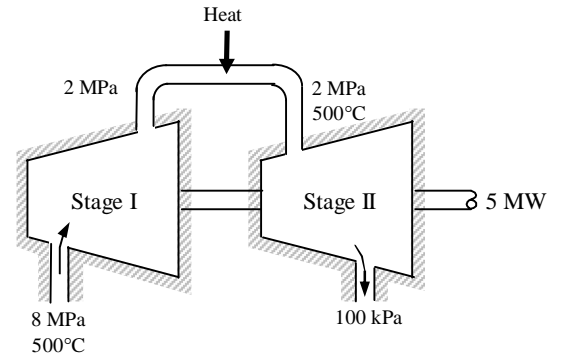
Properties From the steam tables (Tables A-4 through 6)

$$\begin{aligned} P_1 &= 8 \text{ MPa} \quad \left\{ \begin{aligned} h_1 &= 3398.3 \text{ kJ/kg} \\ T_1 &= 500^\circ\text{C} \end{aligned} \right. \quad \left\{ \begin{aligned} s_1 &= 6.7240 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned}$$

$$\begin{aligned} P_{2s} &= 2 \text{ MPa} \quad \left\{ \begin{aligned} h_{2s} &= 3000.3 \text{ kJ/kg} \\ s_{2s} &= s_1 \end{aligned} \right. \end{aligned}$$

$$\begin{aligned} P_3 &= 2 \text{ MPa} \quad \left\{ \begin{aligned} h_3 &= 3467.6 \text{ kJ/kg} \\ T_3 &= 500^\circ\text{C} \end{aligned} \right. \quad \left\{ \begin{aligned} s_3 &= 7.4317 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \end{aligned}$$

$$\begin{aligned} P_{4s} &= 100 \text{ kPa} \quad \left\{ \begin{aligned} h_{4s} &= 2704.2 \text{ kJ/kg} \\ s_{4s} &= s_3 \end{aligned} \right. \end{aligned}$$



Analysis The power output of the actual turbine is given to be 80 MW. Then the power output for the isentropic operation becomes

$$\dot{W}_{s,out} = \dot{W}_{a,out} / \eta_T = (80,000 \text{ kW}) / 0.84 = 95,240 \text{ kW}$$

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

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \Delta \dot{E}_{system} \quad \dot{A}0 \text{ (steady)} = 0 \\ \text{Rate of net energy transfer} & \quad \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ \dot{m}h_1 + \dot{m}h_3 &= \dot{m}h_{2s} + \dot{m}h_{4s} + \dot{W}_{s,out} \\ \dot{W}_{s,out} &= \dot{m}[(h_1 - h_{2s}) + (h_3 - h_{4s})] \end{aligned}$$

Substituting,

$$95,240 \text{ kJ/s} = \dot{m}[(3398.3 - 3000.3) + (3467.6 - 2704.2) \text{ kJ/kg}]$$

which gives

$$\dot{m} = 82.0 \text{ kg/s}$$

7-147 Refrigerant-134a is compressed by a 0.5-kW adiabatic compressor from a specified state to another specified state. The isentropic efficiency, the volume flow rate at the inlet, and the maximum flow rate at the compressor inlet are to be determined.

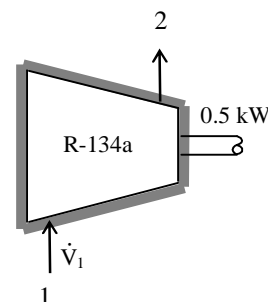
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** The device is adiabatic and thus heat transfer is negligible.

Properties From the R-134a tables (Tables A-11 through A-13)

$$\left. \begin{aligned} P_1 &= 140 \text{ kPa} \\ T_1 &= -10^\circ \text{C} \end{aligned} \right\} \begin{aligned} v_1 &= 0.14549 \text{ m}^3/\text{kg} \\ h_1 &= 243.40 \text{ kJ/kg} \\ s_1 &= 0.9606 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

$$\left. \begin{aligned} P_2 &= 700 \text{ kPa} \\ T_2 &= 60^\circ \text{C} \end{aligned} \right\} h_2 = 296.69 \text{ kJ/kg}$$

$$\left. \begin{aligned} P_2 &= 700 \text{ kPa} \\ s_{2,s} &= s_1 \end{aligned} \right\} h_{2,s} = 278.06 \text{ kJ/kg}$$



Analysis (a) The isentropic efficiency is determined from its definition,

$$\eta_C = \frac{h_{2,s} - h_1}{h_{2,a} - h_1} = \frac{278.06 - 243.40}{296.69 - 243.40} = 0.650 = \mathbf{65.0\%}$$

(b) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual compressor as the system, which is a control volume. The energy balance for this steady-flow system can be expressed as

$$\begin{aligned} \dot{Q} - \dot{W} &= \dot{E}_{\text{system}} \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic, potential, etc. energies} \\ \dot{Q} - \dot{W} &= 0 \quad (\text{steady}) \\ \dot{Q} &= \dot{W} \\ \dot{m}h_1 + \dot{Q} &= \dot{m}h_2 \quad (\text{since } \dot{Q} \equiv \Delta ke \equiv \Delta pe \equiv 0) \\ \dot{m}h_1 &= \dot{m}(h_2 - h_1) \end{aligned}$$

Then the mass and volume flow rates of the refrigerant are determined to be

$$\begin{aligned} \dot{m} &= \frac{\dot{W}_{a,\text{in}}}{h_{2,a} - h_1} = \frac{0.5 \text{ kJ/s}}{(296.69 - 243.40) \text{ kJ/kg}} = 0.0094 \text{ kg/s} \\ \dot{V}_1 &= \dot{m}v_1 = (0.0094 \text{ kg/s})(0.14549 \text{ m}^3/\text{kg}) = 0.00137 \text{ m}^3/\text{s} = \mathbf{82 \text{ L/min}} \end{aligned}$$

(c) The volume flow rate will be a maximum when the process is isentropic, and it is determined similarly from the steady-flow energy equation applied to the isentropic process. It gives

$$\begin{aligned} \dot{m}_{\text{max}} &= \frac{\dot{W}_{s,\text{in}}}{h_{2,s} - h_1} = \frac{0.5 \text{ kJ/s}}{(278.06 - 243.40) \text{ kJ/kg}} = 0.0144 \text{ kg/s} \\ \dot{V}_{1,\text{max}} &= \dot{m}_{\text{max}} v_1 = (0.0144 \text{ kg/s})(0.14549 \text{ m}^3/\text{kg}) = 0.00210 \text{ m}^3/\text{s} = \mathbf{126 \text{ L/min}} \end{aligned}$$

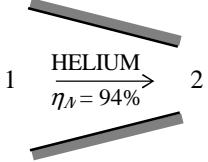
Discussion Note that the raising the isentropic efficiency of the compressor to 100% would increase the volumetric flow rate by more than 50%.

7-148E Helium is accelerated by a 94% efficient nozzle from a low velocity to 1000 ft/s. The pressure and temperature at the nozzle inlet are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Helium 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.

Properties The specific heat ratio of helium is $k = 1.667$. The constant pressure specific heat of helium is 1.25 Btu/lbm·R (Table A-2E).

Analysis 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

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \dot{E}_{system} \quad \dot{E}_{system} = 0 \quad \dot{E}_{in} = \dot{E}_{out} \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic, potential, etc. energies} \\ \dot{E}_{in} &= \dot{E}_{out} \\ h_1 + V_1^2/2 &= h_2 + V_2^2/2 \quad (\text{since } \dot{Q} = \dot{W} = \Delta p e = 0) \\ 0 &= h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} \longrightarrow 0 = C_{p,ave}(T_2 - T_1) + \frac{V_2^2 - V_1^2}{2} \end{aligned}$$


Solving for T_1 and substituting,

$$T_1 = T_{2,a} + \frac{V_2^2 - V_1^2}{2C_p} = 180^\circ\text{F} + \frac{(1000\text{ft/s})^2}{2(1.25\text{Btu/lbm}\cdot\text{R})} \left(\frac{1\text{Btu/lbm}}{25,037\text{ft}^2/\text{s}^2} \right) = \mathbf{196.0^\circ\text{F} = 656\text{R}}$$

From the isentropic efficiency relation,

$$\eta_N = \frac{h_{2,a} - h_1}{h_{2,s} - h_1} = \frac{C_p(T_{2,a} - T_1)}{C_p(T_{2,s} - T_1)}$$

or,

$$T_{2,s} = T_1 + (T_{2,a} - T_1)/\eta_N = 656 + (640 - 656)/(0.94) = 639\text{R}$$

From the isentropic relation, $\frac{T_{2,s}}{T_1} = \left(\frac{P_2}{P_1} \right)^{(k-1)/k}$

$$P_1 = P_2 \left(\frac{T_1}{T_{2,s}} \right)^{k/(k-1)} = (14\text{ psia}) \left(\frac{656\text{ R}}{639\text{ R}} \right)^{1.667/0.667} = \mathbf{14.9\text{ psia}}$$

7-149 [Also solved by EES on enclosed CD] An adiabatic compressor is powered by a direct-coupled steam turbine, which also drives a generator. The net power delivered to the generator and the rate of entropy generation 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 devices are adiabatic and thus heat transfer is negligible. **4** Air is an ideal gas with variable specific heats.

Properties From the steam tables (Tables A-4 through 6) and air table (Table A-17),

$$\begin{aligned} T_1 &= 295 \text{ K} \longrightarrow h_1 = 295.17 \text{ kJ/kg}, s_1^0 = 1.68515 \text{ kJ/kg} \cdot \text{K} \\ T_2 &= 620 \text{ K} \longrightarrow h_2 = 628.07 \text{ kJ/kg}, s_2^0 = 2.44356 \text{ kJ/kg} \cdot \text{K} \\ P_3 &= 12.5 \text{ MPa} \left\{ \begin{aligned} h_3 &= 3341.8 \text{ kJ/kg} \\ s_3 &= 6.4618 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \\ T_3 &= 500^\circ \text{C} \\ P_4 &= 10 \text{ kPa} \left\{ \begin{aligned} h_4 &= h_f + x_4 h_{fg} = 191.83 + (0.92)(2392.8) = 2393.2 \text{ kJ/kg} \\ s_4 &= s_f + x_4 s_{fg} = 0.6493 + (0.92)(7.5009) = 7.5501 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right. \\ x_4 &= 0.92 \end{aligned}$$

Analysis There is only one inlet and one exit for either device, and thus $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$. We take either the turbine or the compressor as the system, which is a control volume since mass crosses the boundary. The energy balance for either steady-flow system can be expressed in the rate form as

$$\begin{aligned} \dot{E}_{in} - \dot{E}_{out} &= \Delta \dot{E}_{system} \\ \text{Rate of net energy transfer} &= \text{Rate of change in internal, kinetic,} \\ \text{by heat, work, and mass} &\quad \text{potential, etc. energies} \end{aligned}$$

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

For the turbine and the compressor it becomes

Compressor: $\dot{m}_{comp, in} h_1 = \dot{m}_{air} h_2 \rightarrow \dot{m}_{comp, in} = \dot{m}_{air} (h_2 - h_1)$

Turbine: $\dot{m}_{steam} h_3 = \dot{m}_{turb, out} h_4 \rightarrow \dot{m}_{turb, out} = \dot{m}_{steam} (h_3 - h_4)$

Substituting,

$$\begin{aligned} \dot{m}_{comp, in} &= (10 \text{ kg/s})(628.07 - 295.17) \text{ kJ/kg} = 3329 \text{ kW} \\ \dot{m}_{turb, out} &= (25 \text{ kg/s})(3341.8 - 2393.2) \text{ kJ/kg} = 23,715 \text{ kW} \end{aligned}$$

Therefore,

$$\dot{W}_{net, out} = \dot{W}_{turb, out} - \dot{W}_{comp, in} = 23,715 - 3329 = \mathbf{20,386 \text{ kW}}$$

Noting that the system is adiabatic, the total rate of entropy change (or generation) during this process is the sum of the entropy changes of both fluids,

$$\dot{S}_{gen} = \dot{m}_{air}(s_2 - s_1) + \dot{m}_{steam}(s_4 - s_3)$$

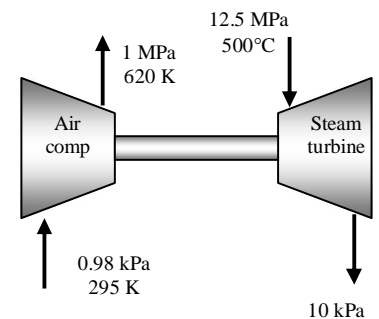
where

$$\dot{m}_{air}(s_2 - s_1) = \dot{m} \left(s_2^0 - s_1^0 - R \ln \frac{P_2}{P_1} \right) = (10 \text{ kg/s}) \left(2.44356 - 1.68515 - 0.287 \ln \frac{1000 \text{ kPa}}{98 \text{ kPa}} \right) \text{ kJ/kg} \cdot \text{K} = 0.92 \text{ kW/K}$$

$$\dot{m}_{steam}(s_4 - s_3) = (25 \text{ kg/s})(7.5501 - 6.4618) \text{ kJ/kg} \cdot \text{K} = 27.2 \text{ kW/K}$$

Substituting, the total rate of entropy generation is determined to be

$$\dot{S}_{gen, total} = \dot{S}_{gen, comp} + \dot{S}_{gen, turb} = 0.92 + 27.2 = \mathbf{28.12 \text{ kW/K}}$$



7-150 Problem 7-149 is reconsidered. The isentropic efficiencies for the compressor and turbine are to be determined, and then the effect of varying the compressor efficiency over the range 0.6 to 0.8 and the turbine efficiency over the range 0.7 to 0.95 on the net work for the cycle and the entropy generated for the process is to be investigated. The net work is to be plotted as a function of the compressor efficiency for turbine efficiencies of 0.7, 0.8, and 0.9.

"Input Data"

```
m_dot_air = 10"kg/s" "air compressor (air) data"
T_air[1]=(295-273)"C" "We will input temperature in C"
P_air[1]=98"kPa"
T_air[2]=(700-273) "C"
P_air[2]=1000"kPa"
m_dot_st=25"kg/s" "steam turbine (st) data"
T_st[1]=500"C"
P_st[1]=12500"kPa"
P_st[2]=10"kPa"
x_st[2]=0.92"quality"
```

"Compressor Analysis:"

"Conservation of mass for the compressor $m_{\dot{\text{air}}_{\text{in}}} = m_{\dot{\text{air}}_{\text{out}}} = m_{\dot{\text{air}}}$ "

"Conservation of energy for the compressor is:"

```
E_dot_comp_in - E_dot_comp_out = DELTAE_dot_comp
DELTAE_dot_comp = 0 "Steady flow requirement"
E_dot_comp_in = m_dot_air*(enthalpy(air,T=T_air[1])) + W_dot_comp_in
E_dot_comp_out = m_dot_air*(enthalpy(air,T=T_air[2]))
```

"Compressor adiabatic efficiency:"

```
Eta_comp = W_dot_comp_in_isen / W_dot_comp_in
W_dot_comp_in_isen = m_dot_air*(enthalpy(air,T=T_air_isen[2]) - enthalpy(air,T=T_air[1]))
s_air[1] = entropy(air,T=T_air[1],P=P_air[1])
s_air[2] = entropy(air,T=T_air[2],P=P_air[2])
s_air_isen[2] = entropy(air,T=T_air_isen[2],P=P_air[2])
s_air_isen[2] = s_air[1]
```

"Turbine Analysis:"

"Conservation of mass for the turbine $m_{\dot{\text{st}}_{\text{in}}} = m_{\dot{\text{st}}_{\text{out}}} = m_{\dot{\text{st}}}$ "

"Conservation of energy for the turbine is:"

```
E_dot_turb_in - E_dot_turb_out = DELTAE_dot_turb
DELTAE_dot_turb = 0 "Steady flow requirement"
E_dot_turb_in = m_dot_st*h_st[1]
h_st[1] = enthalpy(steam,T=T_st[1],P=P_st[1])
E_dot_turb_out = m_dot_st*h_st[2] + W_dot_turb_out
h_st[2] = enthalpy(steam,P=P_st[2],x=x_st[2])
```

"Turbine adiabatic efficiency:"

```
Eta_turb = W_dot_turb_out / W_dot_turb_out_isen
W_dot_turb_out_isen = m_dot_st*(h_st[1] - h_st_isen[2])
s_st[1] = entropy(steam,T=T_st[1],P=P_st[1])
h_st_isen[2] = enthalpy(steam,P=P_st[2],s=s_st[1])
```

"Note: When E_{turb} is specified as an independent variable in the Parametric Table, the iteration process may put the steam state 2 in the superheat region, where the quality is undefined. Thus, $s_{\text{st}}[2]$, $T_{\text{st}}[2]$ are calculated at $P_{\text{st}}[2]$, $h_{\text{st}}[2]$ and not $P_{\text{st}}[2]$ and $x_{\text{st}}[2]$ "

```
s_st[2] = entropy(steam,P=P_st[2],h=h_st[2])
T_st[2] = temperature(steam,P=P_st[2],h=h_st[2])
s_st_isen[2] = s_st[1]
```

"Net work done by the process:"

$$W_{\dot{\text{net}}} = W_{\dot{\text{turb_out}}} - W_{\dot{\text{comp_in}}}$$

"Entropy generation:"

"Since both the compressor and turbine are adiabatic, and thus there is no heat transfer to the surroundings, the entropy generation for the two steady flow devices becomes:"

$$S_{\dot{\text{gen_comp}}} = m_{\dot{\text{air}}} (s_{\text{air}[2]} - s_{\text{air}[1]})$$

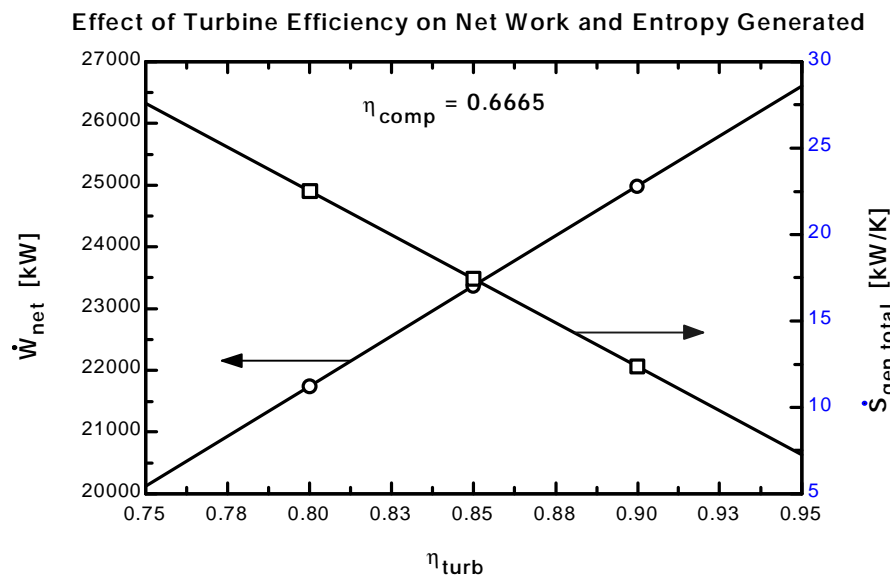
$$S_{\dot{\text{gen_turb}}} = m_{\dot{\text{st}}} (s_{\text{st}[2]} - s_{\text{st}[1]})$$

$$S_{\dot{\text{gen_total}}} = S_{\dot{\text{gen_comp}}} + S_{\dot{\text{gen_turb}}}$$

"To generate the data for Plot Window 1, Comment out the line 'T_air[2]=(700-273) C' and select values for Eta_comp in the Parametric Table, then press F3 to solve the table. EES then solves for the unknown value of T_air[2] for each Eta_comp."

"To generate the data for Plot Window 2, Comment out the two lines 'x_st[2]=0.92 quality' and 'h_st[2]=enthalpy(steam,P=P_st[2], x=x_st[2])' and select values for Eta_turb in the Parametric Table, then press F3 to solve the table. EES then solves for the h_st[2] for each Eta_turb."

W_{net} [kW]	S_{gentotal} [kW/K]	η_{turb}	η_{comp}
20124	27.59	0.75	0.6665
21745	22.51	0.8	0.6665
23365	17.44	0.85	0.6665
24985	12.36	0.9	0.6665
26606	7.281	0.95	0.6665



7-151 Two identical bodies at different temperatures are connected to each other through a heat engine. It is to be shown that the final common temperature of the two bodies will be $T_f = \sqrt{T_1 T_2}$ when the work output of the heat engine is maximum.

Analysis For maximum power production, the entropy generation must be zero. Taking the source, the sink, and the heat engine as our system, which is adiabatic, and noting that the entropy change for cyclic devices is zero, the entropy generation for this system can be expressed as

$$S_{gen} = (\Delta S)_{source} + (\Delta S)_{engine} + (\Delta S)_{sink} = 0$$

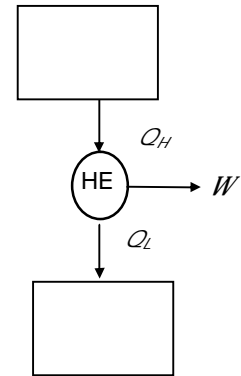
$$mC \ln \frac{T_f}{T_1} + 0 + mC \ln \frac{T_f}{T_2} = 0$$

$$\ln \frac{T_f}{T_1} + \ln \frac{T_f}{T_2} = 0 \longrightarrow \ln \frac{T_f^2}{T_1 T_2} = 0 \longrightarrow T_f^2 = T_1 T_2$$

and thus

$$T_f = \sqrt{T_1 T_2}$$

for maximum power production.



7-152 The pressure in a hot water tank rises to 2 MPa, and the tank explodes. The explosion energy of the water is to be determined, and expressed in terms of its TNT equivalence.

Assumptions **1** The expansion process during explosion is isentropic. **2** Kinetic and potential energy changes are negligible. **3** Heat transfer with the surroundings during explosion is negligible.

Properties The explosion energy of TNT is 3250 kJ/kg. From the steam tables (Tables A-4 through 6)

$$\begin{aligned}
 P_1 = 2 \text{ MPa} \quad \left. \begin{array}{l} \nu_1 = \nu_{f@2\text{MPa}} = 0.001177 \text{ m}^3/\text{kg} \\ u_1 = u_{f@2\text{MPa}} = 906.44 \text{ kJ/kg} \\ s_1 = s_{f@2\text{MPa}} = 2.4474 \text{ kJ/kg} \cdot \text{K} \end{array} \right\} \text{Sat. liquid} \\
 P_2 = 100 \text{ kPa} \quad \left\{ \begin{array}{l} u_f = 417.36, \quad u_{fg} = 2088.7 \text{ kJ/kg} \\ s_f = 1.3026, \quad s_{fg} = 6.0568 \text{ kJ/kg} \cdot \text{K} \end{array} \right. \\
 x_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{2.4474 - 1.3026}{6.0568} = 0.189
 \end{aligned}$$

$$u_2 = u_f + x_2 u_{fg} = 417.36 + (0.189)(2088.7) = 812.1 \text{ kJ/kg}$$

Water
Tank
2 MPa

Analysis We idealize the water tank as a closed system that undergoes a reversible adiabatic process with negligible changes in kinetic and potential energies. The work done during this idealized process represents the explosive energy of the tank, and is determined from the closed system energy balance to be

$$\begin{aligned}
 \cancel{142.43} \quad \cancel{142.43} \quad \cancel{142.43} \quad \cancel{142.43} \\
 \begin{array}{c} E_{\text{net}} \\ \text{Net energy transfer} \\ \text{by heat, work, and mass} \end{array} = \begin{array}{c} \Delta E_{\text{system}} \\ \text{Change in internal, kinetic,} \\ \text{potential, etc. energies} \end{array} \\
 -W_{b,\text{out}} = \Delta U = m(u_2 - u_1)
 \end{aligned}$$

$$E_{\text{exp}} = W_{b,\text{out}} = m(u_1 - u_2)$$

where

$$m = \frac{V}{\nu_1} = \frac{0.1 \text{ m}^3}{0.001177 \text{ m}^3/\text{kg}} = 85.0 \text{ kg}$$

Substituting,

$$E_{\text{exp}} = (85.0 \text{ kg})(906.44 - 812.1) \text{ kJ/kg} = 8019 \text{ kJ}$$

which is equivalent to

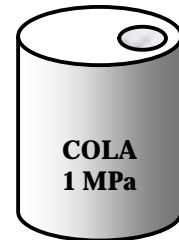
$$m_{\text{TNT}} = \frac{8019 \text{ kJ}}{3250 \text{ kJ/kg}} = \mathbf{2.47 \text{ kg TNT}}$$

7-153 A 0.2-L canned drink explodes at a pressure of 1 MPa. The explosive energy of the drink is to be determined, and expressed in terms of its TNT equivalence. ✓

Assumptions **1** The expansion process during explosion is isentropic. **2** Kinetic and potential energy changes are negligible. **3** Heat transfer with the surroundings during explosion is negligible. **4** The drink can be treated as pure water.

Properties The explosion energy of TNT is 3250 kJ/kg. From the steam tables (Tables A-4 through 6)

$$\begin{aligned}
 P_1 = 1 \text{ MPa} \quad \left\{ \begin{array}{l} v_1 = v_{f@1\text{MPa}} = 0.001127 \text{ m}^3/\text{kg} \\ u_1 = u_{f@1\text{MPa}} = 761.68 \text{ kJ/kg} \\ s_1 = s_{f@1\text{MPa}} = 2.1387 \text{ kJ/kg} \cdot \text{K} \end{array} \right. \\
 \text{Compl. liquid} \\
 P_2 = 100 \text{ kPa} \quad \left\{ \begin{array}{l} u_f = 417.36, \quad u_{fg} = 2088.7 \text{ kJ/kg} \\ s_f = 1.3026, \quad s_{fg} = 6.0568 \text{ kJ/kg} \cdot \text{K} \end{array} \right. \\
 s_2 = s_1 \\
 x_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{2.1387 - 1.3026}{6.0568} = 0.138
 \end{aligned}$$



$$u_2 = u_f + x_2 u_{fg} = 417.36 + (0.138)(2088.7) = 705.6 \text{ kJ/kg}$$

Analysis We idealize the canned drink as a closed system that undergoes a reversible adiabatic process with negligible changes in kinetic and potential energies. The work done during this idealized process represents the explosive energy of the can, and is determined from the closed system energy balance to be

$$\begin{aligned}
 \cancel{E_{in}} - \cancel{E_{out}} &= \cancel{\Delta E_{system}} \\
 \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\
 \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\
 -W_{h,out} &= \Delta U = m(u_2 - u_1)
 \end{aligned}$$

$$E_{\text{exp}} = W_{h,out} = m(u_1 - u_2)$$

where

$$m = \frac{V}{v_1} = \frac{0.0002 \text{ m}^3}{0.001127 \text{ m}^3/\text{kg}} = 0.177 \text{ kg}$$

Substituting,

$$E_{\text{exp}} = (0.177 \text{ kg})(761.68 - 705.6) \text{ kJ/kg} = \mathbf{9.9 \text{ kJ}}$$

which is equivalent to

$$m_{\text{TNT}} = \frac{9.9 \text{ kJ}}{3250 \text{ kJ/kg}} = \mathbf{0.00305 \text{ kg TNT}}$$

Review Problems (cont.)

7-154 The validity of the Clausius inequality is to be demonstrated using a reversible and an irreversible heat engine operating between the same temperature limits.

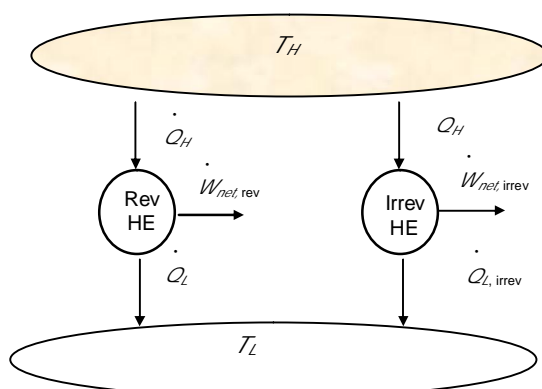
Analysis Consider two heat engines, one reversible and one irreversible, both operating between a high-temperature reservoir at T_H and a low-temperature reservoir at T_L . Both heat engines receive the same amount of heat, Q_H . The reversible heat engine rejects heat in the amount of Q_L and the irreversible one in the amount of $Q_{L, \text{irrev}} = Q_L + Q_{\text{diff}}$ where Q_{diff} is a positive quantity since the irreversible heat engine produces less work. Noting that Q_H and Q_L are transferred at constant temperatures of T_H and T_L respectively, the cyclic integral of $\delta Q/T$ for the reversible and irreversible heat engine cycles become

$$\oint \left(\frac{\delta Q}{T} \right)_{\text{rev}} = \int \frac{\delta Q_H}{T_H} - \int \frac{\delta Q_L}{T_L} = \frac{1}{T_H} \int \delta Q_H - \frac{1}{T_L} \int \delta Q_L = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = 0$$

since $(Q_H/T_H) = (Q_L/T_L)$ for reversible cycles. Also,

$$\oint \left(\frac{\delta Q}{T} \right)_{\text{irr}} = \frac{Q_H}{T_H} - \frac{Q_{L, \text{irrev}}}{T_L} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} - \frac{Q_{\text{diff}}}{T_L} = -\frac{Q_{\text{diff}}}{T_L} < 0$$

since Q_{diff} is a positive quantity. Thus, $\oint \left(\frac{\delta Q}{T} \right) \leq 0$.



7-155 The inner and outer surfaces of a window glass are maintained at specified temperatures. The amount of heat transfer through the glass and the amount of entropy generation within the glass in 5 h are to be determined

Assumptions **1** Steady operating conditions exist since the surface temperatures of the glass remain constant at the specified values. **2** Thermal properties of the glass are constant.

Analysis The amount of heat transfer over a period of 5 h is

$$Q = \dot{Q}_{cond} \Delta t = (3.2 \text{ kJ/s})(5 \times 3600 \text{ s}) = \mathbf{57,600 \text{ kJ}}$$

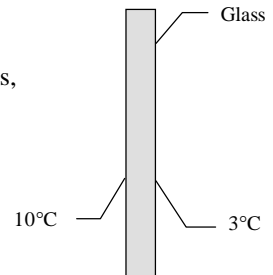
We take the glass to be the system, which is a closed system. Under steady conditions, the rate form of the entropy balance for the glass simplifies to

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \Delta \dot{S}_{system} = 0$$

Rate of net entropy transfer by heat and mass Rate of entropy generation Rate of change of entropy

$$\frac{\dot{Q}_{in}}{T_{b,in}} - \frac{\dot{Q}_{out}}{T_{b,out}} + \dot{S}_{gen,glass} = 0$$

$$\frac{3200 \text{ W}}{283 \text{ K}} - \frac{3200 \text{ W}}{276 \text{ K}} + \dot{S}_{gen,glass} = 0 \rightarrow \dot{S}_{gen,glass} = \mathbf{0.287 \text{ W/K}}$$



Then the amount of entropy generation over a period of 5 h becomes

$$S_{gen,glass} = \dot{S}_{gen,glass} \Delta t = (0.287 \text{ W/K})(5 \times 3600 \text{ s}) = \mathbf{5160 \text{ J/K}}$$

7-156 Two rigid tanks that contain water at different states are connected by a valve. The valve is opened and steam flows from tank A to tank B until the pressure in tank A drops to a specified value. Tank B loses heat to the surroundings. The final temperature in each tank and the entropy generated during this process are to be determined.

Assumptions **1** Tank A is insulated, and thus heat transfer is negligible. **2** The water that remains in tank A undergoes a reversible adiabatic process. **3** The thermal energy stored in the tanks themselves is negligible. **4** The system is stationary and thus kinetic and potential energy changes are negligible. **5** There are no work interactions.

Analysis (a) The steam in tank A undergoes a reversible, adiabatic process, and thus $s_2 = s_1$. From the steam tables (Tables A-4 through A-6),

Tank A :

$$\left. \begin{array}{l} P_1 = 400 \text{ kPa} \\ x_1 = 0.8 \end{array} \right\} \begin{array}{l} v_{1,A} = v_f + x_1 v_{fg} = 0.001084 + (0.8)(0.4625 - 0.001084) = 0.3702 \text{ m}^3/\text{kg} \\ u_{1,A} = u_f + x_1 u_{fg} = 604.31 + (0.8)(1949.3) = 2163.75 \text{ kJ/kg} \\ s_{1,A} = s_f + x_1 s_{fg} = 1.7766 + (0.8)(5.1193) = 5.8720 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_1 = 300 \text{ kPa} \\ s_2 = s_1 \\ (\text{sat. mixture}) \end{array} \right\} \begin{array}{l} T_{2,A} = T_{\text{sat}@300 kPa} = \mathbf{133.55^\circ \text{C}} \\ x_{2,A} = \frac{s_{2,A} - s_f}{s_{fg}} = \frac{5.8720 - 1.6718}{5.3201} = 0.790 \\ v_{2,A} = v_f + x_{2,A} v_{fg} = 0.001073 + (0.790)(0.6058 - 0.001073) = 0.479 \text{ m}^3/\text{kg} \\ u_{2,A} = u_f + x_{2,A} u_{fg} = 561.15 + (0.790)(1982.4 \text{ kJ/kg}) = 2127.2 \text{ kJ/kg} \end{array}$$

Tank B :

$$\left. \begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 250^\circ \text{C} \end{array} \right\} \begin{array}{l} v_{1,B} = 1.1988 \text{ m}^3/\text{kg} \\ u_{1,B} = 2731.2 \text{ kJ/kg} \\ s_{1,B} = 7.7086 \text{ kJ/kg} \cdot \text{K} \end{array}$$

The initial and the final masses in tank A are

$$m_{1,A} = \frac{V_A}{v_{1,A}} = \frac{0.2 \text{ m}^3}{0.3702 \text{ m}^3/\text{kg}} = 0.540 \text{ kg}$$

and

$$m_{2,A} = \frac{V_A}{v_{2,A}} = \frac{0.2 \text{ m}^3}{0.479 \text{ m}^3/\text{kg}} = 0.418 \text{ kg}$$

Thus, $0.540 - 0.418 = 0.122 \text{ kg}$ of mass flows into tank B. Then,

$$m_{2,B} = m_{1,B} - 0.122 = 3 + 0.122 = 3.122 \text{ kg}$$

The final specific volume of steam in tank B is determined from

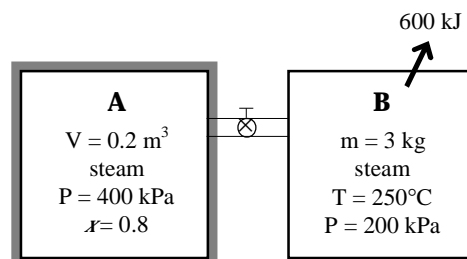
$$v_{2,B} = \frac{V_B}{m_{2,B}} = \frac{(m_1 v_1)_B}{m_{2,B}} = \frac{(3 \text{ kg})(1.1988 \text{ m}^3/\text{kg})}{3.122 \text{ m}^3} = 1.152 \text{ m}^3/\text{kg}$$

We take the entire contents of both tanks as the system, which is a closed system. The energy balance for this stationary closed system can be expressed as

$$\begin{aligned} \cancel{E_{1,A}} + \cancel{E_{1,B}} &= \cancel{E_{2,A}} + \cancel{E_{2,B}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ -Q_{\text{out}} &= \Delta U = (\Delta U)_A + (\Delta U)_B \quad (\text{since } W = \text{KE} = \text{PE} = 0) \\ -Q_{\text{out}} &= (m_2 u_2 - m_1 u_1)_A + (m_2 u_2 - m_1 u_1)_B \end{aligned}$$

Substituting,

$$\begin{aligned} -600 &= \{(0.418)(2127.2) - (0.540)(2163.8)\} + \{(3.122)u_{2,B} - (3)(2731.2)\} \\ u_{2,B} &= 2521.7 \text{ kJ/kg} \end{aligned}$$



Thus,

$$\left. \begin{aligned} v_{2,B} &= 1.152 \text{ m}^3/\text{kg} \\ u_{2,B} &= 2521.7 \text{ kJ/kg} \end{aligned} \right\} \begin{aligned} T_{2,B} &= \mathbf{113^\circ \text{C}} \\ s_{2,B} &= 7.225 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

(*b*) The total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes both tanks and their immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. It gives

$$\underbrace{\sum \dot{Q}_j/T_j}_{\text{Net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{\text{gen}}}_{\text{Entropy generation}} = \underbrace{\Delta \dot{S}_{\text{system}}}_{\text{Change in entropy}}$$

$$-\frac{\dot{Q}_{\text{out}}}{T_{b,\text{surr}}} + \dot{S}_{\text{gen}} = \Delta S_A + \Delta S_B$$

Rearranging and substituting, the total entropy generated during this process is determined to be

$$\begin{aligned} S_{\text{gen}} &= \Delta S_A + \Delta S_B + \frac{\dot{Q}_{\text{out}}}{T_{b,\text{surr}}} = (m_2 s_2 - m_1 s_1)_A + (m_2 s_2 - m_1 s_1)_B + \frac{\dot{Q}_{\text{out}}}{T_{b,\text{surr}}} \\ &= \{(0.418)(5.872) - (0.540)(5.872)\} + \{(3.122)(7.225) - (3)(7.7086)\} + \frac{600 \text{ kJ}}{273 \text{ K}} \\ &= \mathbf{0.912 \text{ kJ/K}} \end{aligned}$$

7-157 Heat is transferred steadily to boiling water in a pan through its bottom. The rate of entropy generation within the bottom plate is to be determined.

Assumptions Steady operating conditions exist since the surface temperatures of the pan remain constant at the specified values.

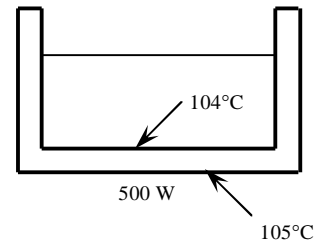
Analysis We take the bottom of the pan to be the system, which is a closed system. Under steady conditions, the rate form of the entropy balance for this system can be expressed as

$$\dot{\mathcal{S}}_{in} - \dot{\mathcal{S}}_{out} + \dot{\mathcal{S}}_{gen} = \Delta \dot{\mathcal{S}}_{system} = 0$$

Rate of net entropy transfer by heat and mass Rate of entropy generation Rate of change of entropy

$$\frac{\dot{\mathcal{S}}_{in}}{T_{b,in}} - \frac{\dot{\mathcal{S}}_{out}}{T_{b,out}} + \dot{\mathcal{S}}_{gen,system} = 0$$

$$\frac{800 \text{ W}}{378 \text{ K}} - \frac{800 \text{ W}}{377 \text{ K}} + \dot{\mathcal{S}}_{gen,system} = 0 \rightarrow \dot{\mathcal{S}}_{gen,system} = \mathbf{0.0056 \text{ W/K}}$$



Discussion Note that there is a small temperature drop across the bottom of the pan, and thus a small amount of entropy generation.

7-158 An electric resistance heater is immersed in water. The time it will take for the electric heater to raise the water temperature to a specified temperature and the entropy generated during this process are to be determined.

Assumptions **1** Water is an incompressible substance with constant specific heats. **2** The energy stored in the container itself and the heater is negligible. **3** Heat loss from the container is negligible.

Properties The specific heat of water at room temperature is $C = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3).

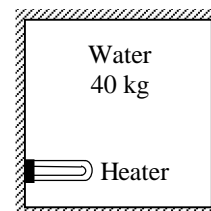
Analysis Taking the water in the container as the system, which is a closed system, the energy balance can be expressed as

$$\cancel{E_{in}} - \cancel{E_{out}} = \Delta E_{\text{system}}$$

Net energy transfer Change in internal, kinetic,
by heat, work, and mass potential, etc. energies

$$W_{e,in} = (\Delta U)_{\text{water}}$$

$$\cancel{W_{e,in}} \Delta t = mC(T_2 - T_1)_{\text{water}}$$



Substituting,

$$(800 \text{ J/s})\Delta t = (40 \text{ kg})(4180 \text{ J/kg} \cdot ^\circ\text{C})(80 - 20)^\circ\text{C}$$

Solving for Δt gives

$$\Delta t = \mathbf{12,540 \text{ s} = 209 \text{ min} = 3.48 \text{ h}}$$

Again we take the water in the tank to be the system. Noting that no heat or mass crosses the boundaries of this system and the energy and entropy contents of the heater are negligible, the entropy balance for it can be expressed as

$$\cancel{S_{in}} + S_{gen} = \cancel{S_{out}} + \Delta S_{\text{system}}$$

Net entropy transfer Entropy Change
by heat and mass generation in entropy

$$0 + S_{gen} = \Delta S_{\text{water}}$$

Therefore, the entropy generated during this process is

$$S_{gen} = \Delta S_{\text{water}} = mC \ln \frac{T_2}{T_1} = (40 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{353 \text{ K}}{293 \text{ K}} = \mathbf{31.15 \text{ kJ/K}}$$

7-159 A hot water pipe at a specified temperature is losing heat to the surrounding air at a specified rate. The rate of entropy generation in the surrounding air due to this heat transfer are to be determined.

Assumptions Steady operating conditions exist.

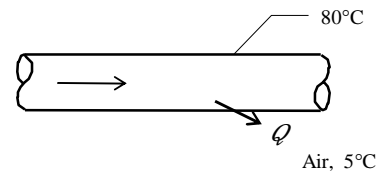
Analysis We take the air in the vicinity of the pipe (excluding the pipe) as our system, which is a closed system.. The system extends from the outer surface of the pipe to a distance at which the temperature drops to the surroundings temperature. In steady operation, the rate form of the entropy balance for this system can be expressed as

$$\dot{\mathcal{S}}_{in} - \dot{\mathcal{S}}_{out} + \dot{\mathcal{S}}_{gen} = \Delta \dot{\mathcal{S}}_{system} = 0$$

Rate of net entropy transfer Rate of entropy Rate of change
by heat and mass generation of entropy

$$\frac{\dot{Q}_{in}}{T_{b,in}} - \frac{\dot{Q}_{out}}{T_{b,out}} + \dot{\mathcal{S}}_{gen,system} = 0$$

$$\frac{2200 \text{ W}}{353 \text{ K}} - \frac{2200 \text{ W}}{278 \text{ K}} + \dot{\mathcal{S}}_{gen,system} = 0 \rightarrow \dot{\mathcal{S}}_{gen,system} = \mathbf{1.68 \text{ W/K}}$$



7-160 The feedwater of a steam power plant is preheated using steam extracted from the turbine. The ratio of the mass flow rates of the extracted steam to the feedwater and entropy generation per unit mass of feedwater 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** Heat loss from the device to the surroundings is negligible.

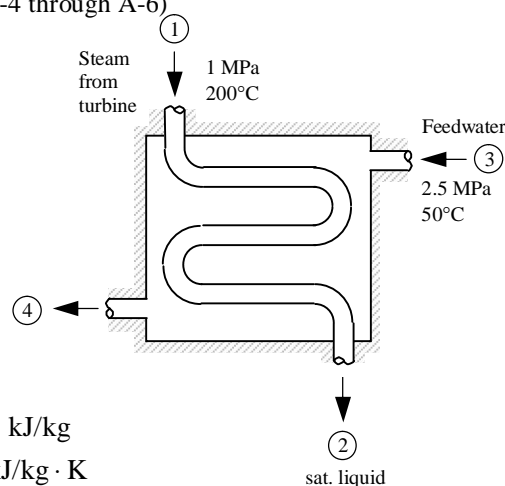
Properties The properties of steam and feedwater are (Tables A-4 through A-6)

$$\left. \begin{array}{l} P_1 = 1 \text{ MPa} \\ T_1 = 200^\circ \text{C} \end{array} \right\} \begin{array}{l} h_1 = 2827.9 \text{ kJ/kg} \\ s_1 = 6.6940 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 1 \text{ MPa} \\ \text{sat. liquid} \end{array} \right\} \begin{array}{l} h_2 = h_{f@1 \text{ MPa}} = 762.81 \text{ kJ/kg} \\ s_2 = s_{f@1 \text{ MPa}} = 2.1387 \text{ kJ/kg} \cdot \text{K} \\ T_2 = 179.91^\circ \text{C} \end{array}$$

$$\left. \begin{array}{l} P_3 = 2.5 \text{ MPa} \\ T_3 = 50^\circ \text{C} \end{array} \right\} \begin{array}{l} h_3 = h_{f@50^\circ \text{C}} = 209.33 \text{ kJ/kg} \\ s_3 = s_{f@50^\circ \text{C}} = 0.7038 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_4 = 2.5 \text{ MPa} \\ T_4 = T_2 - 10^\circ \text{C} \cong 170^\circ \text{C} \end{array} \right\} \begin{array}{l} h_4 = h_{f@170^\circ \text{C}} = 719.21 \text{ kJ/kg} \\ s_4 = s_{f@170^\circ \text{C}} = 2.0419 \text{ kJ/kg} \cdot \text{K} \end{array}$$



Analysis (a) 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 follows:

Mass balance (for each fluid stream):

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{system} \stackrel{\dot{A}=0 \text{ (steady)}}{=} 0 \rightarrow \dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_s \text{ and } \dot{m}_3 = \dot{m}_4 = \dot{m}_{fw}$$

Energy balance (for the heat exchanger):

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system} \stackrel{\dot{A}=0 \text{ (steady)}}{=} 0$$

Rate of net energy transfer by heat, work, and mass Rate of change in internal, kinetic, potential, etc. energies

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

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

Combining the two, $\dot{m}_s (h_2 - h_1) = \dot{m}_{fw} (h_3 - h_4)$

Dividing by \dot{m}_{fw} and substituting, $\frac{\dot{m}_s}{\dot{m}_{fw}} = \frac{h_4 - h_3}{h_1 - h_2} = \frac{(719.2 - 209.33) \text{ kJ/kg}}{(2827.9 - 762.81) \text{ kJ/kg}} = \mathbf{0.247}$

(b) The total entropy change (or entropy generation) during this process per unit mass of feedwater can be determined from an entropy balance expressed in the rate form as

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \Delta \dot{S}_{system} \stackrel{\dot{A}=0}{=} 0$$

Rate of net entropy transfer by heat and mass Rate of entropy generation Rate of change of entropy

$$\dot{m}_1 s_1 - \dot{m}_2 s_2 + \dot{m}_3 s_3 - \dot{m}_4 s_4 + \dot{S}_{gen} = 0$$

$$\dot{m}_s (s_1 - s_2) + \dot{m}_{fw} (s_3 - s_4) + \dot{S}_{gen} = 0$$

$$\frac{\dot{S}_{gen}}{\dot{m}_{fw}} = \frac{\dot{m}_s}{\dot{m}_{fw}} (s_2 - s_1) + (s_4 - s_3) = (0.247)(2.1387 - 6.694) + (2.0419 - 0.7038) = \mathbf{0.213 \text{ kW/(K} \cdot \text{kgfw)}}$$

7-161 Problem 7-160 is reconsidered. The effect of the state of the steam at the inlet to the feedwater heater is to be investigated. The entropy of the extraction steam is assumed to be constant at the value for 1 MPa, 200°C, and the extraction steam pressure is to be varied from 1 MPa to 100 kPa. Both the ratio of the mass flow rates of the extracted steam and the feedwater heater and the total entropy change for this process per unit mass of the feedwater are to be plotted as functions of the extraction pressure.

"Knowns:"

WorkFluid\$ = 'Steam'

P[3] = 1000 "[kPa]" "place {} around P[3] and T[3] equations to solve the table"

T[3] = 200 "[C]"

P[4] = P[3] "[kPa]"

x[4]=0

T[4]=temperature(WorkFluid\$,P=P[4],x=x[4]) "[C]"

P[1] = 2500 "[kPa]"

T[1] = 50 "[C]"

P[2] = 2500 "[kPa]"

T[2] = T[4] - 10 "[C]"

"Since we don't know the mass flow rates and we want to determine the ratio of mass flow rate of the extracted steam and the feedwater, we can assume the mass flow rate of the feedwater is 1 kg/s without loss of generality. We write the conservation of energy."

"Conservation of mass for the steam extracted from the turbine: "

m_dot_steam[3]= m_dot_steam[4]

"Conservation of mass for the condensate flowing through the feedwater heater:"

m_dot_fw[1] = 1 "[kg/s]"

m_dot_fw[2]= m_dot_fw[1] "[kg/s]"

"Conservation of Energy - SSSF energy balance for the feedwater heater -- neglecting the change in potential energy, no heat transfer, no work:"

h[3]=enthalpy(WorkFluid\$,P=P[3],T=T[3]) "[kJ/kg]"

"To solve the table, place {} around s[3] and remove them from the 2nd and 3rd equations"

s[3]=entropy(WorkFluid\$,P=P[3],T=T[3]) "[kJ/kg-K]"

{s[3] = 6.693 "[kJ/kg-K]" "This s[3] is for the initial T[3], P[3]"

T[3]=temperature(WorkFluid\$,P=P[3],s=s[3]) "Use this equation for T[3] only when s[3] is given."}

h[4]=enthalpy(WorkFluid\$,P=P[4],x=x[4]) "[kJ/kg]"

s[4]=entropy(WorkFluid\$,P=P[4],x=x[4]) "[kJ/kg-K]"

h[1]=enthalpy(WorkFluid\$,P=P[1],T=T[1]) "[kJ/kg]"

s[1]=entropy(WorkFluid\$,P=P[1],T=T[1]) "[kJ/kg-K]"

h[2]=enthalpy(WorkFluid\$,P=P[2],T=T[2]) "[kJ/kg]"

s[2]=entropy(WorkFluid\$,P=P[2],T=T[2]) "[kJ/kg-K]"

"For the feedwater heater:"

E_dot_in = E_dot_out "[kW]"

E_dot_in = m_dot_steam[3]*h[3] + m_dot_fw[1]*h[1] "[kW]"

E_dot_out= m_dot_steam[4]*h[4] + m_dot_fw[2]*h[2] "[kW]"

m_ratio = m_dot_steam[3]/ m_dot_fw[1]

"Second Law analysis:"

S_dot_in - S_dot_out + S_dot_gen = DELTAS_dot_sys "[kW/K]"

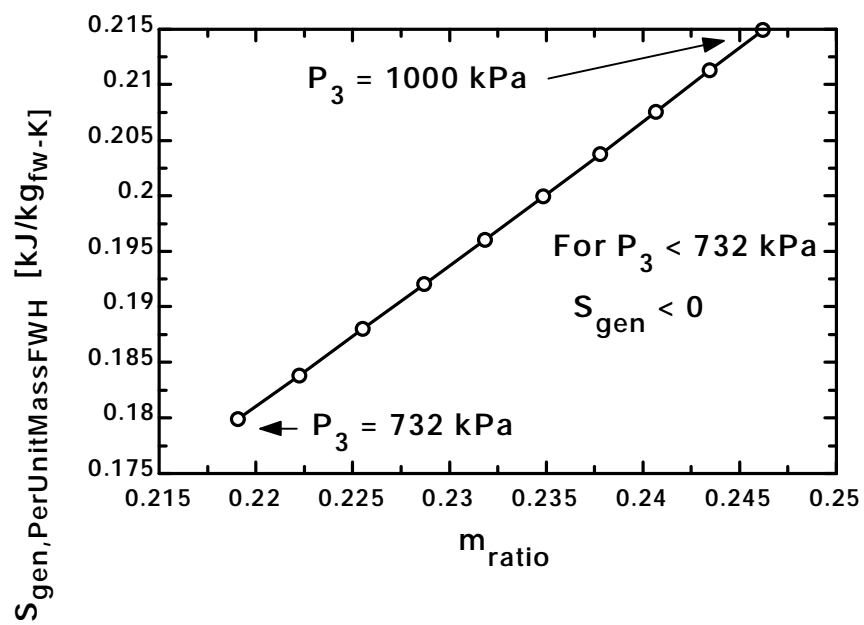
DELTAS_dot_sys = 0 "[kW/K]" "steady-flow result"

S_dot_in = m_dot_steam[3]*s[3] + m_dot_fw[1]*s[1] "[kW/K]"

S_dot_out= m_dot_steam[4]*s[4] + m_dot_fw[2]*s[2] "[kW/K]"

S_gen_PerUnitMassFWH = S_dot_gen/m_dot_fw[1] "[kJ/kg_fw-K]"

m_{ratio}	$S_{\text{gen,PerUnitMass}}$ [kJ/kg-K]	P_3 [kPa]
0.2191	0.1799	732
0.2222	0.1838	760
0.2255	0.188	790
0.2287	0.1921	820
0.2318	0.196	850
0.2349	0.2	880
0.2378	0.2038	910
0.2407	0.2076	940
0.2435	0.2113	970
0.2462	0.215	1000



7-162E A rigid tank initially contains saturated R-134a vapor. The tank is connected to a supply line, and is charged until the tank contains saturated liquid at a specified pressure. The mass of R-134a that entered the tank, the heat transfer with the surroundings at 120°F, and the entropy generated during this process are to be determined.

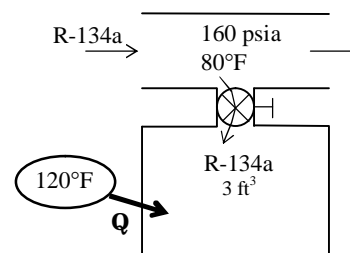
Assumptions **1** This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform-flow process since the state of fluid at the inlet remains constant. **2** Kinetic and potential energies are negligible. **3** There are no work interactions involved. **4** The direction of heat transfer is to the tank (will be verified).

Properties The properties of R-134a are (Tables A-11 through A-13)

$$\left. \begin{array}{l} P_1 = 120 \text{ psia} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} v_1 = v_{g@120 \text{ psia}} = 0.3941 \text{ ft}^3/\text{lbm} \\ u_1 = u_{g@120 \text{ psia}} = 105.06 \text{ Btu/lbm} \\ s_1 = s_{g@120 \text{ psia}} = 0.2165 \text{ Btu/lbm} \cdot \text{R} \end{array}$$

$$\left. \begin{array}{l} P_2 = 140 \text{ psia} \\ \text{sat. liquid} \end{array} \right\} \begin{array}{l} v_2 = v_{f@140 \text{ psia}} = 0.01386 \text{ ft}^3/\text{lbm} \\ u_2 = u_{f@140 \text{ psia}} = 44.07 \text{ Btu/lbm} \\ s_2 = s_{f@140 \text{ psia}} = 0.0902 \text{ Btu/lbm} \cdot \text{R} \end{array}$$

$$\left. \begin{array}{l} P_j = 160 \text{ psia} \\ T_j = 80^\circ \text{F} \end{array} \right\} \begin{array}{l} h_j \cong h_{f@80^\circ \text{F}} = 37.27 \text{ Btu/lbm} \\ s_j \cong s_{f@80^\circ \text{F}} = 0.0774 \text{ Btu/lbm} \cdot \text{R} \end{array}$$



Analysis (*a*) We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u , respectively, the mass and energy balances for this uniform-flow system can be expressed as

Mass balance. $m_{in} - m_{out} = \Delta m_{\text{system}} \rightarrow m_j = m_2 - m_1$

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

$$Q_{in} + m_j h_j = m_2 u_2 - m_1 u_1 \quad (\text{since } W \cong ke \cong pe \cong 0)$$

The initial and the final masses in the tank are

$$m_1 = \frac{V}{v_1} = \frac{3 \text{ ft}^3}{0.3941 \text{ ft}^3/\text{lbm}} = 7.61 \text{ lbm}$$

$$m_2 = \frac{V}{v_2} = \frac{3 \text{ ft}^3}{0.01386 \text{ ft}^3/\text{lbm}} = 216.45 \text{ lbm}$$

Then from the mass balance,

$$m_j = m_2 - m_1 = 216.45 - 7.61 = \mathbf{208.84 \text{ lbm}}$$

(*b*) The heat transfer during this process is determined from the energy balance to be

$$\begin{aligned} Q_{in} &= -m_j h_j + m_2 u_2 - m_1 u_1 \\ &= -(208.84 \text{ lbm})(37.27 \text{ Btu/lbm}) + (216.45 \text{ lbm})(44.07 \text{ Btu/lbm}) - (7.61 \text{ lbm})(105.06 \text{ Btu/lbm}) \\ &= \mathbf{956 \text{ Btu}} \end{aligned}$$

(c) The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the tank and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. The entropy balance for it can be expressed as

$$\underbrace{\dot{S}_{in}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta \dot{S}_{system}}_{\text{Change in entropy}}$$

$$\frac{\dot{Q}_{in}}{T_{b,in}} + m_i s_i + S_{gen} = \Delta S_{\text{tank}} = m_2 s_2 - m_1 s_1$$

Therefore, the total entropy generated during this process is

$$S_{gen} = -m_i s_i + (m_2 s_2 - m_1 s_1) - \frac{\dot{Q}_{in}}{T_{b,in}}$$

$$= -(208.84)(0.0774) + (216.45)(0.0902) - (7.61)(0.2165) - \frac{956 \text{ Btu}}{580 \text{ R}}$$

$$= \mathbf{0.0637 \text{ Btu/R}}$$

7-163 It is to be shown that for thermal energy reservoirs, the entropy change relation $\Delta S = mC \ln(T_2/T_1)$ reduces to $\Delta S = Q/T$ as $T_2 \rightarrow T_1$.

Analysis Consider a thermal energy reservoir of mass m , specific heat C , and initial temperature T_1 . Now heat, in the amount of Q , is transferred to this reservoir. The first law and the entropy change relations for this reservoir can be written as

$$Q = mC(T_2 - T_1) \longrightarrow mC = \frac{Q}{T_2 - T_1}$$

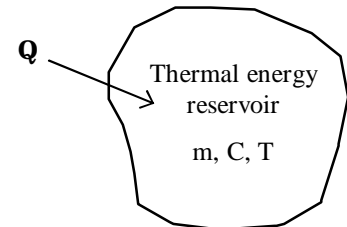
and

$$\Delta S = mC \ln \frac{T_2}{T_1} = Q \frac{\ln(T_2/T_1)}{T_2 - T_1}$$

Taking the limit as $T_2 \rightarrow T_1$ by applying the L'Hospital's rule,

$$\Delta S = Q \frac{1/T_1}{1} = \frac{Q}{T_1}$$

which is the desired result.



7-164 The inner and outer glasses of a double pane window are at specified temperatures. The rates of entropy transfer through both sides of the window and the rate of entropy generation within the window are to be determined.

Assumptions Steady operating conditions exist since the surface temperatures of the glass remain constant at the specified values.

Analysis The entropy flows associated with heat transfer through the left and right glasses are

$$\dot{S}_{\text{left}} = \frac{\dot{Q}_{\text{left}}}{T_{\text{left}}} = \frac{110 \text{ W}}{291 \text{ K}} = \mathbf{0.378 \text{ W/K}}$$

$$\dot{S}_{\text{right}} = \frac{\dot{Q}_{\text{right}}}{T_{\text{right}}} = \frac{110 \text{ W}}{279 \text{ K}} = \mathbf{0.394 \text{ W/K}}$$

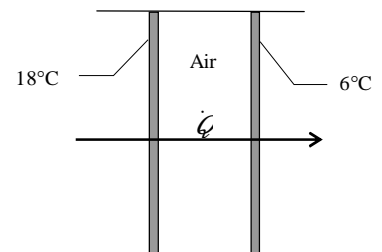
We take the double pane window as the system, which is a closed system.

In steady operation, the rate form of the entropy balance for this system can be expressed as

$$\underbrace{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{\text{gen}}}_{\text{Rate of entropy generation}} = \underbrace{\Delta \dot{S}_{\text{system}}}_{\text{Rate of change of entropy}} = 0$$

$$\frac{\dot{Q}_{\text{in}}}{T_{\text{h,in}}} - \frac{\dot{Q}_{\text{out}}}{T_{\text{h,out}}} + \dot{S}_{\text{gen,system}} = 0$$

$$\frac{110 \text{ W}}{291 \text{ K}} - \frac{110 \text{ W}}{279 \text{ K}} + \dot{S}_{\text{gen,system}} = 0 \longrightarrow \dot{S}_{\text{gen,system}} = \mathbf{0.016 \text{ W/K}}$$



7-165 A well-insulated room is heated by a steam radiator, and the warm air is distributed by a fan. The average temperature in the room after 30 min, the entropy changes of steam and air, and the entropy generated during this process are to be determined.

Assumptions **1** Air is an ideal gas with constant specific heats at room temperature. **2** The kinetic and potential energy changes are negligible. **3** The air pressure in the room remains constant and thus the air expands as it is heated, and some warm air escapes.

Properties The gas constant of air is $R = 0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$ (Table A-1). Also, $C_p = 1.005 \text{ kJ/kg} \cdot \text{K}$ for air at room temperature (Table A-2).

Analysis We first take the radiator 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

$$\begin{aligned} \cancel{E_{in}} - \cancel{E_{out}} &= \Delta E_{\text{system}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ -Q_{out} &= \Delta U = m(u_2 - u_1) \quad (\text{since } W = \text{KE} = \text{PE} = 0) \\ Q_{out} &= m(u_1 - u_2) \end{aligned}$$

Using data from the steam tables (Tables A-4 through A-6), some properties are determined to be

$$\left. \begin{aligned} P_1 &= 200 \text{ kPa} \\ T_1 &= 200^\circ \text{C} \end{aligned} \right\} \begin{aligned} v_1 &= 1.0803 \text{ m}^3/\text{kg} \\ u_1 &= 2654.4 \text{ kJ/kg} \\ s_1 &= 7.5066 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

$$\left. \begin{aligned} P_2 &= 100 \text{ kPa} \\ (v_2 &= v_1) \end{aligned} \right\} \begin{aligned} v_f &= 0.001043, & v_g &= 1.6940 \text{ m}^3/\text{kg} \\ u_f &= 417.46, & u_{fg} &= 2088.7 \text{ kJ/kg} \\ s_f &= 1.3026, & s_{fg} &= 6.0568 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{1.0803 - 0.001043}{1.6940 - 0.001043} = 0.6375$$

$$u_2 = u_f + x_2 u_{fg} = 417.36 + 0.6375 \times 2088.7 = 1748.9 \text{ kJ/kg}$$

$$m = \frac{V_1}{v_1} = \frac{0.015 \text{ m}^3}{1.0803 \text{ m}^3/\text{kg}} = 0.0139 \text{ kg}$$

Substituting,

$$Q_{out} = (0.0139 \text{ kg})(2654.4 - 1748.9) \text{ kJ/kg} = 12.6 \text{ kJ}$$

The volume and the mass of the air in the room are $V = 4 \times 4 \times 5 = 80 \text{ m}^3$ and

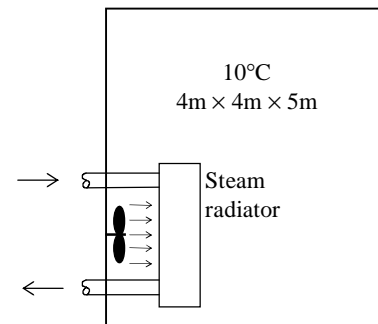
$$m_{air} = \frac{P_1 V_1}{R T_1} = \frac{(100 \text{ kPa})(80 \text{ m}^3)}{(0.2870 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(283 \text{ K})} = 98.5 \text{ kg}$$

The amount of fan work done in 30 min is

$$W_{fan,in} = \dot{W}_{fan,in} \Delta t = (0.120 \text{ kJ/s})(30 \times 60 \text{ s}) = 216 \text{ kJ}$$

We now take the air in the room as the system. The energy balance for this closed system is expressed as

$$\begin{aligned} E_{in} - E_{out} &= \Delta E_{\text{system}} \\ Q_{in} + W_{fan,in} - W_{b,out} &= \Delta U \\ Q_{in} + W_{fan,in} &= \Delta H \equiv m C_p (T_2 - T_1) \end{aligned}$$



since the boundary work and ΔU combine into ΔH for a constant pressure expansion or compression process.

Substituting, $(12.6 \text{ kJ}) + (216 \text{ kJ}) = (98.5 \text{ kg})(1.005 \text{ kJ/kg}^\circ\text{C})(T_2 - 10)^\circ\text{C}$

which yields $T_2 = \mathbf{12.3^\circ\text{C}}$

Therefore, the air temperature in the room rises from 10°C to 12.3°C in 30 mi.

(b) The entropy change of the steam is

$$\Delta S_{\text{steam}} = m(s_2 - s_1) = (0.0139 \text{ kg})(5.1638 - 7.5066) \text{ kJ/kg} \cdot \text{K} = \mathbf{-0.0326 \text{ kJ/K}}$$

(c) Noting that air expands at constant pressure, the entropy change of the air in the room is

$$\Delta S_{\text{air}} = mC_p \ln \frac{T_2}{T_1} - mR \ln \frac{P_2}{P_1} = (98.5 \text{ kg})(1.005 \text{ kJ/kg} \cdot \text{K}) \ln \frac{285.3 \text{ K}}{283 \text{ K}} = \mathbf{0.8013 \text{ kJ/K}}$$

We take the air in the room (including the steam radiator) as our system, which is a closed system. Noting that no heat or mass crosses the boundaries of this system, the entropy balance for it can be expressed as

$$\underbrace{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{\text{gen}}}_{\text{Entropy generation}} = \underbrace{\Delta \dot{S}_{\text{system}}}_{\text{Change in entropy}}$$

$$0 + \dot{S}_{\text{gen}} = \Delta S_{\text{steam}} + \Delta S_{\text{air}}$$

Substituting, the entropy generated during this process is determined to be

$$\dot{S}_{\text{gen}} = \Delta S_{\text{steam}} + \Delta S_{\text{air}} = -0.0326 + 0.8013 = \mathbf{0.7687 \text{ kJ/K}}$$

7-166 The heating of a passive solar house at night is to be assisted by solar heated water. The length of time that the electric heating system would run that night and the amount of entropy generated that night are to be determined.

Assumptions **1** Water is an incompressible substance with constant specific heats. **2** The energy stored in the glass containers themselves is negligible relative to the energy stored in water. **3** The house is maintained at 22°C at all times.

Properties The density and specific heat of water at room temperature are $\rho = 1 \text{ kg/L}$ and $C = 4.18 \text{ kJ/kg}\cdot^\circ\text{C}$ (Table A-3).

Analysis The total mass of water is

$$m_w = \rho V = (1 \text{ kg/L})(50 \times 20 \text{ L}) = 1000 \text{ kg}$$

Taking the contents of the house, including the water as our system, the energy balance relation can be written as

$$\begin{aligned} \cancel{E_{in}} - \cancel{E_{out}} &= \cancel{\Delta E_{system}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ W_{e,in} - Q_{out} &= \Delta U = (\Delta U)_{\text{water}} + (\Delta U)_{\text{air}} \\ &= (\Delta U)_{\text{water}} \\ &= mC(T_2 - T_1)_{\text{water}} \end{aligned}$$

or,

$$W_{e,in} \Delta t - Q_{out} = [mC(T_2 - T_1)]_{\text{water}}$$

Substituting,

$$(15 \text{ kJ/s})\Delta t - (50,000 \text{ kJ/h})(10 \text{ h}) = (1000 \text{ kg})(4.18 \text{ kJ/kg}\cdot^\circ\text{C})(22 - 80)^\circ\text{C}$$

It gives

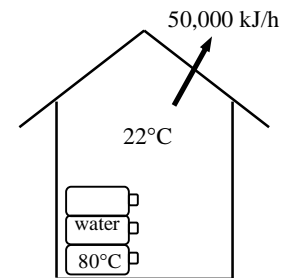
$$\Delta t = 17,170 \text{ s} = \mathbf{4.77 \text{ h}}$$

We take the house as the system, which is a closed system. The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the house and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. The entropy balance for the extended system can be expressed as

$$\begin{aligned} \cancel{S_{in}} - \cancel{S_{out}} + S_{gen} &= \cancel{\Delta S_{system}} \\ \text{Net entropy transfer} & \quad \text{Entropy} & \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{in entropy} \\ -\frac{Q_{out}}{T_{b,out}} + S_{gen} &= \Delta S_{\text{water}} + \Delta S_{\text{air}}^{\bar{A}0} = \Delta S_{\text{water}} \end{aligned}$$

since the state of air in the house remains unchanged. Then the entropy generated during the 10-h period that night is

$$\begin{aligned} S_{gen} &= \Delta S_{\text{water}} + \frac{Q_{out}}{T_{b,out}} = \left(mC \ln \frac{T_2}{T_1} \right)_{\text{water}} + \frac{Q_{out}}{T_{surr}} \\ &= (1000 \text{ kg})(4.18 \text{ kJ/kg}\cdot\text{K}) \ln \frac{295 \text{ K}}{353 \text{ K}} + \frac{500,000 \text{ kJ}}{276 \text{ K}} \\ &= -750 + 1811 = \mathbf{1061 \text{ kJ/K}} \end{aligned}$$



7-167E A steel container that is filled with hot water is allowed to cool to the ambient temperature. The total entropy generated during this process is to be determined.

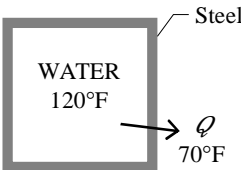
Assumptions **1** Both the water and the steel tank are incompressible substances with constant specific heats at room temperature. **2** The system is stationary and thus the kinetic and potential energy changes are zero. **3** Specific heat of iron can be used for steel. **4** There are no work interactions involved.

Properties The specific heats of water and the iron at room temperature are $C_{p, \text{water}} = 1.00 \text{ Btu/lbm} \cdot ^\circ\text{F}$ and $C_{p, \text{iron}} = 0.107 \text{ Btu/lbm} \cdot ^\circ\text{C}$ (Table A-3E). The density of water at room temperature is 62.1 lbm/ft^3 .

Analysis The mass of the water is

$$m_{\text{water}} = \rho V = (62.1 \text{ lbm/ft}^3)(15 \text{ ft}^3) = 931.5 \text{ lbm}$$

We take the steel container and the water in it as the system, which is a closed system. The energy balance on the system can be expressed as

$$\begin{aligned} \cancel{E_{\text{in}}} - \cancel{E_{\text{out}}} &= \Delta E_{\text{system}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ -Q_{\text{out}} &= \Delta U = \Delta U_{\text{container}} + \Delta U_{\text{water}} \\ &= [mC(T_2 - T_1)]_{\text{container}} + [mC(T_2 - T_1)]_{\text{water}} \end{aligned}$$


Substituting, the heat loss to the surrounding air is determined to be

$$\begin{aligned} Q_{\text{out}} &= [mC(T_1 - T_2)]_{\text{container}} + [mC(T_1 - T_2)]_{\text{water}} \\ &= (75 \text{ lbm})(0.107 \text{ Btu/lbm} \cdot ^\circ\text{F})(120 - 70)^\circ\text{F} + (931.5 \text{ lbm})(1.00 \text{ Btu/lbm} \cdot ^\circ\text{F})(120 - 70)^\circ\text{F} \\ &= 46,976 \text{ Btu} \end{aligned}$$

We again take the container and the water in it as the system. The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the container and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surrounding air at all times. The entropy balance for the extended system can be expressed as

$$\begin{aligned} \cancel{S_{\text{in}}} - \cancel{S_{\text{out}}} + S_{\text{gen}} &= \Delta S_{\text{system}} \\ \text{Net entropy transfer} & \quad \text{Entropy} & \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{in entropy} \\ -\frac{Q_{\text{out}}}{T_{b, \text{out}}} + S_{\text{gen}} &= \Delta S_{\text{container}} + \Delta S_{\text{water}} \end{aligned}$$

where

$$\begin{aligned} \Delta S_{\text{container}} &= mC_{\text{ave}} \ln \frac{T_2}{T_1} = (75 \text{ lbm})(0.107 \text{ Btu/lbm} \cdot \text{R}) \ln \frac{530 \text{ R}}{580 \text{ R}} = -0.72 \text{ Btu/R} \\ \Delta S_{\text{water}} &= mC_{\text{ave}} \ln \frac{T_2}{T_1} = (931.5 \text{ lbm})(1.00 \text{ Btu/lbm} \cdot \text{R}) \ln \frac{530 \text{ R}}{580 \text{ R}} = -83.98 \text{ Btu/R} \end{aligned}$$

Therefore, the total entropy generated during this process is

$$S_{\text{gen}} = \Delta S_{\text{container}} + \Delta S_{\text{water}} + \frac{Q_{\text{out}}}{T_{b, \text{out}}} = -0.72 - 83.98 + \frac{46,976 \text{ Btu}}{70 + 460 \text{ R}} = \mathbf{3.93 \text{ Btu/R}}$$

7-168 Refrigerant-134a is vaporized by air in the evaporator of an air-conditioner. For specified flow rates, the exit temperature of air and the rate of entropy generation are to be determined for the cases of an insulated and uninsulated evaporator. ✓

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 Air is an ideal gas with constant specific heats at room temperature.

Properties The gas constant of air is $0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$ (Table A-1). The constant pressure specific heat of air at room temperature is $C_p = 1.005 \text{ kJ/kg} \cdot \text{K}$ (Table A-2). The properties of R-134a at the inlet and the exit states are (Tables A-11 through A-13)

$$\left. \begin{array}{l} P_1 = 120 \text{ kPa} \\ x_1 = 0.3 \end{array} \right\} \begin{array}{l} h_1 = h_f + x_1 h_{fg} = 21.32 + 0.3 \times 212.54 = 85.08 \text{ kJ/kg} \\ s_1 = s_f + x_1 s_{fg} = 0.0879 + 0.3(0.9354 - 0.0879) = 0.3422 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} T_2 = 120 \text{ kPa} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} h_2 = h_{g@120 \text{ kPa}} = 233.86 \text{ kJ/kg} \\ s_2 = h_{g@120 \text{ kPa}} = 0.9354 \text{ kJ/kg} \cdot \text{K} \end{array}$$

Analysis (a) The mass flow rate of air is

$$\dot{m}_{\text{air}} = \frac{P_3 \dot{V}_3}{RT_3} = \frac{(100 \text{ kPa})(6 \text{ m}^3/\text{min})}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(300 \text{ K})} = 6.97 \text{ kg/min}$$

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):

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

Energy balance (for the entire heat exchanger):

$$\frac{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}{14243} = \frac{\Delta \dot{E}_{\text{system}}}{14243} \quad \dot{A}0 \text{ (steady)} = 0$$

Rate of net energy transfer by heat, work, and mass Rate of change in internal, kinetic, potential, etc. energies

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

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

$$\text{Combining the two, } \dot{m}_R (h_2 - h_1) = \dot{m}_{\text{air}} (h_3 - h_4) = \dot{m}_{\text{air}} C_p (T_3 - T_4)$$

$$\text{Solving for } T_4, \quad T_4 = T_3 - \frac{\dot{m}_R (h_2 - h_1)}{\dot{m}_{\text{air}} C_p}$$

$$\text{Substituting, } T_4 = 27^\circ\text{C} - \frac{(2 \text{ kg/min})(233.86 - 85.08) \text{ kJ/kg}}{(6.97 \text{ kg/min})(1.005 \text{ kJ/kg} \cdot \text{K})} = -15.5^\circ\text{C} = 257.5 \text{ K}$$

Noting that the condenser is well-insulated and thus heat transfer is negligible, the entropy balance for this steady-flow system can be expressed as

$$\frac{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}{14243} + \frac{\dot{S}_{\text{gen}}}{14243} = \frac{\Delta \dot{S}_{\text{system}}}{14243} \quad \dot{A}0 \text{ (steady)}$$

Rate of net entropy transfer by heat and mass Rate of entropy generation Rate of change of entropy

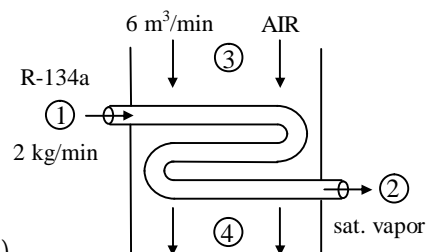
$$\dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{\text{gen}} = 0 \quad (\text{since } \dot{Q} = 0)$$

$$\dot{m}_R s_1 + \dot{m}_{\text{air}} s_3 - \dot{m}_R s_2 - \dot{m}_{\text{air}} s_4 + \dot{S}_{\text{gen}} = 0$$

or,

$$\dot{S}_{\text{gen}} = \dot{m}_R (s_2 - s_1) + \dot{m}_{\text{air}} (s_4 - s_3)$$

where



$$s_4 - s_3 = C_p \ln \frac{T_4}{T_3} - R \ln \frac{P_4}{P_3} = C_p \ln \frac{T_4}{T_3} = (1.005 \text{ kJ/kg} \cdot \text{K}) \ln \frac{257.5 \text{ K}}{300 \text{ K}} = -0.154 \text{ kJ/kg} \cdot \text{K}$$

Substituting,

$$\begin{aligned} \dot{\mathcal{S}}_{gen} &= (2 \text{ kg/min})(0.9354 - 0.3422 \text{ kJ/kg} \cdot \text{K}) + (6.97 \text{ kg/min})(0.154 \text{ kJ/kg} \cdot \text{K}) \\ &= 0.113 \text{ kJ/min} \cdot \text{K} \\ &= \mathbf{0.00188 \text{ kW/K}} \end{aligned}$$

(b) When there is a heat gain from the surroundings at a rate of 30 kJ/min, the steady-flow energy equation reduces to

$$\dot{\mathcal{Q}}_{in} = \dot{m}_R(h_2 - h_1) + \dot{m}_{air}C_p(T_4 - T_3)$$

Solving for T_4 ,
$$T_4 = T_3 + \frac{\dot{\mathcal{Q}}_{in} - \dot{m}_R(h_2 - h_1)}{\dot{m}_{air}C_p}$$

Substituting,
$$T_4 = 27^\circ\text{C} + \frac{(30 \text{ kJ/min}) - (2 \text{ kg/min})(233.86 - 85.08) \text{ kJ/kg}}{(6.97 \text{ kg/min})(1.005 \text{ kJ/kg} \cdot \text{K})} = \mathbf{-11.2^\circ\text{C}}$$

The entropy generation in this case is determined by applying the entropy balance on an *extended system* that includes the evaporator and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surrounding air at all times. The entropy balance for the extended system can be expressed as

$$\underbrace{\frac{\dot{\mathcal{Q}}_{in}}{T_{b,out}} + \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{\mathcal{S}}_{gen}}_{\text{Rate of entropy generation}} = \underbrace{\Delta \dot{\mathcal{S}}_{system}}_{\text{Rate of change of entropy}} \quad \dot{\mathcal{S}}_{gen} = \Delta \dot{\mathcal{S}}_{system} \quad \dot{\mathcal{S}}_{gen} = \Delta \dot{\mathcal{S}}_{system} \quad \dot{\mathcal{S}}_{gen} = \Delta \dot{\mathcal{S}}_{system}$$

$$\frac{\dot{\mathcal{Q}}_{in}}{T_{b,out}} + \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{\mathcal{S}}_{gen} = 0$$

$$\frac{\dot{\mathcal{Q}}_{in}}{T_{surr}} + \dot{m}_R s_1 + \dot{m}_{air} s_3 - \dot{m}_R s_2 - \dot{m}_{air} s_4 + \dot{\mathcal{S}}_{gen} = 0$$

or
$$\dot{\mathcal{S}}_{gen} = \dot{m}_R(s_2 - s_1) + \dot{m}_{air}(s_4 - s_3) - \frac{\dot{\mathcal{Q}}_{in}}{T_0}$$

where $s_4 - s_3 = C_p \ln \frac{T_4}{T_3} - R \ln \frac{P_4}{P_3} = (1.005 \text{ kJ/kg} \cdot \text{K}) \ln \frac{261.8 \text{ K}}{300 \text{ K}} = -0.137 \text{ kJ/kg} \cdot \text{K}$

Substituting,

$$\begin{aligned} \dot{\mathcal{S}}_{gen} &= (2 \text{ kg/min})(0.9354 - 0.3422) \text{ kJ/kg} \cdot \text{K} + (6.97 \text{ kg/min})(-0.137 \text{ kJ/kg} \cdot \text{K}) - \frac{30 \text{ kJ/min}}{305 \text{ K}} \\ &= 0.13315 \text{ kJ/min} \cdot \text{K} \\ &= \mathbf{0.00222 \text{ kW/K}} \end{aligned}$$

Discussion Note that the rate of entropy generation in the second case is greater because of the irreversibility associated with heat transfer between the evaporator and the surrounding air.

7-169 A room is to be heated by hot water contained in a tank placed in the room. The minimum initial temperature of the water needed to meet the heating requirements of this room for a 24-h period and the entropy generated are to be determined.

Assumptions **1** Water is an incompressible substance with constant specific heats. **2** Air is an ideal gas with constant specific heats. **3** The energy stored in the container itself is negligible relative to the energy stored in water. **4** The room is maintained at 20°C at all times. **5** The hot water is to meet the heating requirements of this room for a 24-h period.

Properties The specific heat of water at room temperature is $C = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3).

Analysis Heat loss from the room during a 24-h period is

$$Q_{\text{loss}} = (10,000 \text{ kJ/h})(24 \text{ h}) = 240,000 \text{ kJ}$$

Taking the contents of the room, including the water, as our system, the energy balance can be written as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}} \rightarrow -Q_{\text{out}} = \Delta U = (\Delta U)_{\text{water}} + (\Delta U)_{\text{air}}^{\text{Ao}}$$

or

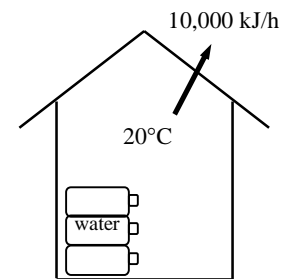
$$-Q_{\text{out}} = [mC(T_2 - T_1)]_{\text{water}}$$

Substituting,

$$-240,000 \text{ kJ} = (1500 \text{ kg})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(20 - T_1)$$

It gives

$$T_1 = \mathbf{58.3^\circ\text{C}}$$



where T_1 is the temperature of the water when it is first brought into the room.

(b) We take the house as the system, which is a closed system. The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the house and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. The entropy balance for the extended system can be expressed as

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}} \\ -\frac{Q_{\text{out}}}{T_{b,\text{out}}} + S_{\text{gen}} = \Delta S_{\text{water}} + \Delta S_{\text{air}}^{\text{Ao}} = \Delta S_{\text{water}}$$

since the state of air in the house (and thus its entropy) remains unchanged. Then the entropy generated during the 24 h period becomes

$$\begin{aligned} S_{\text{gen}} &= \Delta S_{\text{water}} + \frac{Q_{\text{out}}}{T_{b,\text{out}}} = \left(mC \ln \frac{T_2}{T_1} \right)_{\text{water}} + \frac{Q_{\text{out}}}{T_{\text{surr}}} \\ &= (1500 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{293 \text{ K}}{331.3 \text{ K}} + \frac{240,000 \text{ kJ}}{278 \text{ K}} \\ &= -770.3 + 863.3 = \mathbf{93.0 \text{ kJ/K}} \end{aligned}$$

7-170 An insulated cylinder is divided into two parts. One side of the cylinder contains N₂ gas and the other side contains He gas at different states. The final equilibrium temperature in the cylinder and the entropy generated are to be determined for the cases of the piston being fixed and moving freely.

Assumptions **1** Both N₂ and He are ideal gases with constant specific heats. **2** The energy stored in the container itself is negligible. **3** The cylinder is well-insulated and thus heat transfer is negligible.

Properties The gas constants and the constant volume specific heats are $R = 0.2968 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$, $C_v = 0.743 \text{ kJ/kg}\cdot^\circ\text{C}$ and $C_p = 1.039 \text{ kJ/kg}\cdot^\circ\text{C}$ for N₂, and $R = 2.0769 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$, $C_v = 3.1156 \text{ kJ/kg}\cdot^\circ\text{C}$, and $C_p = 5.1926 \text{ kJ/kg}\cdot^\circ\text{C}$ for He (Tables A-1 and A-2)

Analysis The mass of each gas in the cylinder is

$$m_{N_2} = \left(\frac{PV_1}{RT_1} \right)_{N_2} = \frac{(500 \text{ kPa})(1 \text{ m}^3)}{(0.2968 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(353 \text{ K})} = 4.77 \text{ kg}$$

$$m_{He} = \left(\frac{PV_1}{RT_1} \right)_{He} = \frac{(500 \text{ kPa})(1 \text{ m}^3)}{(2.0769 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298 \text{ K})} = 0.808 \text{ kg}$$

N ₂	He
1 m ³	1 m ³
500 kPa	500 kPa
80°C	25°C

Taking the entire contents of the cylinder as our system, the 1st law relation can be written as

$$\begin{aligned} \cancel{E_{12}} \cancel{E_{23}} &= \cancel{E_{123}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ 0 = \Delta U &= (\Delta U)_{N_2} + (\Delta U)_{He} \\ 0 = [mC_v(T_2 - T_1)]_{N_2} &+ [mC_v(T_2 - T_1)]_{He} \end{aligned}$$

Substituting,

$$(4.77 \text{ kg})(0.743 \text{ kJ/kg}\cdot^\circ\text{C})(T_f - 80)^\circ\text{C} + (0.808 \text{ kg})(3.1156 \text{ kJ/kg}\cdot^\circ\text{C})(T_f - 25)^\circ\text{C} = 0$$

It gives $T_f = 57.2^\circ\text{C}$

where T_f is the final equilibrium temperature in the cylinder.

The answer would be the **same** if the piston were not free to move since it would effect only pressure, and not the specific heats.

(\diamond) We take the entire cylinder as our system, which is a closed system. Noting that the cylinder is well-insulated and thus there is no heat transfer, the entropy balance for this closed system can be expressed as

$$\begin{aligned} \cancel{S_{12}} \cancel{S_{23}} + S_{gen} &= \cancel{S_{123}} \\ \text{Net entropy transfer} & \quad \text{Entropy} \quad \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} \quad \quad \text{in entropy} \\ 0 + S_{gen} &= \Delta S_{N_2} + \Delta S_{He} \end{aligned}$$

But first we determine the final pressure in the cylinder:

$$N_{total} = N_{N_2} + N_{He} = \left(\frac{m}{M} \right)_{N_2} + \left(\frac{m}{M} \right)_{He} = \frac{4.77 \text{ kg}}{28 \text{ kg/kmol}} + \frac{0.808 \text{ kg}}{4 \text{ kg/kmol}} = 0.372 \text{ kmol}$$

$$P_2 = \frac{N_{total} R_u T}{V_{total}} = \frac{(0.372 \text{ kmol})(8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(330.2 \text{ K})}{2 \text{ m}^3} = 510.6 \text{ kPa}$$

Then,

$$\begin{aligned} \Delta S_{N_2} &= m \left(C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \right)_{N_2} \\ &= (4.77 \text{ kg}) \left[(1.039 \text{ kJ/kg}\cdot\text{K}) \ln \frac{330.2 \text{ K}}{353 \text{ K}} - (0.2968 \text{ kJ/kg}\cdot\text{K}) \ln \frac{510.6 \text{ kPa}}{500 \text{ kPa}} \right] = -0.361 \text{ kJ/K} \end{aligned}$$

$$\begin{aligned}
\Delta S_{He} &= m \left(C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \right)_{He} \\
&= (0.808 \text{ kg}) \left[(5.1926 \text{ kJ/kg} \cdot \text{K}) \ln \frac{330.2 \text{ K}}{298 \text{ K}} - (2.0769 \text{ kJ/kg} \cdot \text{K}) \ln \frac{510.6 \text{ kPa}}{500 \text{ kPa}} \right] = 0.395 \text{ kJ/K} \\
S_{gen} &= \Delta S_{N_2} + \Delta S_{He} = -0.361 + 0.395 = \mathbf{0.034 \text{ kJ/K}}
\end{aligned}$$

If the piston were not free to move, we would still have $T_2 = 330.2 \text{ K}$ but the volume of each gas would remain constant in this case:

$$\begin{aligned}
\Delta S_{N_2} &= m \left(C_v \ln \frac{T_2}{T_1} - R \ln \frac{V_2}{V_1} \right)_{N_2} = (4.77 \text{ kg}) (0.743 \text{ kJ/kg} \cdot \text{K}) \ln \frac{330.2 \text{ K}}{353 \text{ K}} = -0.237 \text{ kJ/K} \\
\Delta S_{He} &= m \left(C_v \ln \frac{T_2}{T_1} - R \ln \frac{V_2}{V_1} \right)_{He} = (0.808 \text{ kg}) (3.1156 \text{ kJ/kg} \cdot \text{K}) \ln \frac{330.2 \text{ K}}{298 \text{ K}} = 0.258 \text{ kJ/K} \\
S_{gen} &= \Delta S_{N_2} + \Delta S_{He} = -0.237 + 0.258 = \mathbf{0.021 \text{ kJ/K}}
\end{aligned}$$

7-171 Problem 7-170 is reconsidered. The results for constant specific heats to those obtained using variable specific heats are to be compared using built-in EES or other functions.

"Knowns:"

$R_u = 8.314 \text{ [kJ/kmol-K]}$
 $V_{N2[1]} = 1 \text{ [m}^3\text{]}$
 $Cv_{N2} = 0.743 \text{ [kJ/kg-K]}$ "From Table A-2(a) at 27C"
 $R_{N2} = 0.2968 \text{ [kJ/kg-K]}$ "From Table A-2(a)"
 $T_{N2[1]} = 80 \text{ [C]}$
 $P_{N2[1]} = 500 \text{ [kPa]}$
 $Cp_{N2} = R_{N2} + Cv_{N2} \text{ [kJ/kg-K]}$
 $V_{He[1]} = 1 \text{ [m}^3\text{]}$
 $Cv_{He} = 3.1156 \text{ [kJ/kg-K]}$ "From Table A-2(a) at 27C"
 $T_{He[1]} = 25 \text{ [C]}$
 $P_{He[1]} = 500 \text{ [kPa]}$
 $R_{He} = 2.0769 \text{ [kJ/kg-K]}$ "From Table A-2(a)"
 $Cp_{He} = R_{He} + Cv_{He} \text{ [kJ/kg-K]}$

"Solution:"

"mass calculations:"

$P_{N2[1]} \cdot V_{N2[1]} = m_{N2} \cdot R_{N2} \cdot (T_{N2[1]} + 273)$
 $P_{He[1]} \cdot V_{He[1]} = m_{He} \cdot R_{He} \cdot (T_{He[1]} + 273)$

"The entire cylinder is considered to be a closed system, allowing the piston to move."

"Conservation of Energy for the closed system:"

" $E_{in} - E_{out} = \Delta E$, we neglect ΔKE and ΔPE for the cylinder."

$E_{in} - E_{out} = \Delta E$

$E_{in} = 0 \text{ [kJ]}$

$E_{out} = 0 \text{ [kJ]}$

"At the final equilibrium state, N2 and He will have a common temperature."

$\Delta E = m_{N2} \cdot Cv_{N2} \cdot (T_2 - T_{N2[1]}) + m_{He} \cdot Cv_{He} \cdot (T_2 - T_{He[1]}) \text{ [kJ]}$

"Total volume of gases:"

$V_{total} = V_{N2[1]} + V_{He[1]} \text{ [m}^3\text{]}$

$MM_{He} = 4 \text{ [kg/kmol]}$

$MM_{N2} = 28 \text{ [kg/kmol]}$

$N_{total} = m_{He}/MM_{He} + m_{N2}/MM_{N2}$

"Final pressure at equilibrium:"

"Allowing the piston to move, the pressure on both sides is the same, P_2 is:"

$P_2 \cdot V_{total} = N_{total} \cdot R_u \cdot (T_2 + 273) \text{ [kPa]}$

$S_{gen_PistonMoving} = \Delta S_{He_PM} + \Delta S_{N2_PM} \text{ [kJ/K]}$

$\Delta S_{He_PM} = m_{He} \cdot (Cp_{He} \cdot \ln((T_2 + 273)/(T_{He[1]} + 273)) -$

$R_{He} \cdot \ln(P_2/P_{He[1]})) \text{ [kJ/K]}$

$\Delta S_{N2_PM} = m_{N2} \cdot (Cp_{N2} \cdot \ln((T_2 + 273)/(T_{N2[1]} + 273)) -$

$R_{N2} \cdot \ln(P_2/P_{N2[1]})) \text{ [kJ/K]}$

"The final temperature of the system when the piston does not move will be the same as when it does move. The volume of the gases remain constant and the entropy changes are given by:"

$S_{gen_PistNotMoving} = \Delta S_{He_PNM} + \Delta S_{N2_PNM} \text{ [kJ/K]}$

$\Delta S_{He_PNM} = m_{He} \cdot (Cv_{He} \cdot \ln((T_2 + 273)/(T_{He[1]} + 273))) \text{ [kJ/K]}$

$\Delta S_{N2_PNM} = m_{N2} \cdot (Cv_{N2} \cdot \ln((T_2 + 273)/(T_{N2[1]} + 273))) \text{ [kJ/K]}$

"The following uses the EES functions for the nitrogen. Since helium is monatomic, we use the constant specific heat approach to find its property changes."

$E_{in} - E_{out} = \Delta E_{VP}$

$$\text{DELTA E}_{VP} = m_{N2} * (\text{INTENERGY}(N2, T=T_{2_VP}) - \text{INTENERGY}(N2, T=T_{N2[1]})) + m_{He} * C_{v_He} * (T_{2_VP} - T_{He[1]}) \text{ [kJ]}$$

"Final Pressure for moving piston:"

$$P_{2_VP} * V_{total} = N_{total} * R_u * (T_{2_VP} + 273) \text{ [kPa]}$$

$$S_{gen_PistMoving_VP} = \text{DELTA } S_{He_PM_VP} + \text{DELTA } S_{N2_PM_VP} \text{ [kJ/K]}$$

$$\text{DELTA } S_{N2_PM_VP} = m_{N2} * (\text{ENTROPY}(N2, T=T_{2_VP}, P=P_{2_VP}) - \text{ENTROPY}(N2, T=T_{N2[1]}, P=P_{N2[1]})) \text{ [kJ/K]}$$

$$\text{DELTA } S_{He_PM_VP} = m_{He} * (C_{p_He} * \ln((T_{2_VP} + 273)/(T_{He[1]} + 273)) - R_{He} * \ln(P_{2_VP}/P_{He[1]})) \text{ [kJ/K]}$$

"Final N2 Pressure for piston not moving."

$$P_{2_N2_VP} * V_{N2[1]} = m_{N2} * R_{N2} * (T_{2_VP} + 273)$$

$$S_{gen_PistNotMoving_VP} = \text{DELTA } S_{He_PNM_VP} + \text{DELTA } S_{N2_PNM_VP} \text{ [kJ/K]}$$

$$\text{DELTA } S_{N2_PNM_VP} = m_{N2} * (\text{ENTROPY}(N2, T=T_{2_VP}, P=P_{2_N2_VP}) - \text{ENTROPY}(N2, T=T_{N2[1]}, P=P_{N2[1]})) \text{ [kJ/K]}$$

$$\text{DELTA } S_{He_PNM_VP} = m_{He} * (C_{v_He} * \ln((T_{2_VP} + 273)/(T_{He[1]} + 273))) \text{ [kJ/K]}$$

SOLUTION

Variables in Main

$$C_{p_He} = 5.193 \text{ [kJ/kg-K]}$$

$$C_{p_N2} = 1.04 \text{ [kJ/kg-K]}$$

$$C_{v_He} = 3.116 \text{ [kJ/kg-K]}$$

$$C_{v_N2} = 0.743 \text{ [kJ/kg-K]}$$

$$\text{DELTA E} = 0 \text{ [kJ]}$$

$$\text{DELTA E}_{VP} = 0 \text{ [kJ]}$$

$$\text{DELTA } S_{He_PM} = 0.3931 \text{ [kJ/K]}$$

$$\text{DELTA } S_{He_PM_VP} = 0.3931 \text{ [kJ/K]}$$

$$\text{DELTA } S_{He_PNM} = 0.258 \text{ [kJ/K]}$$

$$\text{DELTA } S_{He_PNM_VP} = 0.2583 \text{ [kJ/K]}$$

$$\text{DELTA } S_{N2_PM} = -0.363 \text{ [kJ/K]}$$

$$\text{DELTA } S_{N2_PM_VP} = -0.3631 \text{ [kJ/K]}$$

$$\text{DELTA } S_{N2_PNM} = -0.2371 \text{ [kJ/K]}$$

$$\text{DELTA } S_{N2_PNM_VP} = -0.2372 \text{ [kJ/K]}$$

$$E_{in} = 0 \text{ [kJ]}$$

$$E_{out} = 0 \text{ [kJ]}$$

$$MM_{He} = 4 \text{ [kg/kmol]}$$

$$MM_{N2} = 28 \text{ [kg/kmol]}$$

$$m_{He} = 0.8079 \text{ [kg]}$$

$$m_{N2} = 4.772 \text{ [kg]}$$

$$N_{total} = 0.3724 \text{ [kmol]}$$

$$P_2 = 511.1 \text{ [kPa]}$$

$$P_{2_N2_VP} = 467.7$$

$$P_{2_VP} = 511.2$$

$$P_{He[1]} = 500 \text{ [kPa]}$$

$$P_{N2[1]} = 500 \text{ [kPa]}$$

$$R_{He} = 2.077 \text{ [kJ/kg-K]}$$

$$R_{N2} = 0.2968 \text{ [kJ/kg-K]}$$

$$R_u = 8.314 \text{ [kJ/kmol-K]}$$

$$S_{gen_PistMoving_VP} = 0.02993 \text{ [kJ/K]}$$

$$S_{gen_PistNotMoving} = 0.02089 \text{ [kJ/K]}$$

$$S_{gen_PistNotMoving_VP} = 0.02106 \text{ [kJ/K]}$$

$$S_{gen_PistonMoving} = 0.03004 \text{ [kJ/K]}$$

$$T_2 = 57.17 \text{ [C]}$$

$$T_{2_VP} = 57.2 \text{ [C]}$$

$$T_{He[1]} = 25 \text{ [C]}$$

$$T_{N2[1]} = 80 \text{ [C]}$$

$V_{\text{He}}[1]=1 \text{ [m}^3\text{]}$
 $V_{\text{N2}}[1]=1 \text{ [m}^3\text{]}$
 $V_{\text{total}}=2 \text{ [m}^3\text{]}$

7-172 An insulated cylinder is divided into two parts. One side of the cylinder contains N_2 gas and the other side contains He gas at different states. The final equilibrium temperature in the cylinder and the entropy generated are to be determined for the cases of the piston being fixed and moving freely.

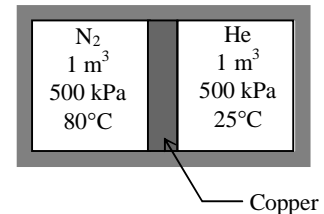
Assumptions **1** Both N_2 and He are ideal gases with constant specific heats. **2** The energy stored in the container itself, except the piston, is negligible. **3** The cylinder is well-insulated and thus heat transfer is negligible. **4** Initially, the piston is at the average temperature of the two gases.

Properties The gas constants and the constant volume specific heats are $R = 0.2968 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$, $C_v = 0.743 \text{ kJ/kg}\cdot^\circ\text{C}$ and $C_p = 1.039 \text{ kJ/kg}\cdot^\circ\text{C}$ for N_2 , and $R = 2.0769 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$, $C_v = 3.1156 \text{ kJ/kg}\cdot^\circ\text{C}$, and $C_p = 5.1926 \text{ kJ/kg}\cdot^\circ\text{C}$ for He (Tables A-1 and A-2). The specific heat of the copper at room temperature is $C = 0.386 \text{ kJ/kg}\cdot^\circ\text{C}$ (Table A-3).

Analysis The mass of each gas in the cylinder is

$$m_{N_2} = \left(\frac{P_1 V_1}{R T_1} \right)_{N_2} = \frac{(500 \text{ kPa})(1 \text{ m}^3)}{(0.2968 \text{ kPa} \cdot \text{m}^3 / \text{kg} \cdot \text{K})(353 \text{ K})} = 4.77 \text{ kg}$$

$$m_{He} = \left(\frac{P_1 V_1}{R T_1} \right)_{He} = \frac{(500 \text{ kPa})(1 \text{ m}^3)}{(2.0769 \text{ kPa} \cdot \text{m}^3 / \text{kg} \cdot \text{K})(353 \text{ K})} = 0.808 \text{ kg}$$



Taking the entire contents of the cylinder as our system, the 1st law relation can be written as

$$\frac{E_{in} - E_{out}}{142.43} = \frac{\Delta E_{\text{system}}}{142.43}$$

Net energy transfer by heat, work, and mass Change in internal, kinetic, potential, etc. energies

$$0 = \Delta U = (\Delta U)_{\text{N}_2} + (\Delta U)_{\text{He}} + (\Delta U)_{\text{Cu}}$$

$$0 = [mC_V(T_2 - T_1)]_{N_2} + [mC_V(T_2 - T_1)]_{He} + [mC(T_2 - T_1)]_{Cu}$$

where

$$T_{1, \text{Cu}} = (80 + 25) / 2 = 52.5^{\circ}\text{C}$$

Substituting,

$$(4.77\text{kg})(0.743\text{kJ/kg}\cdot^{\circ}\text{C})(T_f - 80)^{\circ}\text{C} + (0.808\text{kg})(3.1156\text{kJ/kg}\cdot^{\circ}\text{C})(T_f - 25)^{\circ}\text{C} \\ + (5.0\text{kg})(0.386\text{kJ/kg}\cdot^{\circ}\text{C})(T_f - 52.5)^{\circ}\text{C} = 0$$

It gives

$$T_f = 56.0^\circ\text{C}$$

where T_f is the final equilibrium temperature in the cylinder.

The answer would be the **same** if the piston were not free to move since it would effect only pressure, and not the specific heats.

(*b*) We take the entire cylinder as our system, which is a closed system. Noting that the cylinder is well-insulated and thus there is no heat transfer, the entropy balance for this closed system can be expressed as

$$\begin{aligned} \cancel{\dot{S}_{42}} - \cancel{\dot{S}_{23}} + \dot{S}_{gen} &= \Delta \dot{S}_{\text{system}} \\ \text{Net entropy transfer} & \quad \text{Entropy} & \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{in entropy} \\ 0 + \dot{S}_{gen} &= \Delta \dot{S}_{N_2} + \Delta \dot{S}_{He} + \Delta \dot{S}_{\text{piston}} \end{aligned}$$

But first we determine the final pressure in the cylinder:

$$N_{total} = N_{N_2} + N_{He} = \left(\frac{m}{M} \right)_{N_2} + \left(\frac{m}{M} \right)_{He} = \frac{4.77\text{kg}}{28\text{kg/kmol}} + \frac{0.808\text{kg}}{4\text{kg/kmol}} = 0.372\text{kmol}$$

$$P_2 = \frac{N_{total} R_u T}{V_{total}} = \frac{(0.372\text{kmol})(8.314\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(329\text{K})}{2\text{m}^3} = 508.8\text{kPa}$$

Then,

$$\begin{aligned}
\Delta S_{N_2} &= m \left(C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \right)_{N_2} \\
&= (4.77 \text{ kg}) \left[(1.039 \text{ kJ/kg} \cdot \text{K}) \ln \frac{329 \text{ K}}{353 \text{ K}} - (0.2968 \text{ kJ/kg} \cdot \text{K}) \ln \frac{508.8 \text{ kPa}}{500 \text{ kPa}} \right] = -0.374 \text{ kJ/K} \\
\Delta S_{He} &= m \left(C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \right)_{He} \\
&= (0.808 \text{ kg}) \left[(5.1926 \text{ kJ/kg} \cdot \text{K}) \ln \frac{329 \text{ K}}{298 \text{ K}} - (2.0769 \text{ kJ/kg} \cdot \text{K}) \ln \frac{508.8 \text{ kPa}}{500 \text{ kPa}} \right] = 0.386 \text{ kJ/K} \\
\Delta S_{\text{piston}} &= \left(m C \ln \frac{T_2}{T_1} \right)_{\text{piston}} = (5 \text{ kg}) (0.386 \text{ kJ/kg} \cdot \text{K}) \ln \frac{329 \text{ K}}{325.5 \text{ K}} = 0.021 \text{ kJ/K} \\
S_{\text{gen}} &= \Delta S_{N_2} + \Delta S_{He} + \Delta S_{\text{piston}} = -0.374 + 0.386 + 0.021 = \mathbf{0.033 \text{ kJ/K}}
\end{aligned}$$

If the piston were not free to move, we would still have $T_2 = 329 \text{ K}$ but the volume of each gas would remain constant in this case:

$$\begin{aligned}
\Delta S_{N_2} &= m \left(C_v \ln \frac{T_2}{T_1} - R \ln \frac{V_2}{V_1} \right)_{N_2} = (4.77 \text{ kg}) (0.743 \text{ kJ/kg} \cdot \text{K}) \ln \frac{329 \text{ K}}{353 \text{ K}} = -0.250 \text{ kJ/K} \\
\Delta S_{He} &= m \left(C_v \ln \frac{T_2}{T_1} - R \ln \frac{V_2}{V_1} \right)_{He} = (0.808 \text{ kg}) (3.1156 \text{ kJ/kg} \cdot \text{K}) \ln \frac{329 \text{ K}}{298 \text{ K}} = 0.249 \text{ kJ/K} \\
S_{\text{gen}} &= \Delta S_{N_2} + \Delta S_{He} + \Delta S_{\text{piston}} = -0.250 + 0.249 + 0.021 = \mathbf{0.020 \text{ kJ/K}}
\end{aligned}$$

7-173 An insulated rigid tank equipped with an electric heater initially contains pressurized air. A valve is opened, and air is allowed to escape at constant temperature until the pressure inside drops to a specified value. The amount of electrical work done during this process and the total entropy change are to be determined.

Assumptions **1** This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform-flow process since the exit temperature (and enthalpy) of air remains constant. **2** Kinetic and potential energies are negligible. **3** The tank is insulated and thus heat transfer is negligible. **4** Air is an ideal gas with variable specific heats.

Properties The gas constant of air is $R = 0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$ (Table A-1). The properties of air are (Table A-17)

$$T_e = 330 \text{ K} \longrightarrow h_e = 330.34 \text{ kJ/kg}$$

$$T_1 = 330 \text{ K} \longrightarrow u_1 = 235.61 \text{ kJ/kg}$$

$$T_2 = 330 \text{ K} \longrightarrow u_2 = 235.61 \text{ kJ/kg}$$

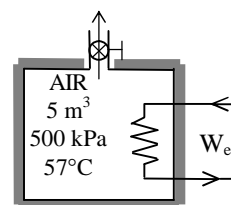
Analysis We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u , respectively, the mass and energy balances for this uniform-flow system can be expressed as

Mass balance. $m_{in} - m_{out} = \Delta m_{\text{system}} \rightarrow m_e = m_1 - m_2$

Energy balance. $E_{in} - E_{out} = \Delta E_{\text{system}}$

$\underbrace{\quad}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\quad}_{\text{Change in internal, kinetic, potential, etc. energies}}$

$$W_{e,in} - m_e h_e = m_2 u_2 - m_1 u_1 \quad (\text{since } Q \equiv ke \equiv pe \equiv 0)$$



The initial and the final masses of air in the tank are

$$m_1 = \frac{P_1 V}{RT_1} = \frac{(500 \text{ kPa})(5 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(330 \text{ K})} = 26.40 \text{ kg}$$

$$m_2 = \frac{P_2 V}{RT_2} = \frac{(200 \text{ kPa})(5 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(330 \text{ K})} = 10.56 \text{ kg}$$

Then from the mass and energy balances,

$$m_e = m_1 - m_2 = 26.40 - 10.56 = 15.84 \text{ kg}$$

$$\begin{aligned} W_{e,in} &= m_e h_e + m_2 u_2 - m_1 u_1 \\ &= (15.84 \text{ kg})(330.34 \text{ kJ/kg}) + (10.56 \text{ kg})(235.61 \text{ kJ/kg}) - (26.40 \text{ kg})(235.61 \text{ kJ/kg}) \\ &= \mathbf{1501 \text{ kJ}} \end{aligned}$$

(∇) The total entropy change, or the total entropy generation within the tank boundaries is determined from an entropy balance on the tank expressed as

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{\text{gen}}}_{\text{Entropy generation}} = \underbrace{\Delta S_{\text{system}}}_{\text{Change in entropy}}$$

$$-m_e s_e + S_{\text{gen}} = \Delta S_{\text{tank}}$$

or,

$$\begin{aligned} S_{\text{gen}} &= m_e s_e + \Delta S_{\text{tank}} = m_e s_e + (m_2 s_2 - m_1 s_1) \\ &= (m_1 - m_2) s_e + (m_2 s_2 - m_1 s_1) = m_2 (s_2 - s_e) - m_1 (s_1 - s_e) \end{aligned}$$

Assuming a constant average pressure of $(500 + 200)/2 = 350$ kPa for the exit stream, the entropy changes are determined to be

$$s_2 - s_e = C_p \ln \frac{T_2}{T_e} - R \ln \frac{P_2}{P_e} = -R \ln \frac{P_2}{P_e} = -(0.287 \text{ kJ/kg} \cdot \text{K}) \ln \frac{200 \text{ kPa}}{350 \text{ kPa}} = 0.1606 \text{ kJ/kg} \cdot \text{K}$$

$$s_1 - s_e = C_p \ln \frac{T_1}{T_e} - R \ln \frac{P_1}{P_e} = -R \ln \frac{P_1}{P_e} = -(0.287 \text{ kJ/kg} \cdot \text{K}) \ln \frac{500 \text{ kPa}}{350 \text{ kPa}} = -0.1024 \text{ kJ/kg} \cdot \text{K}$$

Therefore, the total entropy generated within the tank during this process is

$$\mathcal{S}_{gen} = (10.56 \text{ kg})(0.1606 \text{ kJ/kg} \cdot \text{K}) - (26.40 \text{ kg})(-0.1024 \text{ kJ/kg} \cdot \text{K}) = \mathbf{4.40 \text{ kJ/K}}$$

7-174 A 1-ton (1000 kg) of water is to be cooled in a tank by pouring ice into it. The final equilibrium temperature in the tank and the entropy generation are to be determined.

Assumptions **1** Thermal properties of the ice and water are constant. **2** Heat transfer to the water tank is negligible. **3** There is no stirring by hand or a mechanical device (it will add energy).

Properties The specific heat of water at room temperature is $C = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$, and the specific heat of ice at about 0°C is $C = 2.11 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3). The melting temperature and the heat of fusion of ice at 1 atm are 0°C and 333.7 kJ/kg .

Analysis (a) We take the ice and the water as the system, and disregard any heat transfer between the system and the surroundings. Then the energy balance for this process can be written as

$$\begin{aligned} \cancel{E_{in}} - \cancel{E_{out}} &= \Delta E_{\text{system}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ 0 &= \Delta U \\ 0 &= \Delta U_{\text{ice}} + \Delta U_{\text{water}} \end{aligned}$$

$$[mC(0^\circ\text{C} - T_1)_{\text{solid}} + mh_{if} + mC(T_2 - 0^\circ\text{C})_{\text{liquid}}]_{\text{ice}} + [mC(T_2 - T_1)]_{\text{water}} = 0$$

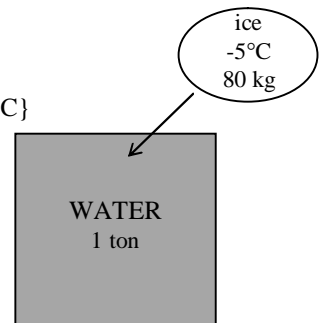
Substituting,

$$\begin{aligned} (80 \text{ kg})\{ (2.11 \text{ kJ/kg} \cdot ^\circ\text{C})[0 - (-5)]^\circ\text{C} + 333.7 \text{ kJ/kg} + (4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(T_2 - 0^\circ\text{C}) \} \\ + (1000 \text{ kg})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(T_2 - 20^\circ\text{C}) = 0 \end{aligned}$$

It gives

$$T_2 = 12.4^\circ\text{C}$$

which is the final equilibrium temperature in the tank.



(b) We take the ice and the water as our system, which is a closed system. Considering that the tank is well-insulated and thus there is no heat transfer, the entropy balance for this closed system can be expressed as

$$\begin{aligned} \cancel{S_{in}} - \cancel{S_{out}} + S_{\text{gen}} &= \Delta S_{\text{system}} \\ \text{Net entropy transfer} & \quad \text{Entropy} & \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{in entropy} \\ 0 + S_{\text{gen}} &= \Delta S_{\text{ice}} + \Delta S_{\text{water}} \end{aligned}$$

where

$$\begin{aligned} \Delta S_{\text{water}} &= \left(mC \ln \frac{T_2}{T_1} \right)_{\text{water}} = (1000 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{285.4 \text{ K}}{293 \text{ K}} = -109.9 \text{ kJ/K} \\ \Delta S_{\text{ice}} &= (\Delta S_{\text{solid}} + \Delta S_{\text{melting}} + \Delta S_{\text{liquid}})_{\text{ice}} \\ &= \left(\left(mC \ln \frac{T_2}{T_1} \right)_{\text{solid}} + \frac{mh_{if}}{T_{\text{melting}}} + \left(mC \ln \frac{T_2}{T_1} \right)_{\text{liquid}} \right)_{\text{ice}} \\ &= (80 \text{ kg}) \left((2.11 \text{ kJ/kg} \cdot \text{K}) \ln \frac{273 \text{ K}}{268 \text{ K}} + \frac{333.7 \text{ kJ/kg}}{273 \text{ K}} + (4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{285.4 \text{ K}}{273 \text{ K}} \right) \\ &= 115.8 \text{ kJ/K} \end{aligned}$$

Then,

$$S_{\text{gen}} = \Delta S_{\text{water}} + \Delta S_{\text{ice}} = -109.9 + 115.8 = 5.9 \text{ kJ/K}$$

7-175 An insulated cylinder initially contains a saturated liquid-vapor mixture of water at a specified temperature. The entire vapor in the cylinder is to be condensed isothermally by adding ice inside the cylinder. The amount of ice added and the entropy generation are to be determined.

Assumptions **1** Thermal properties of the ice are constant. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** There is no stirring by hand or a mechanical device (it will add energy).

Properties The specific heat of ice at about 0°C is $C = 2.11 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3). The melting temperature and the heat of fusion of ice at 1 atm are 0°C and 333.7 kJ/kg.

Analysis (a) We take the contents of the cylinder (ice and saturated water) as our system, which is a closed system. Noting that the temperature and thus the pressure remains constant during this phase change process and thus $W_b + \Delta U = \Delta H$, the energy balance for this system can be written as

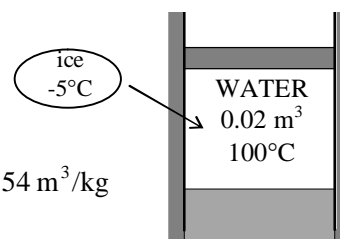
$$\begin{aligned} \cancel{E_{in}} - \cancel{E_{out}} &= \cancel{\Delta E_{system}} \\ \text{Net energy transfer} & \quad \text{Change in internal, kinetic,} \\ \text{by heat, work, and mass} & \quad \text{potential, etc. energies} \\ W_{b,in} = \Delta U &\rightarrow \Delta H = 0 \\ \Delta H_{ice} + \Delta H_{water} &= 0 \\ [mC(0^\circ\text{C} - T_1)_{solid} + mh_{if} + mC(T_2 - 0^\circ\text{C})_{liquid}]_{ice} + [m(h_2 - h_1)]_{water} &= 0 \end{aligned}$$

The properties of water at 100°C are (Table A-4)

$$\begin{aligned} \nu_f &= 0.001044, & \nu_g &= 1.6729 \text{ m}^3/\text{kg} \\ h_f &= 419.04, & h_{fg} &= 2257.0 \text{ kJ/kg} \end{aligned}$$

Then,

$$\begin{aligned} \nu_1 &= \nu_f + x_1 \nu_{fg} = 0.001044 + (0.2)(1.6729 - 0.001044) = 0.3354 \text{ m}^3/\text{kg} \\ h_1 &= h_f + x_1 h_{fg} = 419.04 + (0.2)(2257.0) = 870.4 \text{ kJ/kg} \\ s_1 &= s_f + x_1 s_{fg} = 1.3069 + (0.2)(6.048) = 2.5165 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$



$$\begin{aligned} h_2 &= h_{f@100^\circ\text{C}} = 419.04 \text{ kJ/kg} \\ s_2 &= s_{f@100^\circ\text{C}} = 1.3069 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

$$m_{steam} = \frac{V_1}{\nu_1} = \frac{0.02 \text{ m}^3}{0.3354 \text{ m}^3/\text{kg}} = 0.0596 \text{ kg}$$

Noting that $T_{1,ice} = -5^\circ\text{C}$ and $T_2 = 100^\circ\text{C}$ and substituting gives

$$m\{(2.11 \text{ kJ/kg} \cdot \text{K})[0 - (-5)] + 333.7 \text{ kJ/kg} + (4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(100 - 0)^\circ\text{C}\} + (0.0596 \text{ kg})(419.04 - 870.4) \text{ kJ/kg} = 0$$

$$m = 0.0353 \text{ kg} = \mathbf{35.3 \text{ g ice}}$$

(b) We take the ice and the steam as our system, which is a closed system. Considering that the tank is well-insulated and thus there is no heat transfer, the entropy balance for this closed system can be expressed as

$$\begin{aligned} \cancel{S_{in}} - \cancel{S_{out}} + S_{gen} &= \cancel{\Delta S_{system}} \\ \text{Net entropy transfer} & \quad \text{Entropy} & \quad \text{Change} \\ \text{by heat and mass} & \quad \text{generation} & \quad \text{in entropy} \\ 0 + S_{gen} &= \Delta S_{ice} + \Delta S_{steam} \end{aligned}$$

where

$$\Delta \mathcal{S}_{steam} = m(s_2 - s_1) = (0.0596 \text{ kg})(1.3069 - 2.5165) \text{ kJ/kg} \cdot \text{K} = -0.0721 \text{ kJ/K}$$

$$\begin{aligned} \Delta \mathcal{S}_{ice} &= (\Delta \mathcal{S}_{solid} + \Delta \mathcal{S}_{melting} + \Delta \mathcal{S}_{liquid})_{ice} = \left(\left(mC \ln \frac{T_2}{T_1} \right)_{solid} + \frac{mh_{ig}}{T_{melting}} + \left(mC \ln \frac{T_2}{T_1} \right)_{liquid} \right)_{ice} \\ &= (0.0353 \text{ kg}) \left((2.11 \text{ kJ/kg} \cdot \text{K}) \ln \frac{273 \text{ K}}{268 \text{ K}} + \frac{333.7 \text{ kJ/kg}}{273 \text{ K}} + (4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{373 \text{ K}}{273 \text{ K}} \right) \\ &= 0.0906 \text{ kJ/K} \end{aligned}$$

Then,

$$\mathcal{S}_{gen} = \Delta \mathcal{S}_{steam} + \Delta \mathcal{S}_{ice} = -0.0721 + 0.0906 = \mathbf{0.0185 \text{ kJ/K}}$$

7-176 An evacuated bottle is surrounded by atmospheric air. A valve is opened, and air is allowed to fill the bottle. The amount of heat transfer through the wall of the bottle when thermal and mechanical equilibrium is established and the amount of entropy generated are to be determined.

Assumptions **1** This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform-flow process since the state of fluid at the inlet remains constant. **2** Air is an ideal gas. **3** Kinetic and potential energies are negligible. **4** There are no work interactions involved. **5** The direction of heat transfer is to the air in the bottle (will be verified).

Properties The gas constant of air is $0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$ (Table A-1).

Analysis We take the bottle as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u , respectively, the mass and energy balances for this uniform-flow system can be expressed as

Mass balance: $m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \rightarrow m_i = m_2$ (since $m_{\text{out}} = m_{\text{initial}} = 0$)

Energy balance:

$$\cancel{E_{\text{in}}} - \cancel{E_{\text{out}}} = \Delta E_{\text{system}}$$

Net energy transfer by heat, work, and mass Change in internal, kinetic, potential, etc. energies

$$Q_{\text{in}} + m_i h_i = m_2 u_2 \quad (\text{since } W \cong E_{\text{out}} = E_{\text{initial}} = ke \cong pe \cong 0)$$

Combining the two balances:

$$Q_{\text{in}} = m_2 (u_2 - h_i)$$

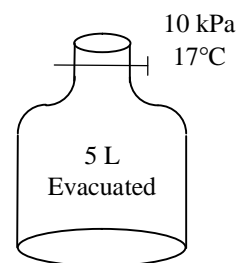
where

$$m_2 = \frac{P_2 V}{RT_2} = \frac{(100 \text{ kPa})(0.005 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(290 \text{ K})} = 0.0060 \text{ kg}$$

$$T_i = T_2 = 290 \text{ K} \xrightarrow{\text{Table A-17}} \begin{aligned} h_i &= 290.16 \text{ kJ/kg} \\ u_2 &= 206.91 \text{ kJ/kg} \end{aligned}$$

Substituting,

$$Q_{\text{in}} = (0.0060 \text{ kg})(206.91 - 290.16) \text{ kJ/kg} = -0.5 \text{ kJ} \rightarrow Q_{\text{out}} = \mathbf{0.5 \text{ kJ}}$$



Note that the negative sign for heat transfer indicates that the assumed direction is wrong. Therefore, we reverse the direction.

The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the bottle and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. The entropy balance for it can be expressed as

$$\cancel{m_i s_i} - \cancel{m_2 s_2} + S_{\text{gen}} = \Delta S_{\text{system}}$$

Net entropy transfer by heat and mass Entropy generation Change in entropy

$$m_i s_i - \frac{Q_{\text{out}}}{T_{b,\text{in}}} + S_{\text{gen}} = \Delta S_{\text{tank}} = m_2 s_2 - m_i s_i^{\text{A0}} = m_2 s_2$$

Therefore, the total entropy generated during this process is

$$S_{\text{gen}} = -m_i s_i + m_2 s_2 + \frac{Q_{\text{out}}}{T_{b,\text{out}}} = m_2 (s_2 - s_i)^{\text{A0}} + \frac{Q_{\text{out}}}{T_{b,\text{out}}} = \frac{Q_{\text{out}}}{T_{\text{surr}}} = \frac{0.5 \text{ kJ}}{290 \text{ K}} = \mathbf{0.0017 \text{ kJ/K}}$$

7-177 (a) Water is heated from 16°C to 43°C by an electric resistance heater placed in the water pipe as it flows through a showerhead steadily at a rate of 10 L/min. The electric power input to the heater and the rate of entropy generation are to be determined. The reduction in power input and entropy generation as a result of installing a 50% efficient regenerator are also to be determined.

Assumptions 1 This is a steady-flow process since there is no change with time at any point within the system and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** Water is an incompressible substance with constant specific heats. **3** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **4** Heat losses from the pipe are negligible.

Properties The density of water is given to be $\rho = 1 \text{ kg/L}$. The specific heat of water at room temperature is $C = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-3).

Analysis We take the pipe as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Then the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{Q}_{e,\text{in}} + \dot{m}h_1}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\Delta \dot{E}_{\text{system}}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} \stackrel{\dot{E}=0 \text{ (steady)}}{=} 0 \rightarrow \dot{Q}_{e,\text{in}} = \dot{m}(h_2 - h_1)$$

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

$$\dot{Q}_{e,\text{in}} = \dot{m}(h_2 - h_1) = \dot{m}C(T_2 - T_1)$$

where

$$\dot{m} = \rho \dot{V} = (1 \text{ kg/L})(10 \text{ L/min}) = 10 \text{ kg/min}$$

Substituting,

$$\dot{Q}_{e,\text{in}} = (10/60 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(43 - 16)^\circ\text{C} = \mathbf{18.8 \text{ kW}}$$

The rate of entropy generation in the heating section during this process is determined by applying the entropy balance on the heating section. Noting that this is a steady-flow process and heat transfer from the heating section is negligible,

$$\underbrace{\dot{Q}_{e,\text{in}}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{\text{gen}}}_{\text{Rate of entropy generation}} = \underbrace{\Delta \dot{S}_{\text{system}}}_{\text{Rate of change of entropy}} \stackrel{\dot{S}=0}{=} 0$$

$$\dot{m}s_1 - \dot{m}s_2 + \dot{S}_{\text{gen}} = 0$$

$$\dot{S}_{\text{gen}} = \dot{m}(s_2 - s_1)$$

Noting that water is an incompressible substance and substituting,

$$\dot{S}_{\text{gen}} = \dot{m}C \ln \frac{T_2}{T_1} = (10/60 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{316 \text{ K}}{289 \text{ K}} = \mathbf{0.0622 \text{ kJ/K}}$$

(b) The energy recovered by the heat exchanger is

$$\dot{Q}_{\text{saved}} = \epsilon \dot{Q}_{\text{max}} = \epsilon \dot{m}C(T_{\text{max}} - T_{\text{min}})$$

$$= 0.5(10/60 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(39 - 16)^\circ\text{C}$$

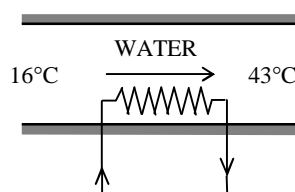
$$= 8.0 \text{ kJ/s} = 8.0 \text{ kW}$$

Therefore, 8.0 kW less energy is needed in this case, and the required electric power in this case reduces to

$$\dot{W}_{\text{in,new}} = \dot{W}_{\text{in,old}} - \dot{Q}_{\text{saved}} = 18.8 - 8.0 = \mathbf{10.8 \text{ kW}}$$

Taking the cold water stream in the heat exchanger as our control volume (a steady-flow system), the temperature at which the cold water leaves the heat exchanger and enters the electric resistance heating section is determined to be

$$\dot{Q} = \dot{m}C(T_{c,\text{out}} - T_{c,\text{in}})$$



Substituting,

$$8 \text{ kJ/s} = (10/60 \text{ kg/s})(4.184 \text{ kJ/kg} \cdot ^\circ\text{C})(T_{c,out} - 16^\circ\text{C})$$

It yields

$$T_{c,out} = 27.5^\circ\text{C} = 300.5 \text{ K}$$

The rate of entropy generation in the heating section in this case is determined similarly to be

$$\dot{S}_{gen} = \dot{m}C \ln \frac{T_2}{T_1} = (10/60 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln \frac{316 \text{ K}}{300.5 \text{ K}} = \mathbf{0.0351 \text{ kJ/K}}$$

Thus the reduction in the rate of entropy generation within the heating section is

$$\dot{S}_{reduction} = 0.0622 - 0.0350 = \mathbf{0.0272 \text{ kW/K}}$$

7-178 Using EES (or other) software, the work input to a multistage compressor is to be determined for a given set of inlet and exit pressures for any number of stages. The pressure ratio across each stage is assumed to be identical and the compression process to be polytropic. The compressor work is to be tabulated and plotted against the number of stages for $P_1 = 100 \text{ kPa}$, $T_1 = 17^\circ\text{C}$, $P_2 = 800 \text{ kPa}$, and $n = 1.35$ for air.

```
GAS$ = 'Air'
Nstage = 2 "number of stages of compression with intercooling, each having same
pressure ratio."
n=1.35
MM=MOLARMASS(GAS$)
R_u = 8.314"[kJ/kmol-K]"
R=R_u/MM"[kJ/kg-K]"
k=1.4
P1=100"[kPa]"
T1=17"[C]"
P2=800"[kPa]"
R_p = (P2/P1)^(1/Nstage)
W_dot_comp= Nstage*n*R*(T1+273)/(n-1)*((R_p)^((n-1)/n) - 1)"[kJ/kg]"
```

Nstage	\dot{W}_{comp} [kJ/kg]
1	229.4
2	198.7
3	189.6
4	185.3
5	182.8
6	181.1
7	179.9
8	179
9	178.4
10	177.8

