Chapter 8
EXERGY – A MEASURE OF WORK POTENTIAL

Exergy, Irreversibility, Reversible Work, and Second-Law Efficiency

8-1C Reversible work differs from the useful work by irreversibilities. For reversible processes both are identical. $W_u = W_{rev} - I$.

8-2C Reversible work and irreversibility are identical for processes that involve no actual useful work.

8-3C The dead state.

8-4C Yes; exergy is a function of the state of the surroundings as well as the state of the system.

8-5C Useful work differs from the actual work by the surroundings work. They are identical for systems that involve no surroundings work such as steady-flow systems.

8-6C Yes.

8-7C No, not necessarily. The well with the higher temperature will have a higher exergy.

8-8C The system that is at the temperature of the surroundings has zero exergy. But the system that is at a lower temperature than the surroundings has some exergy since we can run a heat engine between these two temperature levels.

8-9C They would be identical.

8-10C The second-law efficiency is a measure of the performance of a device relative to its performance under reversible conditions. It differs from the first law efficiency in that it is not a conversion efficiency.

8-11C No. The power plant that has a lower thermal efficiency may have a higher second-law efficiency.

8-12C No. The refrigerator that has a lower COP may have a higher second-law efficiency.

8-13C A processes with $W_{rev} = 0$ is reversible if it involves no actual useful work. Otherwise it is irreversible.

8-14C Yes.

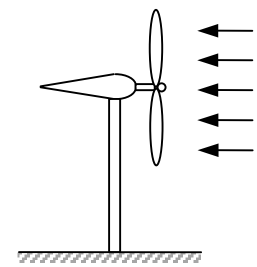
8-15 Windmills are to be installed at a location with steady winds to generate power. The minimum number of windmills that need to be installed is to be determined.

Assumptions Air is at standard conditions of 1 atm and 25°C

Properties The gas constant of air is 0.287 kPa.m^3/kg.K (Table A-1).

Analysis The exergy or work potential of the blowing air is the kinetic energy it possesses,

$$\text{Exergy} = \text{ke} = \frac{V^2}{2} = \frac{(8\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.032\text{ kJ/kg}$$



At standard atmospheric conditions (25°C, 101 kPa), the density and the mass flow rate of air are

$$\rho = \frac{P}{RT} = \frac{101\text{ kPa}}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298\text{ K})} = 1.18\text{ m}^3/\text{kg}$$

and

$$\dot{m} = \rho A V_1 = \rho\frac{\pi D^2}{4}\mathbf{V}_1 = (1.18\text{ kg/m}^3)(\pi/4)(10\text{ m})^2(8\text{ m/s}) = 742\text{ kg/s}$$

Thus,

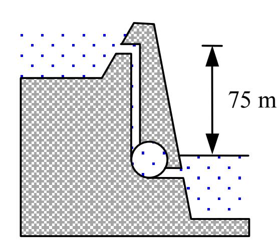
$$\text{Available Power} = \dot{m}\text{ke} = (742\text{ kg/s})(0.032\text{ kJ/kg}) = 23.74\text{ kW}$$

The minimum number of windmills that needs to be installed is

$$N = \frac{\dot{W}_{\text{total}}}{\dot{W}} = \frac{600\text{ kW}}{23.74\text{ kW}} = 25.3 \cong \mathbf{26\ \ windmills}$$

8-16 Water is to be pumped to a high elevation lake at times of low electric demand for use in a hydroelectric turbine at times of high demand. For a specified energy storage capacity, the minimum amount of water that needs to be stored in the lake is to be determined.

Assumptions The evaporation of water from the lake is negligible.



Analysis The exergy or work potential of the water is the potential energy it possesses,

$$\text{Exergy} = \text{PE} = \text{mgh}$$

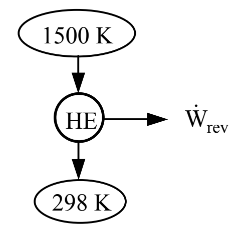
Thus,

$$m = \frac{PE}{gh} = \frac{5\times10^6\text{ kWh}}{(9.8\text{ m/s}^2)(75\text{ m})}\left(\frac{3600\text{ s}}{1\text{ h}}\right)\left(\frac{1000\text{ m}^2/\text{s}^2}{1\text{ kW}\cdot\text{s/kg}}\right) = \mathbf{2.45\times10^{10}\ kg}$$

8-17 A heat reservoir at a specified temperature can supply heat at a specified rate. The exergy of this heat supplied is to be determined.

Analysis The exergy of the supplied heat, in the rate form, is the amount of power that would be produced by a reversible heat engine,

$$\eta_{\text{th,max}} = \eta_{\text{th,rev}} = 1 - \frac{T_0}{T_H} = 1 - \frac{298\ \text{K}}{1500\ \text{K}} = 0.8013$$



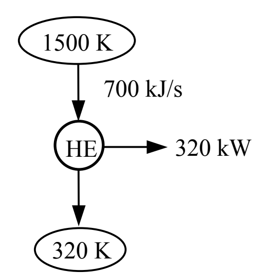
$$\begin{aligned}\text{Exergy} = \dot{W}_{\text{max,out}} = \dot{W}_{\text{rev,out}} &= \eta_{\text{th,rev}}\dot{Q}_{\text{in}} \\ &= (0.8013)(150{,}000 / 3600\ \text{kJ/s}) \\ &= \mathbf{33.4\ kW}\end{aligned}$$

8-18 [*Also solved by EES on enclosed CD*] A heat engine receives heat from a source at a specified temperature at a specified rate, and rejects the waste heat to a sink. For a given power output, the reversible power, the rate of irreversibility, and the 2nd law efficiency are to be determined.

Analysis (a) The reversible power is the power produced by a reversible heat engine operating between the specified temperature limits,

$$\eta_{\text{th,max}} = \eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H} = 1 - \frac{320\ \text{K}}{1500\ \text{K}} = 0.787$$

$$\dot{W}_{\text{rev,out}} = \eta_{\text{th,rev}}\dot{Q}_{\text{in}} = (0.787)(700\ \text{kJ/s}) = \mathbf{550.7\ \ kW}$$



(b) The irreversibility rate is the difference between the reversible power and the actual power output:

$$\dot{I} = \dot{W}_{\text{rev,out}} - \dot{W}_{\text{u,out}} = 550.7 - 320 = \mathbf{230.7\ kW}$$

(c) The second law efficiency is determined from its definition,

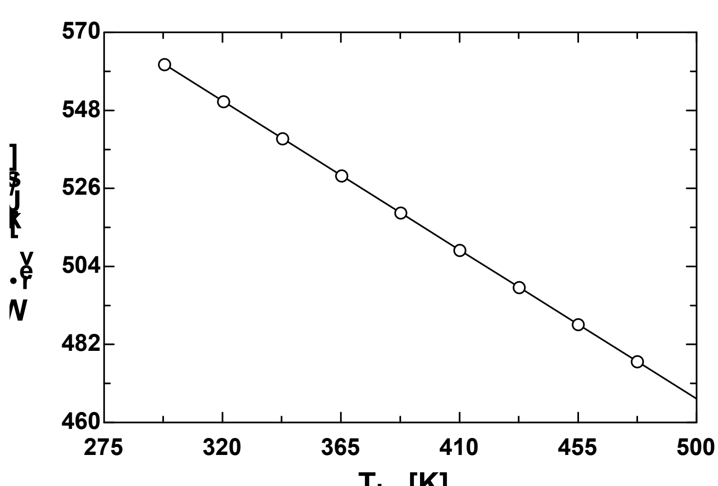
$$\eta_{\text{II}} = \frac{W_{\text{u,out}}}{W_{\text{rev,out}}} = \frac{320\ \text{kW}}{550.7\ \text{kW}} = \mathbf{58.1\%}$$

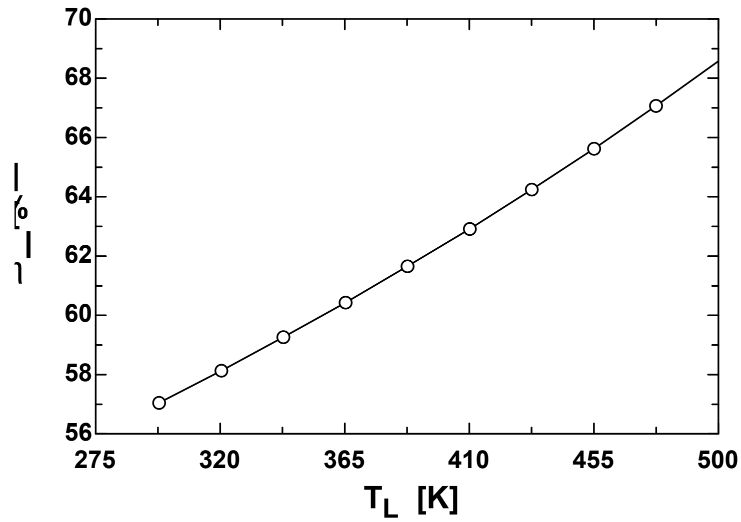
8-19 EES Problem 8-18 is reconsidered. The effect of reducing the temperature at which the waste heat is rejected on the reversible power, the rate of irreversibility, and the second law efficiency is to be studied and the results are to be plotted.

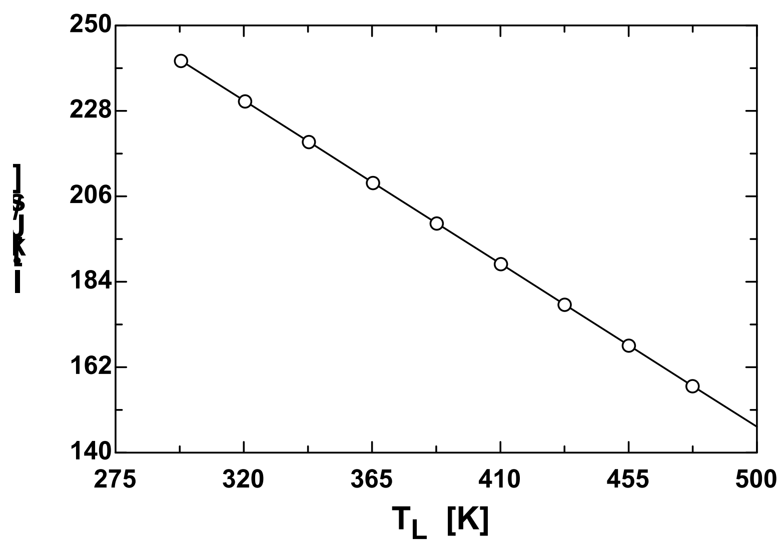
Analysis The problem is solved using EES, and the solution is given below.

```
"Input Data"
T_H= 1500 [K]
Q_dot_H= 700 [kJ/s]
{T_L=320 [K]}
W_dot_out = 320 [kW]
T_Lsurr =25 [C]

"The reversible work is the maximum work done by the Carnot Engine
between T_H and T_L:"
Eta_Carnot=1 - T_L/T_H
W_dot_rev=Q_dot_H*Eta_Carnot
"The irreversibility is given as:"
I_dot = W_dot_rev-W_dot_out

"The thermal efficiency is, in percent:"
Eta_th = Eta_Carnot*Convert(, %)

"The second law efficiency is, in percent:"
Eta_II = W_dot_out/W_dot_rev*Convert(, %)
```

η_{II} [%]	I [kJ/s]	W_{rev} [kJ/s]	T_L [K]
68.57	146.7	466.7	500
67.07	157.1	477.1	477.6
65.63	167.6	487.6	455.1
64.25	178.1	498.1	432.7
62.92	188.6	508.6	410.2
61.65	199	519	387.8
60.43	209.5	529.5	365.3
59.26	220	540	342.9
58.13	230.5	550.5	320.4
57.05	240.9	560.9	298




70
68
66
64
62
60
58
56
275
320
365
410
455
500
T_L [K]


250
228
206
184
162
140
275
320
365
410
455
500
T_L [K]

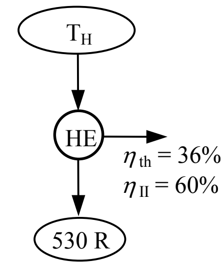
8-20E The thermal efficiency and the second-law efficiency of a heat engine are given. The source temperature is to be determined.

Analysis From the definition of the second law efficiency,

$$\eta_{\mathrm{II}} = \frac{\eta_{\mathrm{th}}}{\eta_{\mathrm{th,rev}}} \longrightarrow \eta_{\mathrm{th,rev}} = \frac{\eta_{\mathrm{th}}}{\eta_{\mathrm{II}}} = \frac{0.36}{0.60} = 0.60$$

Thus,

$$\eta_{\mathrm{th,rev}} = 1 - \frac{T_L}{T_H} \longrightarrow T_H = T_L/(1-\eta_{\mathrm{th,rev}}) = (530\ \mathrm{R})/0.40 = \mathbf{1325\ R}$$

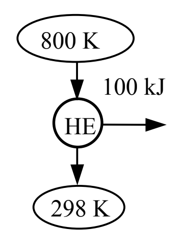


8-21 A body contains a specified amount of thermal energy at a specified temperature. The amount that can be converted to work is to be determined.

Analysis The amount of heat that can be converted to work is simply the amount that a reversible heat engine can convert to work,

$$\eta_{\mathrm{th,rev}} = 1 - \frac{T_0}{T_H} = 1 - \frac{298\ \mathrm{K}}{800\ \mathrm{K}} = 0.6275$$

$$\begin{aligned} W_{\mathrm{max,out}} &= W_{\mathrm{rev,out}} = \eta_{\mathrm{th,rev}} Q_{\mathrm{in}} \\ &= (0.6275)(100\ \mathrm{kJ}) \\ &= \mathbf{62.75\ kJ} \end{aligned}$$



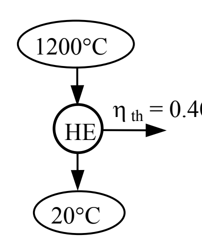
8-22 The thermal efficiency of a heat engine operating between specified temperature limits is given. The second-law efficiency of a engine is to be determined.

Analysis The thermal efficiency of a reversible heat engine operating between the same temperature reservoirs is

$$\eta_{\mathrm{th,rev}} = 1 - \frac{T_0}{T_H} = 1 - \frac{293\ \mathrm{K}}{1200 + 273\ \mathrm{K}} = 0.801$$

Thus,

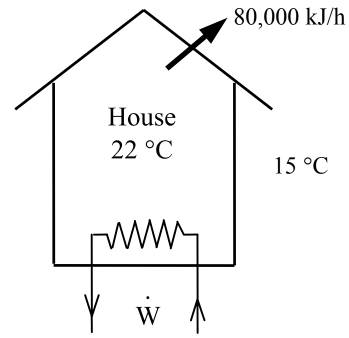
$$\eta_{\mathrm{II}} = \frac{\eta_{\mathrm{th}}}{\eta_{\mathrm{th,rev}}} = \frac{0.40}{0.801} = \mathbf{49.9\%}$$



8-23 A house is maintained at a specified temperature by electric resistance heaters. The reversible work for this heating process and irreversibility are to be determined.

Analysis The reversible work is the minimum work required to accomplish this process, and the irreversibility is the difference between the reversible work and the actual electrical work consumed. The actual power input is

$$\dot{W}_{\text{in}} = \dot{Q}_{\text{out}} = \dot{Q}_H = 80{,}000\ \text{kJ/h} = 22.22\ \text{kW}$$



The COP of a reversible heat pump operating between the specified temperature limits is

$$\text{COP}_{\text{HP,rev}} = \frac{1}{1 - T_L / T_H} = \frac{1}{1 - 288/295} = 42.14$$

Thus,

$$\dot{W}_{\text{rev,in}} = \frac{\dot{Q}_H}{\text{COP}_{\text{HP,rev}}} = \frac{22.22\ \text{kW}}{42.14} = \mathbf{0.53\ \ kW}$$

and

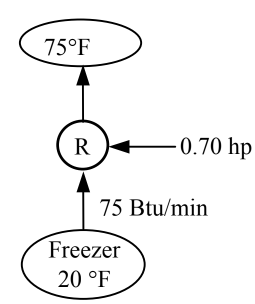
$$\dot{I} = \dot{W}_{\text{u,in}} - \dot{W}_{\text{rev,in}} = 22.22 - 0.53 = \mathbf{21.69\ \ kW}$$

8-24E A freezer is maintained at a specified temperature by removing heat from it at a specified rate. The power consumption of the freezer is given. The reversible power, irreversibility, and the second-law efficiency are to be determined.

Analysis (a) The reversible work is the minimum work required to accomplish this task, which is the work that a reversible refrigerator operating between the specified temperature limits would consume,

$$\text{COP}_{\text{R,rev}} = \frac{1}{T_H / T_L - 1} = \frac{1}{535/480 - 1} = 8.73$$

$$\dot{W}_{\text{rev,in}} = \frac{\dot{Q}_L}{COP_{\text{R,rev}}} = \frac{75\ \text{Btu/min}}{8.73}\left(\frac{1\ \text{hp}}{42.41\ \text{Btu/min}}\right) = \mathbf{0.20\ hp}$$



(b) The irreversibility is the difference between the reversible work and the actual electrical work consumed,

$$\dot{I} = \dot{W}_{\text{u,in}} - \dot{W}_{\text{rev,in}} = 0.70 - 0.20 = \mathbf{0.50\ hp}$$

(c) The second law efficiency is determined from its definition,

$$\eta_{\text{II}} = \frac{\dot{W}_{\text{rev}}}{\dot{W}_u} = \frac{0.20\ \text{hp}}{0.7\ \text{hp}} = \mathbf{28.9\%}$$

8-25 It is to be shown that the power produced by a wind turbine is proportional to the cube of the wind velocity and the square of the blade span diameter.

Analysis The power produced by a wind turbine is proportional to the kinetic energy of the wind, which is equal to the product of the kinetic energy of air per unit mass and the mass flow rate of air through the blade span area. Therefore,

$$\begin{aligned}\text{Wind power} &= \text{(Efficiency)(Kinetic energy)(Mass flow rate of air)}\\ &= \eta_{\text{wind}}\frac{V^2}{2}(\rho AV) = \eta_{\text{wind}}\frac{V^2}{2}\rho\frac{\pi D^2}{4}V\\ &= \eta_{\text{wind}}\rho\frac{\pi V^3 D^2}{8} = (\text{Constant})V^3 D^2\end{aligned}$$

which completes the proof that wind power is proportional to the cube of the wind velocity and to the square of the blade span diameter.

8-26 A geothermal power produces 14 MW power while the exergy destruction in the plant is 18.5 MW. The exergy of the geothermal water entering to the plant, the second-law efficiency of the plant, and the exergy of the heat rejected from the plant are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Water properties are used for geothermal water.

Analysis (*a*) The properties of geothermal water at the inlet of the plant and at the dead state are (Tables A-4 through A-6)

$$\left.\begin{array}{l}T_1 = 160°\text{C}\\ x_1 = 0\end{array}\right\}\begin{array}{l}h_1 = 675.47\ \text{kJ/kg}\\ s_1 = 1.9426\ \text{kJ/kg.K}\end{array}$$

$$\left.\begin{array}{l}T_0 = 25°\text{C}\\ x_0 = 0\end{array}\right\}\begin{array}{l}h_0 = 104.83\ \text{kJ/kg}\\ s_0 = 0.36723\ \text{kJ/kg.K}\end{array}$$

The exergy of geothermal water entering the plant is

$$\begin{aligned}\dot{X}_{\text{in}} &= \dot{m}[h_1 - h_0 - T_0(s_1 - s_0)]\\ &= (440\ \text{kg/s})[(675.47 - 104.83)\ \text{kJ/kg} + 0 - (25 + 273\ \text{K})(1.9426 - 0.36723)\text{kJ/kg.K}]\\ &= 44{,}525\ \text{kW} = \mathbf{44.53\ MW}\end{aligned}$$

(*b*) The second-law efficiency of the plant is the ratio of power produced to the exergy input to the plant

$$\eta_{II} = \frac{\dot{W}_{\text{out}}}{\dot{X}_{\text{in}}} = \frac{14{,}000\ \text{kW}}{44{,}525\ \text{kW}} = \mathbf{0.314}$$

(*c*) The exergy of the heat rejected from the plant may be determined from an exergy balance on the plant

$$\dot{X}_{\text{heat,out}} = \dot{X}_{\text{in}} - \dot{W}_{\text{out}} - \dot{X}_{\text{dest}} = 44{,}525 - 14{,}000 - 18{,}500 = 12{,}025\ \text{kW} = \mathbf{12.03\ MW}$$

Second-Law Analysis of Closed Systems

8-27C Yes.

8-28C Yes, it can. For example, the 1st law efficiency of a reversible heat engine operating between the temperature limits of 300 K and 1000 K is 70%. However, the second law efficiency of this engine, like all reversible devices, is 100%.

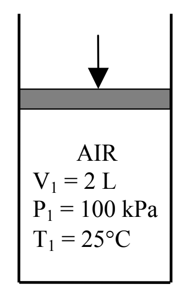
8-29 A cylinder initially contains air at atmospheric conditions. Air is compressed to a specified state and the useful work input is measured. The exergy of the air at the initial and final states, and the minimum work input to accomplish this compression process, and the second-law efficiency are to be determined

Assumptions **1** Air is an ideal gas with constant specific heats. **2** The kinetic and potential energies are negligible.

Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1). The specific heats of air at the average temperature of (298+423)/2=360 K are c_p = 1.009 kJ/kg·K and c_v = 0.722 kJ/kg·K (Table A-2).

Analysis (a) We realize that $X_1 = \Phi_1 = \mathbf{0}$ since air initially is at the dead state. The mass of air is

$$m = \frac{P_1 \boldsymbol{V}_1}{RT_1} = \frac{(100\text{ kPa})(0.002\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298\text{ K})} = 0.00234\text{ kg}$$



Also,
$$\frac{P_2 \boldsymbol{V}_2}{T_2} = \frac{P_1 \boldsymbol{V}_1}{T_1} \longrightarrow \boldsymbol{V}_2 = \frac{P_1 T_2}{P_2 T_1}\boldsymbol{V}_1 = \frac{(100\text{ kPa})(423\text{ K})}{(600\text{ kPa})(298\text{ K})}(2\text{ L}) = 0.473\text{ L}$$

and

$$\begin{aligned} s_2 - s_0 &= c_{p,\text{avg}} \ln\frac{T_2}{T_0} - R\ln\frac{P_2}{P_0} \\ &= (1.009\text{ kJ/kg}\cdot\text{K})\ln\frac{423\text{ K}}{298\text{ K}} - (0.287\text{ kJ/kg}\cdot\text{K})\ln\frac{600\text{ kPa}}{100\text{ kPa}} \\ &= -0.1608\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

Thus, the exergy of air at the final state is

$$\begin{aligned} X_2 = \Phi_2 &= m\left[c_{v,\text{avg}}(T_2 - T_0) - T_0(s_2 - s_0)\right] + P_0(\boldsymbol{V}_2 - \boldsymbol{V}_0) \\ &= (0.00234\text{ kg})\left[(0.722\text{ kJ/kg}\cdot\text{K})(423\text{ - }298)\text{K - }(298\text{ K})(\text{-}0.1608\text{ kJ/kg}\cdot\text{K})\right] \\ &\quad + (100\text{ kPa})(0.000473\text{ - }0.002)\text{m}^3[\text{kJ/m}^3\cdot\text{kPa}] \\ &= \mathbf{0.171\text{ kJ}} \end{aligned}$$

(*b*) The minimum work input is the reversible work input, which can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer}\\ \text{by heat, work, and mass}}} \underbrace{- X_{\text{destroyed}}^{\nearrow 0\text{ (reversible)}}}_{\substack{\text{Exergy}\\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change}\\ \text{in exergy}}}$$

$$\begin{aligned} W_{\text{rev,in}} &= X_2 - X_1 \\ &= 0.171 - 0 = \mathbf{0.171\text{kJ}} \end{aligned}$$

(c) The second-law efficiency of this process is

$$\eta_{\text{II}} = \frac{W_{\text{rev,in}}}{W_{\text{u,in}}} = \frac{0.171\text{ kJ}}{1.2\text{ kJ}} = \mathbf{14.3\%}$$

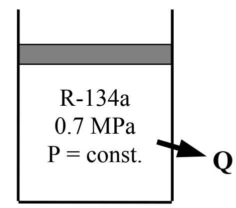
8-30 A cylinder is initially filled with R-134a at a specified state. The refrigerant is cooled and condensed at constant pressure. The exergy of the refrigerant at the initial and final states, and the exergy destroyed during this process are to be determined.

Assumptions The kinetic and potential energies are negligible.

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

$$\left.\begin{array}{l} P_1 = 0.7\text{ MPa} \\ T_1 = 60°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = 0.034875\text{ m}^3/\text{kg} \\ u_1 = 274.01\text{ kJ/kg} \\ s_1 = 1.0256\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 0.7\text{ MPa} \\ T_2 = 24°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_2 \cong \boldsymbol{v}_{f@24°\text{C}} = 0.0008261\text{ m}^3/\text{kg} \\ u_2 \cong u_{f@24°\text{C}} = 84.44\text{ kJ/kg} \\ s_2 \cong s_{f@24°\text{C}} = 0.31958\text{ kJ/kg}\cdot\text{K} \end{array}$$



$$\left.\begin{array}{l} P_0 = 0.1\text{ MPa} \\ T_0 = 24°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_0 = 0.23718\text{ m}^3/\text{kg} \\ u_0 = 251.84\text{ kJ/kg} \\ s_0 = 1.1033\text{ kJ/kg}\cdot\text{K} \end{array}$$

Analysis (*a*) From the closed system exergy relation,

$$X_1 = \Phi_1 = m\{(u_1 - u_0) - T_0(s_1 - s_0) + P_0(\boldsymbol{v}_1 - \boldsymbol{v}_0)\}$$

$$= (5\text{ kg})\{(274.01 - 251.84)\text{ kJ/kg} - (297\text{ K})(1.0256 - 1.1033)\text{ kJ/kg}\cdot\text{K}$$

$$+ (100\text{ kPa})(0.034875 - 0.23718)\text{m}^3/\text{kg}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)\}$$

$$= \mathbf{125.1\ kJ}$$

and,

$$X_2 = \Phi_2 = m\{(u_2 - u_0) - T_0(s_2 - s_0) + P_0(\boldsymbol{v}_2 - \boldsymbol{v}_0)\}$$

$$= (5\text{ kg})\{(84.44 - 251.84)\text{ kJ/kg - }(297\text{ K})(0.31958 - 1.1033)\text{ kJ/kg}\cdot\text{K}$$

$$+ (100\text{ kPa})(0.0008261 - 0.23718)\text{m}^3/\text{kg}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)\}$$

$$= \mathbf{208.6\ kJ}$$

(*b*) The reversible work input, which represents the minimum work input $W_{\text{rev,in}}$ in this case can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer}\\ \text{by heat, work, and mass}}} - \underbrace{X_{\text{destroyed}}^{\nearrow 0\text{ (reversible)}}}_{\substack{\text{Exergy}\\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change}\\ \text{in exergy}}}$$

$$W_{\text{rev,in}} = X_2 - X_1 = 208.6 - 125.1 = 83.5\text{ kJ}$$

Noting that the process involves only boundary work, the useful work input during this process is simply the boundary work in excess of the work done by the surrounding air,

$$W_{\text{u,in}} = W_{\text{in}} - W_{\text{surr,in}} = W_{\text{in}} - P_0(\boldsymbol{V}_1 - \boldsymbol{V}_2) = P(\boldsymbol{V}_1 - \boldsymbol{V}_2) - P_0 m(\boldsymbol{v}_1 - \boldsymbol{v}_2)$$

$$= m(P - P_0)(\boldsymbol{v}_1 - \boldsymbol{v}_2)$$

$$= (5\text{ kg})(700\text{ - }100\text{ kPa})(0.034875 - 0.0008261\text{ m}^3/\text{kg})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 102.1\text{ kJ}$$

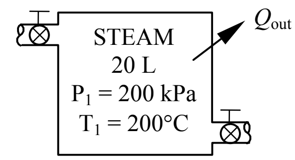
Knowing both the actual useful and reversible work inputs, the exergy destruction or irreversibility that is the difference between the two is determined from its definition to be

$$X_{\text{destroyed}} = I = W_{\text{u,in}} - W_{\text{rev,in}} = 102.1 - 83.5 = \mathbf{18.6\ kJ}$$

8-31 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 pressure drops to a specified value by transferring heat to the room. The amount of heat transfer to the room and the maximum amount of heat that can be supplied to the room are to be determined.

Assumptions Kinetic and potential energies are negligible.

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



$$\left.\begin{array}{l} P_1 = 200\ \text{kPa} \\ T_1 = 200°\text{C} \end{array}\right\} \begin{array}{l} \mathbf{v}_1 = 1.0805\ \text{m}^3/\text{kg} \\ u_1 = 2654.6\ \text{kJ/kg} \\ s_1 = 7.5081\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_2 = 80°\text{C} \\ (\mathbf{v}_2 = \mathbf{v}_1) \end{array}\right\} \begin{array}{l} x_2 = \dfrac{\mathbf{v}_2 - \mathbf{v}_f}{\mathbf{v}_{fg}} = \dfrac{1.0805 - 0.001029}{3.4053 - 0.001029} = 0.3171 \\ u_2 = u_f + x_2 u_{fg} = 334.97 + 0.3171 \times 2146.6 = 1015.6\ \text{kJ/kg} \\ s_2 = s_f + x_2 s_{fg} = 1.0756 + 0.3171 \times 6.5355 = 3.1479\ \text{kJ/kg}\cdot\text{K} \end{array}$$

Analysis (a) The mass of the steam is

$$m = \frac{\mathbf{V}}{\mathbf{v}_1} = \frac{0.020\ \text{m}^3}{1.0805\ \text{m}^3/\text{kg}} = 0.01851\ \text{kg}$$

The amount of heat transfer to the room is determined from an energy balance on the radiator expressed as

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

$$-Q_{\text{out}} = \Delta U = m(u_2 - u_1) \quad (\text{since } W = \text{KE} = \text{PE} = 0)$$

$$Q_{\text{out}} = m(u_1 - u_2)$$

or,

$$Q_{\text{out}} = (0.01851\ \text{kg})(2654.6 - 1015.6)\ \text{kJ/kg} = \mathbf{30.3\ kJ}$$

(*b*) The reversible work output, which represents the maximum work output $W_{\text{rev,out}}$ in this case can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer} \\ \text{by heat, work, and mass}}} \underbrace{- X_{\text{destroyed}}^{\nearrow 0\ (\text{reversible})}}_{\substack{\text{Exergy} \\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change} \\ \text{in exergy}}}$$

$$-W_{\text{rev,out}} = X_2 - X_1 \ \rightarrow\ W_{\text{rev,out}} = X_1 - X_2 = \Phi_1 - \Phi_2$$

Substituting the closed system exergy relation, the reversible work during this process is determined to be

$$\begin{aligned} W_{\text{rev,out}} &= m\left[(u_1 - u_2) - T_0(s_1 - s_2) + P_0(\mathbf{v}_1 - \mathbf{v}_2)^{\nearrow 0}\right] \\ &= m\left[(u_1 - u_2) - T_0(s_1 - s_2)\right] \\ &= (0.01851\ \text{kg})\left[(2654.6\text{-}1015.6)\text{kJ/kg} - (273\ \text{K})(7.5081\text{-}3.1479)\text{kJ/kg}\cdot\text{K}\right] = 8.305\ \text{kJ} \end{aligned}$$

When this work is supplied to a reversible heat pump, it will supply the room heat in the amount of

$$Q_H = \text{COP}_{\text{HP,rev}} W_{\text{rev}} = \frac{W_{\text{rev}}}{1 - T_L/T_H} = \frac{8.305\ \text{kJ}}{1\text{-}273/294} = \mathbf{116.3\ kJ}$$

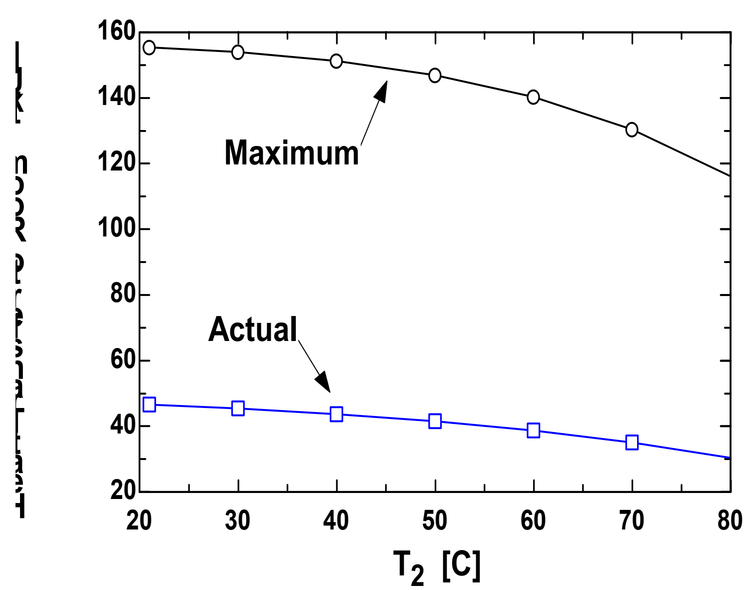
Discussion Note that the amount of heat supplied to the room can be increased by about 3 times by eliminating the irreversibility associated with the irreversible heat transfer process.

8-32 EES Problem 8-31 is reconsidered. The effect of the final steam temperature in the radiator on the amount of actual heat transfer and the maximum amount of heat that can be transferred is to be investigated.

Analysis The problem is solved using EES, and the solution is given below.

```
T_1=200 [C]
P_1=200 [kPa]
V=20 [L]
T_2=80 [C]
T_o=0 [C]
P_o=100 [kPa]

"Conservation of energy for closed system is:"
E_in - E_out = DELTAE
DELTAE = m*(u_2 - u_1)
E_in=0
E_out= Q_out
u_1 =intenergy(steam_iapws,P=P_1,T=T_1)
v_1 =volume(steam_iapws,P=P_1,T=T_1)
s_1 =entropy(steam_iapws,P=P_1,T=T_1)
v_2 = v_1
u_2 = intenergy(steam_iapws, v=v_2,T=T_2)
s_2 = entropy(steam_iapws, v=v_2,T=T_2)
m=V*convert(L,m^3)/v_1
W_rev=-m*(u_2 - u_1 -(T_o+273.15)*(s_2-s_1)+P_o*(v_1-v_2))

"When this work is supplied to a reversible heat pump, the heat pump will supply the room heat in
the amount of :"

Q_H = COP_HP*W_rev
COP_HP = T_H/(T_H-T_L)
T_H = 294 [K]
T_L = 273 [K]
```

Q_H [kJ]	Q_{out} [kJ]	T_2 [C]	W_{rev} [kJ]
155.4	46.66	21	11.1
153.9	45.42	30	11
151.2	43.72	40	10.8
146.9	41.55	50	10.49
140.3	38.74	60	10.02
130.4	35.09	70	9.318
116.1	30.34	80	8.293



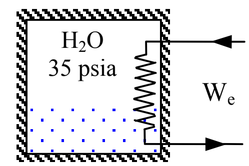
8-33E An insulated rigid tank contains saturated liquid-vapor mixture of water at a specified pressure. An electric heater inside is turned on and kept on until all the liquid is vaporized. The exergy destruction and the second-law efficiency are to be determined.

Assumptions Kinetic and potential energies are negligible.

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

$$\left.\begin{array}{l} P_1 = 35\text{ psia} \\ x_1 = 0.25 \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = \boldsymbol{v}_f + x_1 \boldsymbol{v}_{fg} = 0.01708 + 0.25 \times (11.901 - 0.01708) = 2.9880\text{ ft}^3\text{ / lbm} \\ u_1 = u_f + x_1 u_{fg} = 227.92 + 0.25 \times 862.19 = 443.47\text{ Btu / lbm} \\ s_1 = s_f + x_1 s_{fg} = 0.38093 + 0.25 \times 1.30632 = 0.70751\text{ Btu / lbm}\cdot\text{R} \end{array}$$

$$\left.\begin{array}{l} \boldsymbol{v}_2 = \boldsymbol{v}_1 \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} u_2 = u_{g @ \boldsymbol{v}_g = 2.9880\text{ ft}^3/\text{lbm}} = 1110.9\text{ Btu/lbm} \\ s_2 = s_{g @ \boldsymbol{v}_g = 2.9880\text{ ft}^3/\text{lbm}} = 1.5692\text{ Btu/lbm}\cdot\text{R} \end{array}$$



Analysis (*a*) The irreversibility can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$ where the entropy generation is determined from an entropy balance on the tank, which is an insulated closed system,

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$S_{\text{gen}} = \Delta S_{\text{system}} = m(s_2 - s_1)$$

Substituting,

$$\begin{aligned} X_{\text{destroyed}} &= T_0 S_{\text{gen}} = m T_0 (s_2 - s_1) \\ &= (6\text{ lbm})(535\text{ R})(1.5692 - 0.70751)\text{Btu/lbm}\cdot\text{R} = \mathbf{2766\ \ Btu} \end{aligned}$$

(*b*) Noting that V = constant during this process, the W and W_u are identical and are determined from the energy balance on the closed system energy equation,

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

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

or,

$$W_{\text{e,in}} = (6\text{ lbm})(1110.9 - 443.47)\text{Btu/lbm} = 4005\text{ Btu}$$

Then the reversible work during this process and the second-law efficiency become

$$W_{\text{rev,in}} = W_{\text{u,in}} - X_{\text{destroyed}} = 4005 - 2766 = 1239\text{ Btu}$$

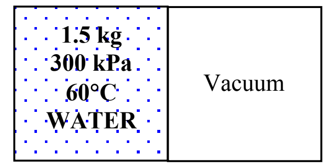
Thus,

$$\eta_{\text{II}} = \frac{W_{\text{rev}}}{W_u} = \frac{1239\text{ Btu}}{4005\text{ Btu}} = \mathbf{30.9\%}$$

8-34 A rigid tank is divided into two equal parts by a partition. One part is filled with compressed liquid while the other side is evacuated. The partition is removed and water expands into the entire tank. The exergy destroyed during this process is to be determined.

Assumptions Kinetic and potential energies are negligible.

Analysis The properties of the water are (Tables A-4 through A-6)



$$\left.\begin{array}{l} P_1 = 300\text{ kPa} \\ T_1 = 60°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 \cong \boldsymbol{v}_{f@60°\text{C}} = 0.001017\text{ m}^3/\text{kg} \\ u_1 \cong u_{f@60°\text{C}} = 251.16\text{ kJ/kg} \\ s_1 \cong s_{f@60°\text{C}} = 0.8313\text{ kJ/kg}\cdot\text{K} \end{array}$$

Noting that $\boldsymbol{v}_2 = 2\boldsymbol{v}_1 = 2\times 0.001017 = 0.002034\text{ m}^3/\text{kg}$,

$$\left.\begin{array}{l} P_2 = 15\text{ kPa} \\ \text{v}_2 = 0.002034 \end{array}\right\} \begin{array}{l} x_2 = \dfrac{\boldsymbol{v}_2 - \boldsymbol{v}_f}{\boldsymbol{v}_{fg}} = \dfrac{0.002034 - 0.001014}{10.02 - 0.001014} = 0.0001017 \\ u_2 = u_f + x_2 u_{fg} = 225.93 + 0.0001017\times 2222.1 = 226.15\text{ kJ/kg} \\ s_2 = s_f + x_2 s_{fg} = 0.7549 + 0.0001017\times 7.2522 = 0.7556\text{ kJ/kg}\cdot\text{K} \end{array}$$

Taking the direction of heat transfer to be *to* the tank, the energy balance on this closed system becomes

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

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

or,

$$Q_{\text{in}} = (1.5\text{ kg})(226.15 - 251.16)\text{kJ/kg} = -37.51\text{ kJ} \;\rightarrow\; Q_{\text{out}} = 37.51\text{ kJ}$$

The irreversibility can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$ where the entropy generation is determined from an 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,

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$-\frac{Q_{\text{out}}}{T_{\text{b,out}}} + S_{\text{gen}} = \Delta S_{\text{system}} = m(s_2 - s_1)$$

$$S_{\text{gen}} = m(s_2 - s_1) + \frac{Q_{\text{out}}}{T_{\text{surr}}}$$

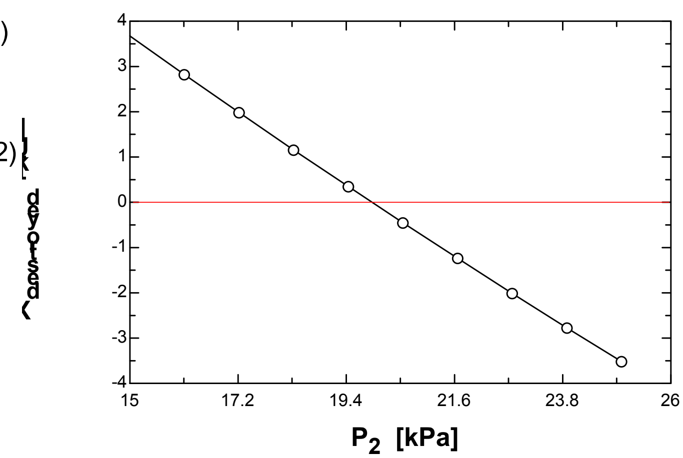
Substituting,

$$\begin{aligned} X_{\text{destroyed}} &= T_0 S_{\text{gen}} = T_0\left(m(s_2 - s_1) + \frac{Q_{\text{out}}}{T_{\text{surr}}}\right) \\ &= (298\text{ K})\left[(1.5\text{ kg})(0.7556 - 0.8313)\text{kJ/kg}\cdot\text{K} + \frac{37.51\text{ kJ}}{298\text{ K}}\right] \\ &= \mathbf{3.67\ kJ} \end{aligned}$$

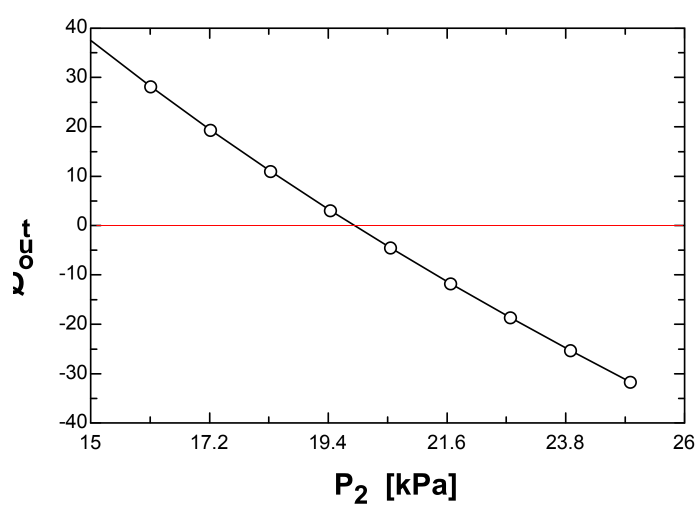
8-35 EES Problem 8-34 is reconsidered. The effect of final pressure in the tank on the exergy destroyed during the process is to be investigated.

Analysis The problem is solved using EES, and the solution is given below.

```
T_1=60 [C]
P_1=300 [kPa]
m=1.5 [kg]
P_2=15 [kPa]
T_o=25 [C]
P_o=100 [kPa]
T_surr = T_o

"Conservation of energy for closed system is:"
E_in - E_out = DELTAE
DELTAE = m*(u_2 - u_1)
E_in=0
E_out= Q_out
u_1 =intenergy(steam_iapws,P=P_1,T=T_1)
v_1 =volume(steam_iapws,P=P_1,T=T_1)
s_1 =entropy(steam_iapws,P=P_1,T=T_1)
v_2 = 2*v_1
u_2 = intenergy(steam_iapws, v=v_2,P=P_2)
s_2 = entropy(steam_iapws, v=v_2,P=P_2)
S_in -S_out+S_gen=DELTAS_sys
S_in=0 [kJ/K]
S_out=Q_out/(T_surr+273)
DELTAS_sys=m*(s_2 - s_1)
X_destroyed = (T_o+273)*S_gen
```



P_2 [kPa]	$X_{destroyed}$ [kJ]	Q_{out} [kJ]
15	3.666	37.44
16.11	2.813	28.07
17.22	1.974	19.25
18.33	1.148	10.89
19.44	0.336	2.95
20.56	-0.4629	-4.612
21.67	-1.249	-11.84
22.78	-2.022	-18.75
23.89	-2.782	-25.39
25	-3.531	-31.77

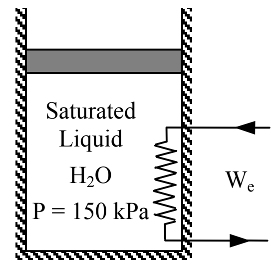


8-36 An insulated cylinder is initially filled with saturated liquid water at a specified pressure. The water is heated electrically at constant pressure. The minimum work by which this process can be accomplished and the exergy destroyed are to be determined.

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 compression or expansion process is quasi-equilibrium.

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

$$\left.\begin{array}{l} P_1 = 150\text{ kPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} u_1 = u_{f@150\text{ kPa}} = 466.97\text{ kJ/kg} \\ v_1 = v_{f@150\text{ kPa}} = 0.001053\text{ m}^3/\text{kg} \\ h_1 = h_{f@150\text{ kPa}} = 467.13\text{ kJ/kg} \\ s_1 = s_{f@150\text{ kPa}} = 1.4337\text{ kJ/kg}\cdot\text{K} \end{array}$$



The mass of the steam is

$$m = \frac{V}{v_1} = \frac{0.002\text{ m}^3}{0.001053\text{ m}^3/\text{kg}} = 1.899\text{ kg}$$

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

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}} \longrightarrow W_{\text{e,in}} - W_{\text{b,out}} = \Delta U \longrightarrow W_{\text{e,in}} = m(h_2 - h_1)$$

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

$$h_2 = h_1 + \frac{W_{e,in}}{m} = 467.13 + \frac{2200\text{ kJ}}{1.899\text{ kg}} = 1625.1\text{ kJ/kg}$$

Thus,

$$\left.\begin{array}{l} P_2 = 150\text{ kPa} \\ h_2 = 1625.1\text{ kJ/kg} \end{array}\right\} \begin{array}{l} x_2 = \dfrac{h_2 - h_f}{h_{fg}} = \dfrac{1625.1 - 467.13}{2226.0} = 0.5202 \\ s_2 = s_f + x_2 s_{fg} = 1.4337 + 0.5202 \times 5.7894 = 4.4454\text{ kJ/kg}\cdot\text{K} \\ u_2 = u_f + x_2 u_{fg} = 466.97 + 0.5202 \times 2052.3 = 1534.6\text{ kJ/kg} \\ v_2 = v_f + x_2 v_{fg} = 0.001053 + 0.5202 \times (1.1594 - 0.001053) = 0.6037\text{ m}^3/\text{kg} \end{array}$$

The reversible work input, which represents the minimum work input $W_{\text{rev,in}}$ in this case can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer}\\ \text{by heat, work, and mass}}} \underbrace{- X_{\text{destroyed}}^{\nearrow 0\text{ (reversible)}}}_{\substack{\text{Exergy}\\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change}\\ \text{in exergy}}} \rightarrow W_{\text{rev,in}} = X_2 - X_1$$

Substituting the closed system exergy relation, the reversible work input during this process becomes

$$\begin{aligned} W_{\text{rev,in}} &= -m[(u_1 - u_2) - T_0(s_1 - s_2) + P_0(v_1 - v_2)] \\ &= -(1.899\text{ kg})\{(466.97 - 1534.6)\text{ kJ/kg} - (298\text{ K})(1.4337 - 4.4454)\text{ kJ/kg}\cdot\text{K} \\ &\quad + (100\text{ kPa})(0.001053 - 0.6037)\text{m}^3/\text{kg}[1\text{ kJ/1 kPa}\cdot\text{m}^3]\} \\ &= \mathbf{437.7\ kJ} \end{aligned}$$

(b) The exergy destruction (or irreversibility) associated with this process can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$ where the entropy generation is determined from an entropy balance on the cylinder, which is an insulated closed system,

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change}\\ \text{in entropy}}}$$

$$S_{\text{gen}} = \Delta S_{\text{system}} = m(s_2 - s_1)$$

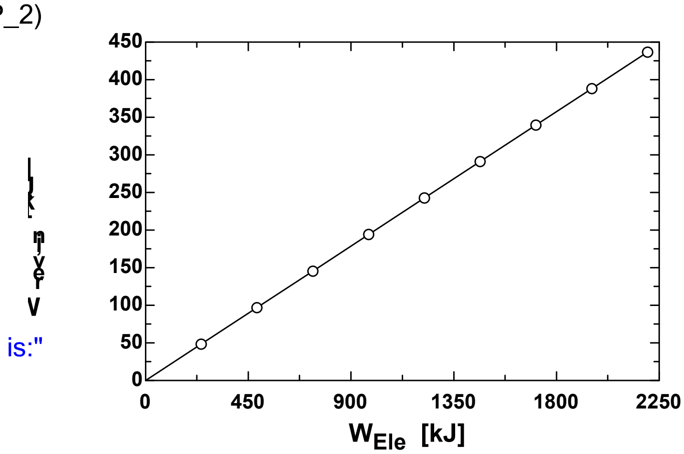
Substituting,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = mT_0(s_2 - s_1) = (298\text{ K})(1.899\text{ kg})(4.4454 - 1.4337)\text{kJ/kg}\cdot\text{K} = \mathbf{1705\ kJ}$$

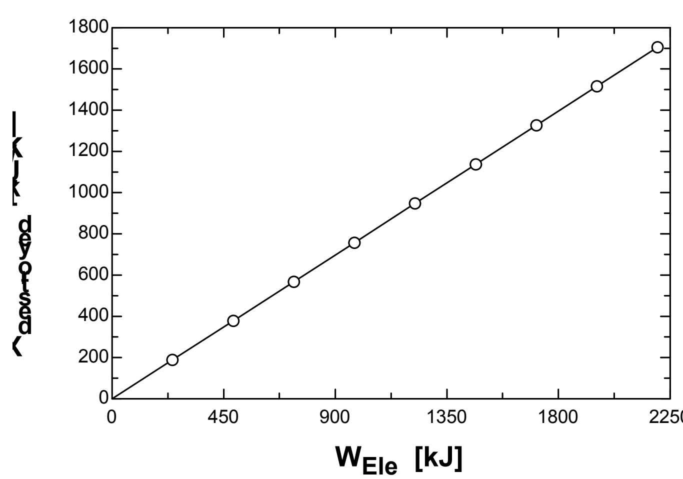
8-37 EES Problem 8-36 is reconsidered. The effect of the amount of electrical work on the minimum work and the exergy destroyed is to be investigated.

Analysis The problem is solved using EES, and the solution is given below.

```
x_1=0
P_1=150 [kPa]
V=2 [L]
P_2=P_1
{W_Ele = 2200 [kJ]}
T_o=25 [C]
P_o=100 [kPa]

"Conservation of energy for closed system is:"
E_in - E_out = DELTAE
DELTAE = m*(u_2 - u_1)
E_in=W_Ele
E_out= W_b
W_b = m*P_1*(v_2-v_1)
u_1 =intenergy(steam_iapws,P=P_1,x=x_1)
v_1 =volume(steam_iapws,P=P_1,x=x_1)
s_1 =entropy(steam_iapws,P=P_1,x=x_1)
u_2 = intenergy(steam_iapws, v=v_2,P=P_2)
s_2 = entropy(steam_iapws, v=v_2,P=P_2)
m=V*convert(L,m^3)/v_1
W_rev_in=m*(u_2 - u_1 -(T_o+273.15)
            *(s_2-s_1)+P_o*(v_2-v_1))

"Entropy Balance:"
S_in - S_out+S_gen = DELTAS_sys
DELTAS_sys = m*(s_2 - s_1)
S_in=0 [kJ/K]
S_out= 0 [kJ/K]

"The exergy destruction or irreversibility is:"
X_destroyed = (T_o+273.15)*S_gen
```



W_{Ele} [kJ]	$W_{rev,in}$ [kJ]	$X_{destroyed}$ [kJ]
0	0	0
244.4	48.54	189.5
488.9	97.07	379.1
733.3	145.6	568.6
977.8	194.1	758.2
1222	242.7	947.7
1467	291.2	1137
1711	339.8	1327
1956	388.3	1516
2200	436.8	1706

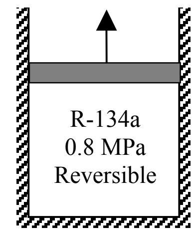


8-38 An insulated cylinder is initially filled with saturated R-134a vapor at a specified pressure. The refrigerant expands in a reversible manner until the pressure drops to a specified value. The change in the exergy of the refrigerant during this process and the reversible work are to be determined.

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 This is a reversible adiabatic (i.e., isentropic) process, and thus $s_2 = s_1$. From the refrigerant tables (Tables A-11 through A-13),

$$\left.\begin{array}{l} P_1 = 0.8\text{ MPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = \boldsymbol{v}_{g@0.8\text{ MPa}} = 0.02562\text{ m}^3/\text{kg} \\ u_1 = u_{g@0.8\text{ MPa}} = 246.79\text{ kJ/kg} \\ s_1 = s_{g@0.8\text{ MPa}} = 0.9183\text{ kJ/kg}\cdot\text{K} \end{array}$$



The mass of the refrigerant is

$$m = \frac{\boldsymbol{V}}{\boldsymbol{v}_1} = \frac{0.05\text{ m}^3}{0.02562\text{ m}^3/\text{kg}} = 1.952\text{ kg}$$

$$\left.\begin{array}{l} P_2 = 0.2\text{ MPa} \\ s_2 = s_1 \end{array}\right\} \begin{array}{l} x_2 = \dfrac{s_2 - s_f}{s_{fg}} = \dfrac{0.9183 - 0.15457}{0.78316} = 0.9753 \\ \boldsymbol{v}_2 = \boldsymbol{v}_f + x_2\boldsymbol{v}_{fg} = 0.0007533 + 0.099867 \times (0.099867 - 0.0007533) = 0.09741\text{ m}^3/\text{kg} \\ u_2 = u_f + x_2 u_{fg} = 38.28 + 0.9753 \times 186.21 = 219.88\text{ kJ/kg} \end{array}$$

The reversible work output, which represents the maximum work output $W_{\text{rev,out}}$ can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer} \\ \text{by heat, work, and mass}}} \underbrace{- X_{\text{destroyed}}^{\nearrow 0\text{ (reversible)}}}_{\substack{\text{Exergy} \\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change} \\ \text{in exergy}}}$$

$$\begin{aligned} -W_{\text{rev,out}} &= X_2 - X_1 \\ W_{\text{rev,out}} &= X_1 - X_2 \\ &= \Phi_1 - \Phi_2 \end{aligned}$$

Therefore, the change in exergy and the reversible work are identical in this case. Using the definition of the closed system exergy and substituting, the reversible work is determined to be

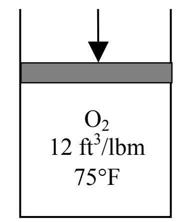
$$\begin{aligned} W_{\text{rev,out}} &= \Phi_1 - \Phi_2 = m\left[(u_1 - u_2) - T_0(s_1 - s_2)^{\nearrow 0} + P_0(\text{v}_1 - \text{v}_2)\right] = m\left[(u_1 - u_2) + P_0(\boldsymbol{v}_1 - \boldsymbol{v}_2)\right] \\ &= (1.952\text{ kg})[(246.79 - 219.88)\text{ kJ/kg} + (100\text{ kPa})(0.02562 - 0.09741)\text{m}^3/\text{kg}[\text{kJ/kPa}\cdot\text{m}^3]] \\ &= \mathbf{38.5\ kJ} \end{aligned}$$

8-39E Oxygen gas is compressed from a specified initial state to a final specified state. The reversible work and the increase in the exergy of the oxygen during this process are to be determined.

Assumptions At specified conditions, oxygen can be treated as an ideal gas with constant specific heats.

Properties The gas constant of oxygen is R = 0.06206 Btu/lbm.R (Table A-1E). The constant-volume specific heat of oxygen at the average temperature is

$$T_{avg} = (T_1 + T_2)/2 = (75 + 525)/2 = 300°\text{F} \longrightarrow c_{v,avg} = 0.164 \text{ Btu/lbm}\cdot\text{R}$$



Analysis The entropy change of oxygen is

$$\begin{aligned} s_2 - s_1 &= c_{v,avg} \ln\left(\frac{T_2}{T_1}\right) + R\ln\left(\frac{v_2}{v_1}\right) \\ &= (0.164 \text{ Btu/lbm}\cdot\text{R})\ln\left(\frac{985 \text{ R}}{535 \text{ R}}\right) + (0.06206 \text{ Btu/lbm}\cdot\text{R})\ln\left(\frac{1.5 \text{ ft}^3\text{/lbm}}{12 \text{ ft}^3\text{/lbm}}\right) \\ &= -0.02894 \text{ Btu/lbm}\cdot\text{R} \end{aligned}$$

The reversible work input, which represents the minimum work input $W_{rev,in}$ in this case can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{in} - X_{out}}_{\substack{\text{Net exergy transfer} \\ \text{by heat, work, and mass}}} \underbrace{- X_{destroyed}^{\nearrow 0 \text{ (reversible)}}}_{\substack{\text{Exergy} \\ \text{destruction}}} = \underbrace{\Delta X_{system}}_{\substack{\text{Change} \\ \text{in exergy}}} \rightarrow W_{rev,in} = X_2 - X_1$$

Therefore, the change in exergy and the reversible work are identical in this case. Substituting the closed system exergy relation, the reversible work input during this process is determined to be

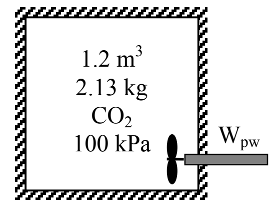
$$\begin{aligned} w_{rev,in} &= \phi_2 - \phi_1 = -[(u_1 - u_2) - T_0(s_1 - s_2) + P_0(v_1 - v_2)] \\ &= -\{(0.164 \text{ Btu/lbm}\cdot\text{R})(535 - 985)\text{R} - (535 \text{ R})(0.02894 \text{ Btu/lbm}\cdot\text{R}) \\ &\quad + (14.7 \text{ psia})(12 - 1.5)\text{ft}^3\text{/lbm}[\text{Btu/5.4039 psia}\cdot\text{ft}^3]\} \\ &= \mathbf{60.7 \text{ Btu/lbm}} \end{aligned}$$

Also, the increase in the exergy of oxygen is

$$\phi_2 - \phi_1 = w_{rev,in} = \mathbf{60.7 \text{ Btu/lbm}}$$

8-40 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 actual paddle-wheel work and the minimum paddle-wheel work by which this process can be accomplished are to be determined.

Assumptions **1** At specified conditions, CO_2 can be treated as an ideal gas with constant specific heats at the average temperature. **2** The surroundings temperature is 298 K.



Analysis (a) The initial and final temperature of CO_2 are

$$T_1 = \frac{P_1 \boldsymbol{v}_1}{mR} = \frac{(100\ \text{kPa})(1.2\ \text{m}^3)}{(2.13\ \text{kg})(0.1889\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})} = 298.2\ \text{K}$$

$$T_2 = \frac{P_2 \boldsymbol{v}_2}{mR} = \frac{(120\ \text{kPa})(1.2\ \text{m}^3)}{(2.13\ \text{kg})(0.1889\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})} = 357.9\ \text{K}$$

$$T_{\text{avg}} = (T_1 + T_2)/2 = (298.2 + 357.9)/2 = 328\ \text{K} \longrightarrow c_{\boldsymbol{v},\text{avg}} = 0.684\ \text{kJ/kg}\cdot\text{K}$$

The actual paddle-wheel work done is determined from the energy balance on the CO gas in the tank,

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

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

$$W_{\text{pw,in}} = \Delta U = mc_{\boldsymbol{v}}(T_2 - T_1)$$

or,

$$W_{\text{pw,in}} = (2.13\ \text{kg})(0.684\ \text{kJ/kg}\cdot\text{K})(357.9 - 298.2)\text{K} = \mathbf{87.0\ kJ}$$

(b) The minimum paddle-wheel work with which this process can be accomplished is the reversible work, which can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer}\\ \text{by heat, work, and mass}}} \underbrace{- X_{\text{destroyed}}^{\nearrow 0\ (\text{reversible})}}_{\substack{\text{Exergy}\\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change}\\ \text{in exergy}}} \rightarrow W_{\text{rev,in}} = X_2 - X_1$$

Substituting the closed system exergy relation, the reversible work input for this process is determined to be

$$\begin{aligned} W_{\text{rev,in}} &= m\left[(u_2 - u_1) - T_0(s_2 - s_1) + P_0(\boldsymbol{v}_2^{\nearrow 0} - \boldsymbol{v}_1)\right] \\ &= m\left[c_{\boldsymbol{v},\text{avg}}(T_2 - T_1) - T_0(s_2 - s_1)\right] \\ &= (2.13\ \text{kg})\left[(0.684\ \text{kJ/kg}\cdot\text{K})(357.9 - 298.2)\text{K} - (298.2)(0.1253\ \text{kJ/kg}\cdot\text{K})\right] \\ &= \mathbf{7.74\ kJ} \end{aligned}$$

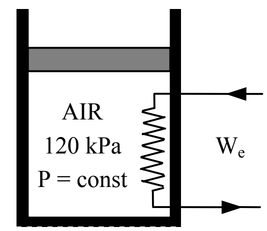
since

$$s_2 - s_1 = c_{\boldsymbol{v},\text{avg}} \ln\frac{T_2}{T_1} + R\ln\frac{\boldsymbol{v}_2}{\boldsymbol{v}_1}^{\nearrow 0} = (0.684\ \text{kJ/kg}\cdot\text{K})\ln\left(\frac{357.9\ \text{K}}{298.2\ \text{K}}\right) = 0.1253\ \text{kJ/kg}\cdot\text{K}$$

8-41 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 exergy destruction during this process is to be determined.

Assumptions Air is an ideal gas with variable specific heats.

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



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

$$m = \frac{P_1 \boldsymbol{V}_1}{RT_1} = \frac{(120\,\text{kPa})(0.03\,\text{m}^3)}{(0.287\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\,\text{K})} = 0.0418\,\text{kg}$$

$$W_e = \dot{W}_e \Delta t = (-0.05\text{ kJ/s})(5\times 60\text{ s}) = -15\text{ kJ}$$

Also,

$$T_1 = 300\text{ K} \longrightarrow h_1 = 300.19\text{ kJ/kg} \quad \text{and} \quad s_1^o = 1.70202\text{ kJ/kg}\cdot\text{K}$$

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

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

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

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

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

$$h_2 = h_1 + \frac{W_{e,in}}{m} = 300.19 + \frac{15\,\text{kJ}}{0.0418\,\text{kg}} = 659.04\,\text{kJ/kg} \longrightarrow \begin{array}{l} T_2 = 650\,\text{K} \\ s_2^o = 2.49364\,\text{kJ/kg}\cdot\text{K} \end{array}$$

Also, $$s_2 - s_1 = s_2^o - s_1^o - R\ln\left(\frac{P_2}{P_1}\right)^{\nearrow 0} = s_2^o - s_1^o = 2.49364 - 1.70202 = 0.79162\,\text{kJ/kg}\cdot\text{K}$$

The exergy destruction (or irreversibility) associated with this process can be determined from its definition $X_{destroyed} = T_0 S_{gen}$ where the entropy generation is determined from an entropy balance on the cylinder, which is an insulated closed system,

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change}\\ \text{in entropy}}}$$

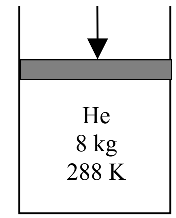
$$S_{gen} = \Delta S_{system} = m(s_2 - s_1)$$

Substituting,

$$X_{destroyed} = T_0 S_{gen} = mT_0(s_2 - s_1) == (300\,\text{K})(0.0418\,\text{kg})(0.79162\ \text{kJ/kg}\cdot\text{K}) = \mathbf{9.9\ kJ}$$

8-42 A fixed mass of helium undergoes a process from a specified state to another specified state. The increase in the useful energy potential of helium is to be determined.

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 = 2.0769 kJ/kg.K (Table A-1). The constant volume specific heat of helium is c_v = 3.1156 kJ/kg.K (Table A-2).

Analysis From the ideal-gas entropy change relation,

$$s_2 - s_1 = c_{v,\text{avg}} \ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1}$$

$$= (3.1156\ \text{kJ/kg}\cdot\text{K})\ln\frac{353\ \text{K}}{288\ \text{K}} + (2.0769\ \text{kJ/kg}\cdot\text{K})\ln\frac{0.5\ \text{m}^3/\text{kg}}{3\ \text{m}^3/\text{kg}} = -3.087\ \text{kJ/kg}\cdot\text{K}$$

The increase in the useful potential of helium during this process is simply the increase in exergy,

$$\Phi_2 - \Phi_1 = -m\left[(u_1 - u_2) - T_0(s_1 - s_2) + P_0(v_1 - v_2)\right]$$

$$= -(8\ \text{kg})\{(3.1156\ \text{kJ/kg}\cdot\text{K})(288-353)\ \text{K} - (298\ \text{K})(3.087\ \text{kJ/kg}\cdot\text{K})$$

$$+(100\ \text{kPa})(3-0.5)\text{m}^3/\text{kg}[\text{kJ/kPa}\cdot\text{m}^3]\}$$

$$= \mathbf{6980\ \ kJ}$$

8-43 One side of a partitioned insulated rigid tank contains argon gas at a specified temperature and pressure while the other side is evacuated. The partition is removed, and the gas fills the entire tank. The exergy destroyed during this process is to be determined.

Assumptions Argon is an ideal gas with constant specific heats, and thus ideal gas relations apply.

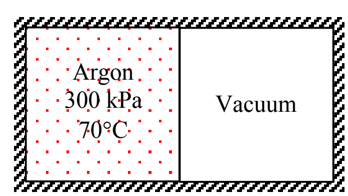
Properties The gas constant of argon is R = 0.208 kJ/kg.K (Table A-1).

Analysis Taking the entire rigid tank as the system, the energy balance can be expressed as

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

$$0 = \Delta U = m(u_2 - u_1)$$

$$u_2 = u_1 \quad\rightarrow\quad T_2 = T_1$$



since $u = u(T)$ for an ideal gas.

The exergy destruction (or irreversibility) associated with this process can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$ where the entropy generation is determined from an entropy balance on the entire tank, which is an insulated closed system,

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change}\\ \text{in entropy}}}$$

$$S_{\text{gen}} = \Delta S_{\text{system}} = m(s_2 - s_1)$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = m\left(c_{v,\text{avg}}\ln\frac{T_2}{T_1}^{\nearrow 0} + R\ln\frac{V_2}{V_1}\right) = mR\ln\frac{V_2}{V_1}$$

$$= (3\ \text{kg})(0.208\ \text{kJ/kg}\cdot\text{K})\ln(2) = 0.433\ \text{kJ/K}$$

Substituting,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = mT_0(s_2 - s_1) = (298\ \text{K})(0.433\ \text{kJ/K}) = \mathbf{129\ \ kJ}$$

8-44E A hot copper block is dropped into water in an insulated tank. The final equilibrium temperature of the tank and the work potential wasted during this process are to be determined.

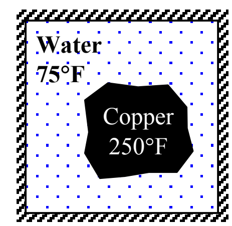
Assumptions **1** Both the water and the copper block are incompressible substances with constant specific heats at room temperature. **2** The system is stationary and thus the kinetic and potential energies are negligible. **3** The tank is well-insulated and thus there is no heat transfer.

Properties The density and specific heat of water at the anticipated average temperature of 90°F are ρ = 62.1 lbm/ft^3 and c_p = 1.00 Btu/lbm.°F. The specific heat of copper at the anticipated average temperature of 100°F is c_p = 0.0925 Btu/lbm.°F (Table A-3E).

Analysis We take the entire contents of the tank, water + copper block, as the *system*, which is a closed system. The energy balance for this system can be expressed as

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

$$0 = \Delta U$$



or,

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

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

where

$$m_w = \rho \boldsymbol{V} = (62.1\text{ lbm/ft}^3)(1.5\text{ ft}^3) = 93.15\text{ lbm}$$

Substituting,

$$0 = (70\text{ lbm})(0.0925\text{ Btu/lbm}\cdot{}^\circ\text{F})(\text{T}_2 - 250^\circ\text{F}) + (93.15\text{ lbm})(1.0\text{ Btu/lbm}\cdot{}^\circ\text{F})(T_2 - 75^\circ\text{F})$$

$$T_2 = \mathbf{86.4^\circ F} = 546.4\text{ R}$$

The wasted work potential is equivalent to the exergy destruction (or irreversibility), and it can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$ where the entropy generation is determined from an entropy balance on the system, which is an insulated closed system,

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change}\\ \text{in entropy}}}$$

$$S_{\text{gen}} = \Delta S_{\text{system}} = \Delta S_{\text{water}} + \Delta S_{\text{copper}}$$

where

$$\Delta S_{\text{copper}} = mc_{\text{avg}} \ln\left(\frac{T_2}{T_1}\right) = (70\text{ lbm})(0.092\text{ Btu/lbm}\cdot\text{R})\ln\left(\frac{546.4\text{ R}}{710\text{ R}}\right) = -1.696\text{ Btu/R}$$

$$\Delta S_{\text{water}} = mc_{\text{avg}} \ln\left(\frac{T_2}{T_1}\right) = (93.15\text{ lbm})(1.0\text{ Btu/lbm}\cdot\text{R})\ln\left(\frac{546.4\text{ R}}{535\text{ R}}\right) = 1.960\text{ Btu/R}$$

Substituting,

$$X_{\text{destroyed}} = (535\text{ R})(-1.696 + 1.960)\text{Btu/R} = \mathbf{140.9\ Btu}$$

8-45 A hot iron block is dropped into water in an insulated tank that is stirred by a paddle-wheel. The mass of the iron block and the exergy destroyed 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 energies are negligible. **3** The tank is well-insulated and thus there is no heat transfer.

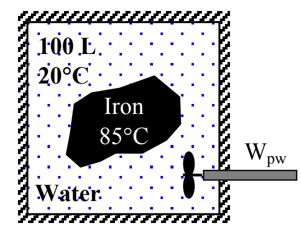
Properties The density and specific heat of water at 25°C are ρ = 997 kg/m³ and c_p = 4.18 kJ/kg.°F. The specific heat of iron at room temperature (the only value available in the tables) is c_p = 0.45 kJ/kg.°C (Table A-3).

Analysis We take the entire contents of the tank, water + iron block, as the system, which is a closed system. The energy balance for this system can be expressed as

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

$$W_{pw,in} = \Delta U = \Delta U_{iron} + \Delta U_{water}$$

$$W_{pw,in} = [mc(T_2 - T_1)]_{iron} + [mc(T_2 - T_1)]_{water}$$



where

$$m_{water} = \rho \boldsymbol{V} = (997\ \text{kg/m}^3)(0.1\ \text{m}^3) = 99.7\ \text{kg}$$

$$W_{pw} = \dot{W}_{pw,in} \Delta t = (0.2\ \text{kJ/s})(20 \times 60\ \text{s}) = 240\ \text{kJ}$$

Substituting,

$$240\ \text{kJ} = m_{iron}(0.45\ \text{kJ/kg}\cdot°\text{C})(24-85)°\text{C} + (99.7\ \text{kg})(4.18\ \text{kJ/kg}\cdot°\text{C})(24-20)°\text{C}$$

$$m_{iron} = \mathbf{52.0\ kg}$$

(*b*) The exergy destruction (or irreversibility) can be determined from its definition $X_{destroyed} = T_0 S_{gen}$ where the entropy generation is determined from an entropy balance on the system, which is an insulated closed system,

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$S_{gen} = \Delta S_{system} = \Delta S_{iron} + \Delta S_{water}$$

where

$$\Delta S_{iron} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (52.0\ \text{kg})(0.45\ \text{kJ/kg}\cdot\text{K}) \ln\left(\frac{297\ \text{K}}{358\ \text{K}}\right) = -4.371\ \text{kJ/K}$$

$$\Delta S_{water} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (99.7\ \text{kg})(4.18\ \text{kJ/kg}\cdot\text{K}) \ln\left(\frac{297\ \text{K}}{293\ \text{K}}\right) = 5.651\ \text{kJ/K}$$

Substituting,

$$X_{destroyed} = T_0 S_{gen} = (293\ \text{K})(-4.371 + 5.651)\ \text{kJ/K} = \mathbf{375.0\ kJ}$$

8-46 An iron block and a copper block are dropped into a large lake where they cool to lake temperature. The amount of work that could have been produced is to be determined.

Assumptions **1** The iron and copper blocks and water are incompressible substances with constant specific heats at room temperature. **2** Kinetic and potential energies are negligible.

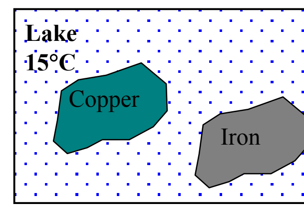
Properties The specific heats of iron and copper at room temperature are $c_{p,\text{ iron}}$ = 0.45 kJ/kg.°C and $c_{p,\text{copper}}$ = 0.386 kJ/kg.°C (Table A-3).

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.

We take both the iron and the copper blocks as the system, which is a closed system. The energy balance for this system can be expressed as

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

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



or,

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

Substituting,

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

The work that could have been produced is equal to the wasted work potential. It is equivalent to the exergy destruction (or irreversibility), and it can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. The entropy generation is determined from an entropy balance on an *extended system* that includes the blocks and the water in their immediate surroundings so that the boundary temperature of the extended system is the temperature of the lake water at all times,

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change}\\ \text{in entropy}}}$$

$$-\frac{Q_{\text{out}}}{T_{\text{b,out}}} + S_{\text{gen}} = \Delta S_{\text{system}} = \Delta S_{\text{iron}} + \Delta S_{\text{copper}}$$

$$S_{\text{gen}} = \Delta S_{\text{iron}} + \Delta S_{\text{copper}} + \frac{Q_{\text{out}}}{T_{\text{lake}}}$$

where

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

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

Substituting,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = (293\text{ K})\left(-4.579 - 1.571 + \frac{1964\text{ kJ}}{288\text{ K}}\right)\text{kJ/K} = \mathbf{196\ \ kJ}$$

8-47E A rigid tank is initially filled with saturated mixture of R-134a. Heat is transferred to the tank from a source until the pressure inside rises to a specified value. The amount of heat transfer to the tank from the source and the exergy destroyed are to be determined.

Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** There is no heat transfer with the environment.

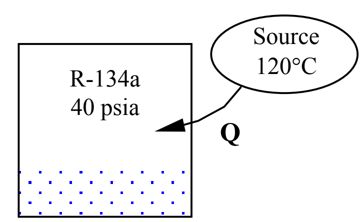
Properties From the refrigerant tables (Tables A-11E through A-13E),

$$\left.\begin{array}{l} P_1 = 40 \text{ psia} \\ x_1 = 0.55 \end{array}\right\} \begin{array}{l} u_1 = u_f + x_1 u_{fg} = 21.246 + 0.55 \times 77.307 = 63.76 \text{ Btu/lbm} \\ s_1 = s_f + x_1 s_{fg} = 0.04688 + 0.55 \times 0.17580 = 0.1436 \text{ Btu/lbm}\cdot\text{R} \\ v_1 = v_f + x_1 v_{fg} = 0.01232 + 0.55 \times 1.16368 = 0.65234 \text{ ft}^3/\text{lbm} \end{array}$$

$$\left.\begin{array}{l} P_2 = 60 \text{ psia} \\ (v_2 = v_1) \end{array}\right\} \begin{array}{l} x_2 = \dfrac{v_2 - v_f}{v_{fg}} = \dfrac{0.65234 - 0.01270}{0.79361 - 0.01270} = 0.8191 \\ s_2 = s_f + x_2 s_{fg} = 0.06029 + 0.8191 \times 0.16098 = 0.1922 \text{ Btu/lbm}\cdot\text{R} \\ u_2 = u_f + x_2 u_{fg} = 27.939 + 0.8191 \times 73.360 = 88.03 \text{ Btu/lbm} \end{array}$$

Analysis (*a*) The mass of the refrigerant is

$$m = \frac{V}{v_1} = \frac{12 \text{ ft}^3}{0.65234 \text{ ft}^3/\text{lbm}} = 18.40 \text{ lbm}$$



We take the tank as the system, which is a closed system. The energy balance for this stationary closed system can be expressed as

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

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

Substituting,

$$Q_{in} = m(u_2 - u_1) = (18.40 \text{ lbm})(88.03 - 63.76) \text{ Btu/lbm} = \mathbf{446.3 \text{ Btu}}$$

(*b*) The exergy destruction (or irreversibility) can be determined from its definition $X_{destroyed} = T_0 S_{gen}$. The entropy generation is determined from an entropy balance on an *extended system* that includes the tank and the region in its immediate surroundings so that the boundary temperature of the extended system where heat transfer occurs is the source temperature,

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$\frac{Q_{in}}{T_{b,in}} + S_{gen} = \Delta S_{system} = m(s_2 - s_1),$$

$$S_{gen} = m(s_2 - s_1) - \frac{Q_{in}}{T_{source}}$$

Substituting,

$$X_{destroyed} = T_0 S_{gen} = (535 \text{ R})\left[(18.40 \text{ lbm})(0.1922 - 0.1436)\text{Btu/lbm}\cdot\text{R} - \frac{446.3 \text{ Btu}}{580 \text{ R}}\right] = \mathbf{66.5 \text{ Btu}}$$

8-48 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 exergy destruction 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 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 are dropped into the chiller at a rate of 500 per hour. Therefore, chickens can be considered to flow steadily through the chiller at a mass flow rate of

$$\dot{m}_{\text{chicken}} = (500\text{ chicken / h})(2.2\text{ kg / chicken}) = 1100\text{ kg / h} = 0.3056\text{ kg / s}$$

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

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

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

$$\dot{Q}_{\text{out}} = \dot{Q}_{\text{chicken}} = \dot{m}_{\text{chicken}} c_p (T_1 - T_2)$$

Then the rate of heat removal from the chickens as they are cooled from 15°C to 3ºC becomes

$$\dot{Q}_{\text{chicken}} = (\dot{m}c_p \Delta T)_{\text{chicken}} = (0.3056\text{ kg/s})(3.54\text{ kJ/kg.}^\circ\text{C})(15-3)^\circ\text{C} = \mathbf{13.0\ kW}$$

The chiller gains heat from the surroundings as a rate of 200 kJ/h = 0.0556 kJ/s. Then the total rate of heat gain by the water is

$$\dot{Q}_{\text{water}} = \dot{Q}_{\text{chicken}} + \dot{Q}_{\text{heat gain}} = 13.0 + 0.056 = 13.056\text{ kW}$$

Noting that the temperature rise of water is not to exceed 2ºC as it flows through the chiller, the mass flow rate of water must be at least

$$\dot{m}_{\text{water}} = \frac{\dot{Q}_{\text{water}}}{(c_p \Delta T)_{\text{water}}} = \frac{13.056\text{ kW}}{(4.18\text{ kJ/kg.}^\circ\text{C})(2^\circ\text{C})} = 1.56\text{ kg/s}$$

(*b*) The exergy destruction can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. The rate of entropy generation during this chilling process is determined by applying the rate form of the entropy balance on an *extended system* that includes the chiller and the immediate surroundings so that the boundary temperature is the surroundings temperature:

$$\underbrace{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}_{\substack{\text{Rate of net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{\dot{S}_{\text{gen}}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{\Delta \dot{S}_{\text{system}}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change}\\ \text{of entropy}}}$$

$$\dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_3 s_4 + \frac{Q_{\text{in}}}{T_{\text{surr}}} + \dot{S}_{\text{gen}} = 0$$

$$\dot{m}_{\text{chicken}} s_1 + \dot{m}_{\text{water}} s_3 - \dot{m}_{\text{chicken}} s_2 - \dot{m}_{\text{water}} s_4 + \frac{Q_{\text{in}}}{T_{\text{surr}}} + \dot{S}_{\text{gen}} = 0$$

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{chicken}} (s_2 - s_1) + \dot{m}_{\text{water}} (s_4 - s_3) - \frac{Q_{\text{in}}}{T_{\text{surr}}}$$

Noting that both streams are incompressible substances, the rate of entropy generation is determined to be

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{chicken}} c_p \ln\frac{T_2}{T_1} + \dot{m}_{\text{water}} c_p \ln\frac{T_4}{T_3} - \frac{\dot{Q}_{in}}{T_{\text{surr}}}$$

$$= (0.3056\text{ kg/s})(3.54\text{ kJ/kg.K}) \ln\frac{276}{288} + (1.56\text{ kg/s})(4.18\text{ kJ/kg.K}) \ln\frac{275.5}{273.5} - \frac{0.0556\text{ kW}}{298\text{ K}} = 0.00128\text{ kW/K}$$

Finally, $\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}} = (298\text{ K})(0.00128\text{ kW/K}) = \mathbf{0.381\ kW}$

8-49 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 exergy destruction 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. **5** The temperature of the surrounding medium is 25°C.

Properties The density and specific heat of the egg are given to be ρ = 1020 kg/m^3 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

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

$$Q_{\text{in}} = \Delta U_{\text{egg}} = m(u_2 - u_1) = mc(T_2 - T_1)$$

Then the mass of the egg and the amount of heat transfer become

$$m = \rho V = \rho \frac{\pi D^3}{6} = (1020\ \text{kg/m}^3)\frac{\pi(0.055\ \text{m})^3}{6} = 0.0889\ \text{kg}$$

$$Q_{\text{in}} = mc_p(T_2 - T_1) = (0.0889\ \text{kg})(3.32\ \text{kJ/kg.°C})(70-8)\text{°C} = \mathbf{18.3\ \ kJ}$$

The exergy destruction can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. 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:

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$\frac{Q_{\text{in}}}{T_b} + S_{\text{gen}} = \Delta S_{\text{system}} \quad \rightarrow \quad S_{\text{gen}} = -\frac{Q_{\text{in}}}{T_b} + \Delta S_{\text{system}}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mc_{\text{avg}} \ln\frac{T_2}{T_1} = (0.0889\ \text{kg})(3.32\ \text{kJ/kg.K}) \ln\frac{70+273}{8+273} = 0.0588\ \text{kJ/K}$$

Substituting,

$$S_{\text{gen}} = -\frac{Q_{\text{in}}}{T_b} + \Delta S_{\text{system}} = -\frac{18.3\ \text{kJ}}{370\ \text{K}} + 0.0588\ \text{kJ/K} = 0.00934\ \ \text{kJ/K} \quad \text{(per egg)}$$

Finally,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = (298\ \text{K})(0.00934\ \text{kJ/K}) = \mathbf{2.78\ \ kJ}$$

8-50 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 exergy destruction 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 ρ = 8085 kg/m^3 and c_p = 0.480 kJ/kg.°C.

Analysis (a) We take a single bearing ball as the system. The energy balance for this closed system can be expressed as

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

$$-Q_{\text{out}} = \Delta U_{\text{ball}} = m(u_2 - u_1)$$

$$Q_{\text{out}} = mc(T_1 - T_2)$$

The total amount of heat transfer from a ball is

$$m = \rho \boldsymbol{V} = \rho \frac{\pi D^3}{6} = (8085\ \text{kg/m}^3)\frac{\pi(0.012\ \text{m})^3}{6} = 0.007315\ \text{kg}$$

$$Q_{\text{out}} = mc(T_1 - T_2) = (0.007315\ \text{kg})(0.480\ \text{kJ/kg.°C})(900 - 850)\text{°C} = 0.1756\ \text{kJ/ball}$$

Then the rate of heat transfer from the balls to the air becomes

$$\dot{Q}_{\text{total}} = \dot{n}_{\text{ball}} Q_{\text{out (per ball)}} = (1400\ \text{balls/min}) \times (0.1756\ \text{kJ/ball}) = \mathbf{245.8\ kJ/min} = \mathbf{4.10\ kW}$$

Therefore, heat is lost to the air at a rate of 4.10 kW.

(*b*) The exergy destruction can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. 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:

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$-\frac{Q_{\text{out}}}{T_b} + S_{\text{gen}} = \Delta S_{\text{system}} \rightarrow S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mc_{\text{avg}} \ln\frac{T_2}{T_1} = (0.007315\ \text{kg})(0.480\ \text{kJ/kg.K}) \ln\frac{850 + 273}{900 + 273} = -0.0001530\ \text{kJ/K}$$

Substituting,

$$S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}} = \frac{0.1756\ \text{kJ}}{303\ \text{K}} - 0.0001530\ \text{kJ/K} = 0.0004265\ \text{kJ/K} \quad \text{(per ball)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{\text{gen}} = S_{\text{gen}} \dot{n}_{\text{ball}} = (0.0004265\ \text{kJ/K} \cdot \text{ball})(1400\ \text{balls/min}) = 0.597\ \text{kJ/min.K} = \mathbf{0.00995\ kW/K}$$

Finally,

$$\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}} = (303\ \text{K})(0.00995\ \text{kW/K}) = \mathbf{3.01\ kW/K}$$

8-51 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 exergy destruction 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 ρ = 7833 kg/m^3 and c_p = 0.465 kJ/kg.°C.

Analysis (*a*) We take a single ball as the system. The energy balance for this closed system can be expressed as

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

$$-Q_{\text{out}} = \Delta U_{\text{ball}} = m(u_2 - u_1)$$

$$Q_{\text{out}} = mc(T_1 - T_2)$$

The amount of heat transfer from a single ball is

$$m = \rho \boldsymbol{V} = \rho \frac{\pi D^3}{6} = (7833\text{ kg/m}^3)\frac{\pi (0.008\text{ m})^3}{6} = 0.00210\text{ kg}$$

$$Q_{\text{out}} = mc_p(T_1 - T_2) = (0.0021\text{ kg})(0.465\text{ kJ/kg.°C})(900 - 100)\text{°C} = 781\text{ J} = 0.781\text{ kJ (per ball)}$$

Then the total rate of heat transfer from the balls to the ambient air becomes

$$\dot{Q}_{\text{out}} = \dot{n}_{\text{ball}} Q_{\text{out}} = (1200\text{ balls/h}) \times (0.781\text{ kJ/ball}) = 936\text{ kJ/h} = \mathbf{260\ W}$$

(*b*) The exergy destruction (or irreversibility) can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. 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:

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change}\\ \text{in entropy}}}$$

$$-\frac{Q_{\text{out}}}{T_b} + S_{\text{gen}} = \Delta S_{\text{system}} \rightarrow S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mc_{\text{avg}} \ln\frac{T_2}{T_1} = (0.00210\text{ kg})(0.465\text{ kJ/kg.K})\ln\frac{100+273}{900+273} = -0.00112\text{ kJ/K}$$

Substituting,

$$S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}} = \frac{0.781\text{ kJ}}{308\text{ K}} - 0.00112\text{ kJ/K} = 0.00142\text{ kJ/K} \quad \text{(per ball)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{\text{gen}} = S_{\text{gen}}\dot{n}_{\text{ball}} = (0.00142\text{ kJ/K}\cdot\text{ball})(1200\text{ balls/h}) = 1.704\text{ kJ/h.K} = 0.000473\text{ kW/K}$$

Finally,

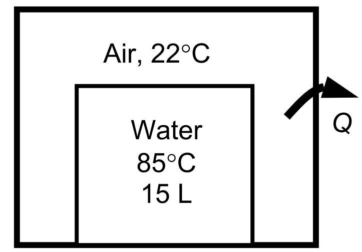
$$\dot{X}_{\text{destroyed}} = T_0\dot{S}_{\text{gen}} = (308\text{ K})(0.000473\text{ kW/K}) = 0.146\text{ kW} = \mathbf{146\ W}$$

8-52 A tank containing hot water is placed in a larger tank. The amount of heat lost to the surroundings and the exergy destruction during the process are to be determined.

Assumptions **1** Kinetic and potential energy changes are negligible. **2** Air is an ideal gas with constant specific heats. **3** The larger tank is well-sealed.

Properties The properties of air at room temperature are R = 0.287 kPa.m^3/kg.K, c_p = 1.005 kJ/kg.K, c_v = 0.718 kJ/kg.K (Table A-2). The properties of water at room temperature are ρ = 1000 kg/m^3, c_w = 4.18 kJ/kg.K.

Analysis (*a*) The final volume of the air in the tank is



$$V_{a2} = V_{a1} - V_w = 0.04 - 0.015 = 0.025\ \text{m}^3$$

The mass of the air in the room is

$$m_a = \frac{P_1 V_{a1}}{RT_{a1}} = \frac{(100\ \text{kPa})(0.04\ \text{m}^3)}{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(22+273\ \text{K})} = 0.04724\ \text{kg}$$

The pressure of air at the final state is

$$P_{a2} = \frac{m_a RT_{a2}}{V_{a2}} = \frac{(0.04724\ \text{kg})(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(44+273\ \text{K})}{0.025\ \text{m}^3} = 171.9\ \text{kPa}$$

The mass of water is

$$m_w = \rho_w V_w = (1000\ \text{kg/m}^3)(0.015\ \text{m}^3) = 14.53\ \text{kg}$$

An energy balance on the system consisting of water and air is used to determine heat lost to the surroundings

$$\begin{aligned} Q_{\text{out}} &= -\left[m_w c_w (T_2 - T_{w1}) + m_a c_v (T_2 - T_{a1})\right] \\ &= -(14.53\ \text{kg})(4.18\ \text{kJ/kg.K})(44-85) - (0.04724\ \text{kg})(0.718\ \text{kJ/kg.K})(44-22) \\ &= \mathbf{2489\ kJ} \end{aligned}$$

(*b*) An exergy balance written on the (system + immediate surroundings) can be used to determine exergy destruction. But we first determine entropy and internal energy changes

$$\Delta S_w = m_w c_w \ln\frac{T_{w1}}{T_2} = (14.53\ \text{kg})(4.18\ \text{kJ/kg.K})\ln\frac{(85+273)\ \text{K}}{(44+273)\ \text{K}} = 7.3873\ \text{kJ/K}$$

$$\begin{aligned} \Delta S_a &= m_a\left[c_p \ln\frac{T_{a1}}{T_2} - R\ln\frac{P_{a1}}{P_2}\right] \\ &= (0.04724\ \text{kg})\left[(1.005\ \text{kJ/kg.K})\ln\frac{(22+273)\ \text{K}}{(44+273)\ \text{K}} - (0.287\ \text{kJ/kg.K})\ln\frac{100\ \text{kPa}}{171.9\ \text{kPa}}\right] \\ &= 0.003931\ \text{kJ/K} \end{aligned}$$

$$\Delta U_w = m_w c_w (T_{1w} - T_2) = (14.53\ \text{kg})(4.18\ \text{kJ/kg.K})(85\text{ - }44)\text{K} = 2490\ \text{kJ}$$

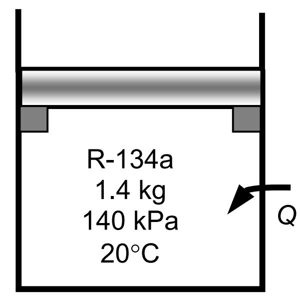
$$\Delta U_a = m_a c_v (T_{1a} - T_2) = (0.04724\ \text{kg})(0.718\ \text{kJ/kg.K})(22\text{ - }44)\text{K} = -0.7462\ \text{kJ}$$

$$\begin{aligned} X_{\text{dest}} &= \Delta X_w + \Delta X_a \\ &= \Delta U_w - T_0\Delta S_w + \Delta U_a - T_0\Delta S_a \\ &= 2490\ \text{kJ} - (295\ \text{K})(7.3873\ \text{kJ/K}) + (\text{-}0.7462\ \text{kJ}) - (295\ \text{K})(0.003931\ \text{kJ/K}) \\ &= \mathbf{308.8\ kJ} \end{aligned}$$

8-53 Heat is transferred to a piston-cylinder device with a set of stops. The work done, the heat transfer, the exergy destroyed, and the second-law efficiency are to be determined.

Assumptions **1** The device is stationary and kinetic and potential energy changes are zero. **2** There is no friction between the piston and the cylinder.

Analysis (*a*) The properties of the refrigerant at the initial and final states are (Tables A-11 through A-13)



$$\left.\begin{array}{l} P_1 = 120\text{ kPa} \\ T_1 = 20°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = 0.16544\text{ m}^3\text{/kg} \\ u_1 = 248.22\text{ kJ/kg} \\ s_1 = 1.0624\text{ kJ/kg.K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 180\text{ kPa} \\ T_2 = 120°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_2 = 0.17563\text{ m}^3\text{/kg} \\ u_2 = 331.96\text{ kJ/kg} \\ s_2 = 1.3118\text{ kJ/kg.K} \end{array}$$

The boundary work is determined to be

$$W_{\text{b,out}} = mP_2(\boldsymbol{v}_2 - \boldsymbol{v}_1) = (1.4\text{ kg})(180\text{ kPa})(0.17563 - 0.16544)\text{m}^3\text{/kg} = \mathbf{2.57\ kJ}$$

(*b*) The heat transfer can be determined from an energy balance on the system

$$Q_{\text{in}} = m(u_2 - u_1) + W_{\text{b,out}} = (1.4\text{ kg})(331.96 - 248.22)\text{kJ/kg} + 2.57\text{ kJ} = \mathbf{119.8\ kJ}$$

(*c*) The exergy difference between the inlet and exit states is

$$\begin{aligned} \Delta X &= m\left[u_2 - u_1 - T_0(s_2 - s_1) + P_0(\boldsymbol{v}_2 - \boldsymbol{v}_1)\right] \\ &= (1.4\text{ kg})\left[(331.96 - 248.22)\text{kJ/kg} - (298\text{ K})(1.3118 - 1.0624)\text{kg.K} + (100\text{ kPa})(0.17563 - 0.16544)\text{m}^3\text{/kg}\right] \\ &= 14.61\text{ kJ} \end{aligned}$$

The useful work output for the process is

$$W_{\text{u,out}} = W_{\text{b,out}} - mP_0(\boldsymbol{v}_2 - \boldsymbol{v}_1) = 2.57\text{ kJ} - (1.4\text{ kg})(100\text{ kPa})(0.17563 - 0.16544)\text{m}^3\text{/kg} = 1.14\text{ kJ}$$

The exergy destroyed is the difference between the exergy difference and the useful work output

$$X_{\text{dest}} = \Delta X - W_{\text{u,out}} = 14.61 - 1.14 = \mathbf{13.47\ kJ}$$

(*d*) The second-law efficiency for this process is

$$\eta_{\text{II}} = \frac{W_{\text{u,out}}}{\Delta X} = \frac{1.14\text{ kJ}}{14.61\text{ kJ}} = \mathbf{0.078}$$