Solutions Manual

for

Introduction to Thermodynamics and Heat Transfer

Yunus A. Cengel

2nd Edition, 2008

Chapter 5

ENERGY ANALYSIS OF CLOSED SYSTEMS

Moving Boundary Work

5-1C It represents the boundary work for quasi-equilibrium processes.

5-2C Yes.

5-3C The area under the process curve, and thus the boundary work done, is greater in the constant pressure case.

5-4C $1\text{ kPa}\cdot\text{m}^3 = 1\text{ k(N/m}^2)\cdot\text{m}^3 = 1\text{ kN}\cdot\text{m} = 1\text{ kJ}$

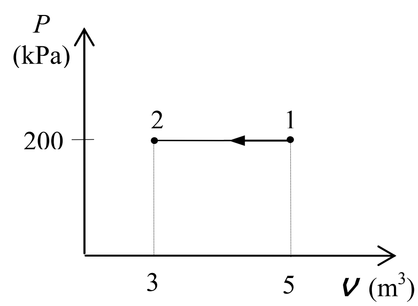
5-5 Helium is compressed in a piston-cylinder device. The initial and final temperatures of helium and the work required to compress it are to be determined.

Assumptions The process is quasi-equilibrium.

Properties The gas constant of helium is R = 2.0769 kJ/kg·K (Table A-1).

Analysis The initial specific volume is

$$\boldsymbol{v}_1 = \frac{\boldsymbol{V}_1}{m} = \frac{5\text{ m}^3}{1\text{ kg}} = 5\text{ m}^3/\text{kg}$$



Using the ideal gas equation,

$$T_1 = \frac{P_1\boldsymbol{v}_1}{R} = \frac{(200\text{ kPa})(5\text{ m}^3/\text{kg})}{2.0769\text{ kJ/kg}\cdot\text{K}} = \mathbf{481.5\text{ K}}$$

Since the pressure stays constant,

$$T_2 = \frac{\boldsymbol{V}_2}{\boldsymbol{V}_1}T_1 = \frac{3\text{ m}^3}{5\text{ m}^3}(481.5\text{ K}) = \mathbf{288.9\text{ K}}$$

and the work integral expression gives

$$W_{b,\text{out}} = \int_1^2 P\,d\boldsymbol{V} = P(\boldsymbol{V}_2 - \boldsymbol{V}_1) = (200\text{ kPa})(3-5)\text{ m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = -400\text{ kJ}$$

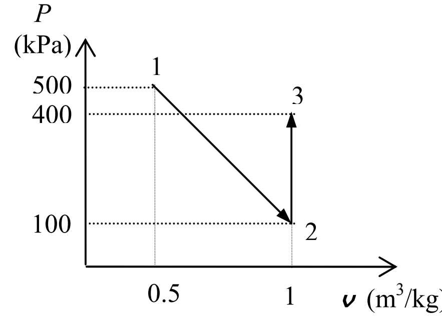
That is,

$$W_{b,\text{in}} = \mathbf{400\text{ kJ}}$$

5-6 The boundary work done during the process shown in the figure is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis No work is done during the process 2-3 since the area under process line is zero. Then the work done is equal to the area under the process line 1-2:

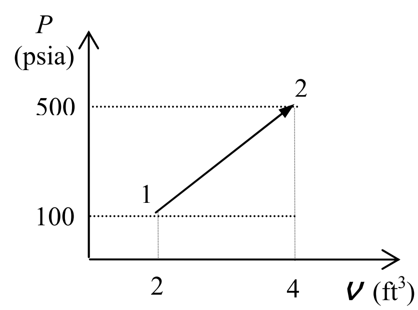


$$
\begin{aligned}
W_{b,\text{out}} &= \text{Area} = \frac{P_1 + P_2}{2} m(\boldsymbol{v}_2 - \boldsymbol{v}_1) \\
&= \frac{(100+500)\text{kPa}}{2}(2\text{ kg})(1.0-0.5)\text{m}^3/\text{kg}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\
&= \mathbf{300\ kJ}
\end{aligned}
$$

5-7E The boundary work done during the process shown in the figure is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis The work done is equal to the area under the process line 1-2:

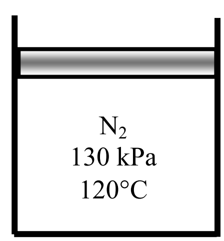


$$
\begin{aligned}
W_{b,\text{out}} &= \text{Area} = \frac{P_1 + P_2}{2}(\boldsymbol{V}_2 - \boldsymbol{V}_1) \\
&= \frac{(100+500)\text{psia}}{2}(4.0-2.0)\text{ft}^3\left(\frac{1\text{ Btu}}{5.404\text{ psia}\cdot\text{ft}^3}\right) \\
&= \mathbf{111\,Btu}
\end{aligned}
$$

5-8 A piston-cylinder device contains nitrogen gas at a specified state. The boundary work is to be determined for the polytropic expansion of nitrogen.

Properties The gas constant for nitrogen is 0.2968 kJ/kg.K (Table A-2).

Analysis The mass and volume of nitrogen at the initial state are



$$
m = \frac{P_1\boldsymbol{V}_1}{RT_1} = \frac{(130\text{ kPa})(0.07\text{ m}^3)}{(0.2968\text{ kJ/kg.K})(120+273\text{ K})} = 0.07802\text{ kg}
$$

$$
\boldsymbol{V}_2 = \frac{mRT_2}{P_2} = \frac{(0.07802\text{ kg})(0.2968\text{ kPa.m}^3/\text{kg.K})(100+273\text{ K})}{100\text{ kPa}} = 0.08637\text{ m}^3
$$

The polytropic index is determined from

$$
P_1\boldsymbol{V}_1^n = P_2\boldsymbol{V}_2^n \longrightarrow (130\text{ kPa})(0.07\text{ m}^3)^n = (100\text{ kPa})(0.08637\text{ m}^3)^n \longrightarrow n = 1.249
$$

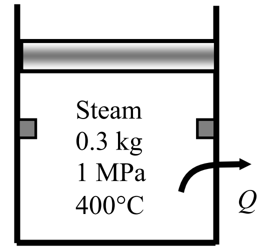
The boundary work is determined from

$$
W_b = \frac{P_2\boldsymbol{V}_2 - P_1\boldsymbol{V}_1}{1-n} = \frac{(100\text{ kPa})(0.08637\text{ m}^3) - (130\text{ kPa})(0.07\text{ m}^3)}{1-1.249} = \mathbf{1.86\ kJ}
$$

5-9 A piston-cylinder device with a set of stops contains steam at a specified state. Now, the steam is cooled. The compression work for two cases and the final temperature are to be determined.

Analysis (a) The specific volumes for the initial and final states are (Table A-6)

$$\left.\begin{array}{l} P_1 = 1\,\text{MPa} \\ T_1 = 400°\text{C} \end{array}\right\} \boldsymbol{v}_1 = 0.30661\,\text{m}^3/\text{kg} \qquad \left.\begin{array}{l} P_2 = 1\,\text{MPa} \\ T_2 = 250°\text{C} \end{array}\right\} \boldsymbol{v}_2 = 0.23275\,\text{m}^3/\text{kg}$$



Noting that pressure is constant during the process, the boundary work is determined from

$$W_b = mP(\boldsymbol{v}_1 - \boldsymbol{v}_2) = (0.3\,\text{kg})(1000\,\text{kPa})(0.30661 - 0.23275)\text{m}^3/\text{kg} = \mathbf{22.16\,kJ}$$

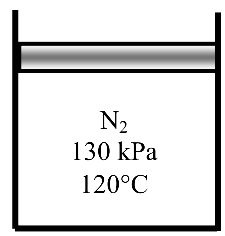
(b) The volume of the cylinder at the final state is 60% of initial volume. Then, the boundary work becomes

$$W_b = mP(\boldsymbol{v}_1 - 0.60\boldsymbol{v}_1) = (0.3\,\text{kg})(1000\,\text{kPa})(0.30661 - 0.60 \times 0.30661)\text{m}^3/\text{kg} = \mathbf{36.79\,kJ}$$

The temperature at the final state is

$$\left.\begin{array}{l} P_2 = 0.5\,\text{MPa} \\ \boldsymbol{v}_2 = (0.60 \times 0.30661)\,\text{m}^3/\text{kg} \end{array}\right\} T_2 = \mathbf{151.8°C} \quad \text{(Table A-5)}$$

5-10 A piston-cylinder device contains nitrogen gas at a specified state. The final temperature and the boundary work are to be determined for the isentropic expansion of nitrogen.



Properties The properties of nitrogen are R = 0.2968 kJ/kg.K , k = 1.4 (Table A-2a)

Analysis The mass and the final volume of nitrogen are

$$m = \frac{P_1\boldsymbol{V}_1}{RT_1} = \frac{(130\,\text{kPa})(0.07\,\text{m}^3)}{(0.2968\,\text{kJ/kg.K})(120 + 273\,\text{K})} = 0.07802\,\text{kg}$$

$$P_1\boldsymbol{V}_1^k = P_2\boldsymbol{V}_2^k \longrightarrow (130\,\text{kPa})(0.07\,\text{m}^3)^{1.4} = (100\,\text{kPa})\boldsymbol{V}_2^{1.4} \longrightarrow \boldsymbol{V}_2 = 0.08443\,\text{m}^3$$

The final temperature and the boundary work are determined as

$$T_2 = \frac{P_2\boldsymbol{V}_2}{mR} = \frac{(100\,\text{kPa})(0.08443\,\text{m}^3)}{(0.07802\,\text{kg})(0.2968\,\text{kPa.m}^3/\text{kg.K})} = \mathbf{364.6\,K}$$

$$W_b = \frac{P_2\boldsymbol{V}_2 - P_1\boldsymbol{V}_1}{1-k} = \frac{(100\,\text{kPa})(0.08443\,\text{m}^3) - (130\,\text{kPa})(0.07\,\text{m}^3)}{1 - 1.4} = \mathbf{1.64\,kJ}$$

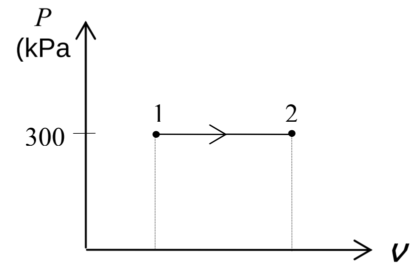
5-11 Saturated water vapor in a cylinder is heated at constant pressure until its temperature rises to a specified value. The boundary work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Properties Noting that the pressure remains constant during this process, the specific volumes at the initial and the final states are (Table A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 300 \text{ kPa} \\ \text{Sat. vapor} \end{array}\right\} \boldsymbol{v}_1 = \boldsymbol{v}_{g\,@\,300\text{ kPa}} = 0.60582 \text{ m}^3\text{/kg}$$

$$\left.\begin{array}{l} P_2 = 300 \text{ kPa} \\ T_2 = 200°\text{C} \end{array}\right\} \boldsymbol{v}_2 = 0.71643 \text{ m}^3\text{/kg}$$



Analysis The boundary work is determined from its definition to be

$$W_{b,\text{out}} = \int_1^2 P\,d\boldsymbol{V} = P(\boldsymbol{V}_2 - \boldsymbol{V}_1) = mP(\boldsymbol{v}_2 - \boldsymbol{v}_1)$$

$$= (5 \text{ kg})(300 \text{ kPa})(0.71643 - 0.60582) \text{ m}^3\text{/kg}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{165.9\ kJ}$$

Discussion The positive sign indicates that work is done by the system (work output).

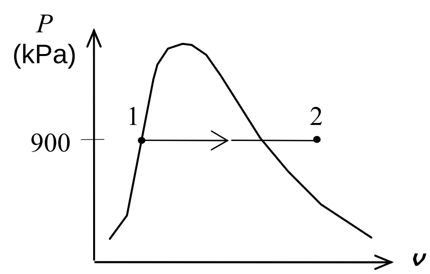
5-12 Refrigerant-134a in a cylinder is heated at constant pressure until its temperature rises to a specified value. The boundary work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Properties Noting that the pressure remains constant during this process, the specific volumes at the initial and the final states are (Table A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 900 \text{ kPa} \\ \text{Sat. liquid} \end{array}\right\} \boldsymbol{v}_1 = \boldsymbol{v}_{f\,@\,900\text{ kPa}} = 0.0008580 \text{ m}^3\text{/kg}$$

$$\left.\begin{array}{l} P_2 = 900 \text{ kPa} \\ T_2 = 70°\text{C} \end{array}\right\} \boldsymbol{v}_2 = 0.027413 \text{ m}^3\text{/kg}$$



Analysis The boundary work is determined from its definition to be

$$m = \frac{\boldsymbol{V}_1}{\boldsymbol{v}_1} = \frac{0.2 \text{ m}^3}{0.0008580 \text{ m}^3\text{/kg}} = 233.1 \text{ kg}$$

and

$$W_{b,\text{out}} = \int_1^2 P\,d\boldsymbol{V} = P(\boldsymbol{V}_2 - \boldsymbol{V}_1) = mP(\boldsymbol{v}_2 - \boldsymbol{v}_1)$$

$$= (233.1 \text{ kg})(900 \text{ kPa})(0.027413 - 0.0008580)\text{m}^3\text{/kg}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$

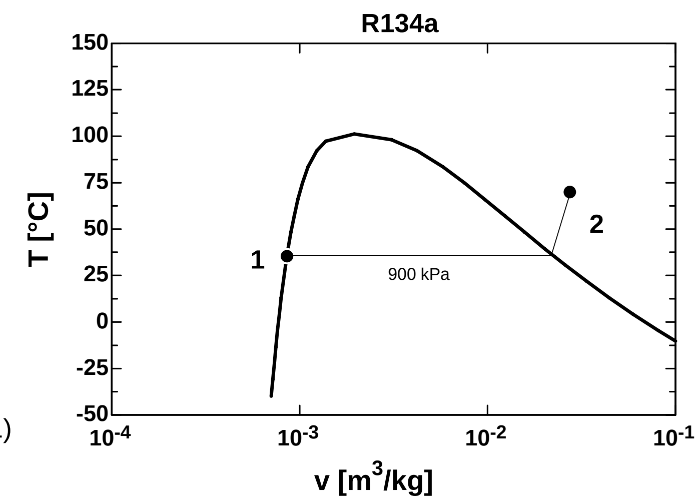
$$= \mathbf{5571\ kJ}$$

Discussion The positive sign indicates that work is done by the system (work output).

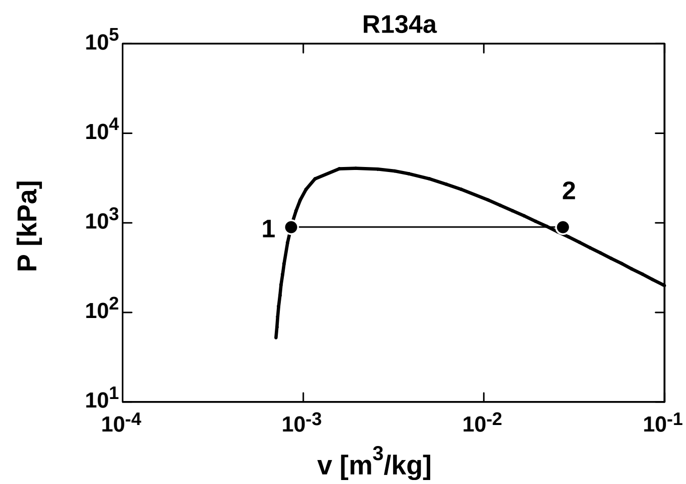
5-13 EES Problem 5-12 is reconsidered. The effect of pressure on the work done as the pressure varies from 400 kPa to 1200 kPa is to be investigated. The work done is to be plotted versus the pressure.

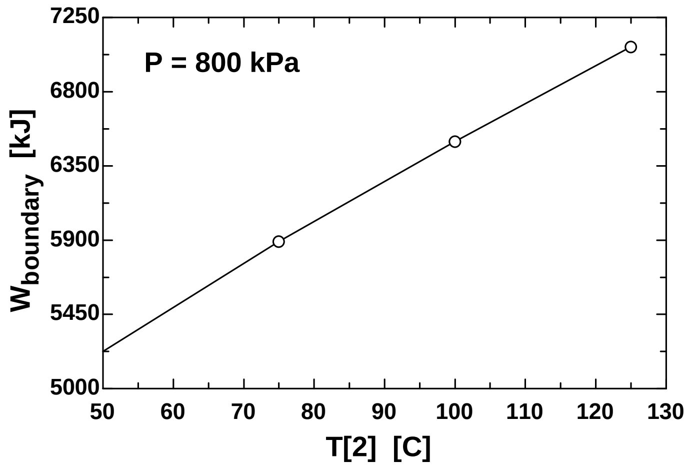
Analysis The problem is solved using EES, and the solution is given below.

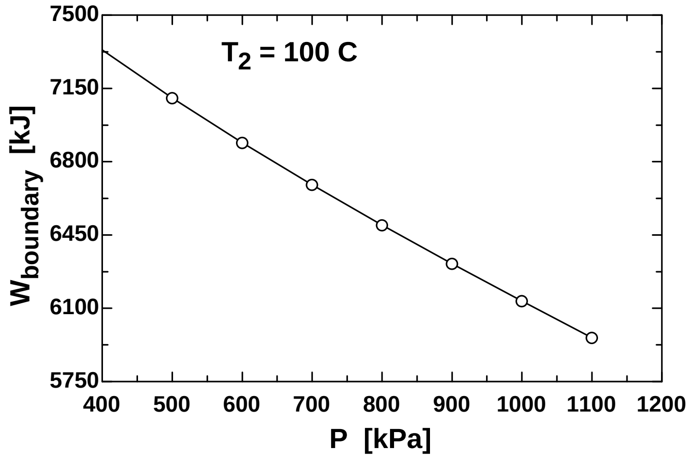
```
"Knowns"
Vol_1L=200 [L]
x_1=0 "saturated liquid state"
P=900 [kPa]
T_2=70 [C]

"Solution"
Vol_1=Vol_1L*convert(L,m^3)
"The work is the boundary work done by the R-134a during the constant pressure process."

W_boundary=P*(Vol_2-Vol_1)

"The mass is:"

Vol_1=m*v_1
v_1=volume(R134a,P=P,x=x_1)
Vol_2=m*v_2
v_2=volume(R134a,P=P,T=T_2)

"Plot information:"
v[1]=v_1
v[2]=v_2
P[1]=P
P[2]=P
T[1]=temperature(R134a,P=P,x=x_1)
T[2]=T_2
```

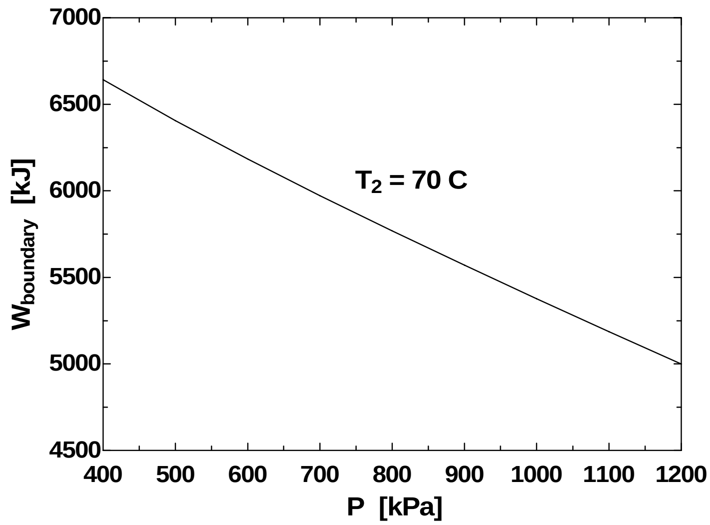


P [kPa]	$W_{boundary}$ [kJ]
400	6643
500	6405
600	6183
700	5972
800	5769
900	5571
1000	5377
1100	5187
1200	4999




P = 800 kPa
W boundary [kJ]
T[2] [C]
7250
6800
6350
5900
5450
5000
50
60
70
80
90
100
110
120
130


T2 = 100 C
W boundary [kJ]
P [kPa]
7500
7150
6800
6450
6100
5750
400
500
600
700
800
900
1000
1100
1200


T2 = 70 C
W boundary [kJ]
P [kPa]
7000
6500
6000
5500
5000
4500
400
500
600
700
800
900
1000
1100
1200

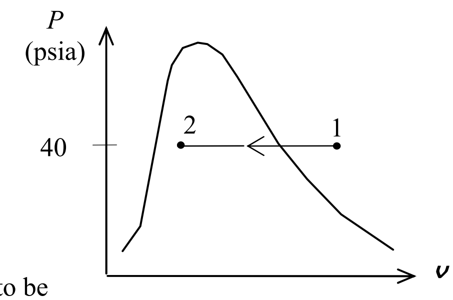
5-14E Superheated water vapor in a cylinder is cooled at constant pressure until 70% of it condenses. The boundary work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Properties Noting that the pressure remains constant during this process, the specific volumes at the initial and the final states are (Table A-4E through A-6E)

$$\left.\begin{array}{l} P_1 = 40 \text{ psia} \\ T_1 = 600°\text{F} \end{array}\right\} \boldsymbol{v}_1 = 15.686 \text{ ft}^3/\text{lbm}$$

$$\left.\begin{array}{l} P_2 = 40 \text{ psia} \\ x_2 = 0.3 \end{array}\right\} \begin{aligned} \boldsymbol{v}_2 &= \boldsymbol{v}_f + x_2 \boldsymbol{v}_{fg} \\ &= 0.01715 + 0.3(10.501 - 0.01715) \\ &= 3.1623 \text{ ft}^3/\text{lbm} \end{aligned}$$



Analysis The boundary work is determined from its definition to be

$$\begin{aligned} W_{b,\text{out}} &= \int_1^2 P\,d\boldsymbol{V} = P(\boldsymbol{V}_2 - \boldsymbol{V}_1) = mP(\boldsymbol{v}_2 - \boldsymbol{v}_1) \\ &= (16 \text{ lbm})(40 \text{ psia})(3.1623 - 15.686)\text{ft}^3/\text{lbm}\left(\frac{1 \text{ Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right) \\ &= \mathbf{-1483\ Btu} \end{aligned}$$

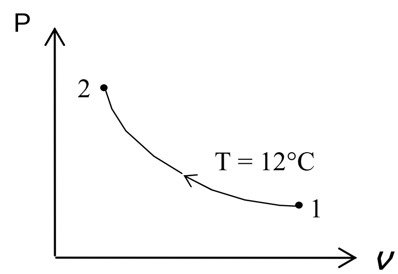
Discussion The negative sign indicates that work is done on the system (work input).

5-15 Air in a cylinder is compressed at constant temperature until its pressure rises to a specified value. The boundary work done during this process is to be determined.

Assumptions **1** The process is quasi-equilibrium. **2** Air is an ideal gas.

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

Analysis The boundary work is determined from its definition to be



$$\begin{aligned} W_{b,\text{out}} &= \int_1^2 P\,d\boldsymbol{V} = P_1\boldsymbol{V}_1 \ln\frac{\boldsymbol{V}_2}{\boldsymbol{V}_1} = mRT\ln\frac{P_1}{P_2} \\ &= (2.4 \text{ kg})(0.287 \text{ kJ/kg}\cdot\text{K})(285 \text{ K})\ln\frac{150 \text{ kPa}}{600 \text{ kPa}} \\ &= \mathbf{-272\ \ kJ} \end{aligned}$$

Discussion The negative sign indicates that work is done on the system (work input).

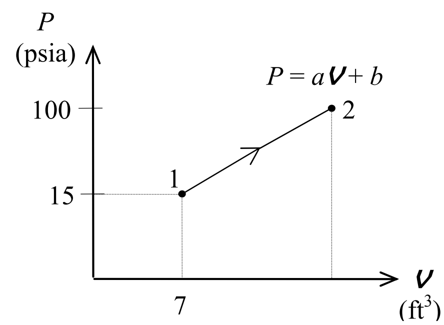
5-16E A gas in a cylinder is heated and is allowed to expand to a specified pressure in a process during which the pressure changes linearly with volume. The boundary work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis (*a*) The pressure of the gas changes linearly with volume, and thus the process curve on a P-V diagram will be a straight line. The boundary work during this process is simply the area under the process curve, which is a trapezoidal. Thus,

At state 1:

$$P_1 = a V_1 + b$$
$$15 \text{ psia} = (5 \text{ psia/ft}^3)(7 \text{ ft}^3) + b$$
$$b = -20 \text{ psia}$$



At state 2:

$$P_2 = a V_2 + b$$
$$100 \text{ psia} = (5 \text{ psia/ft}^3) V_2 + (-20 \text{ psia})$$
$$V_2 = 24 \text{ ft}^3$$

and,

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1) = \frac{(100+15)\text{psia}}{2}(24-7)\text{ft}^3 \left(\frac{1 \text{ Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right)$$
$$= \mathbf{181 \ Btu}$$

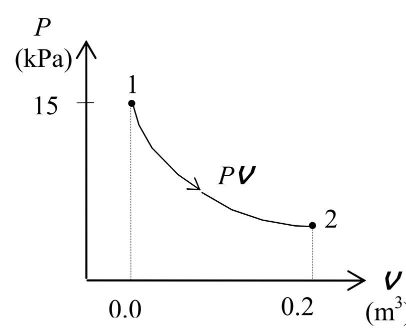
Discussion The positive sign indicates that work is done by the system (work output).

5-17 CD EES A gas in a cylinder expands polytropically to a specified volume. The boundary work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis The boundary work for this polytropic process can be determined directly from

$$P_2 = P_1\left(\frac{V_1}{V_2}\right)^n = (150 \text{ kPa})\left(\frac{0.03 \text{ m}^3}{0.2 \text{ m}^3}\right)^{1.3} = 12.74 \text{ kPa}$$



and,

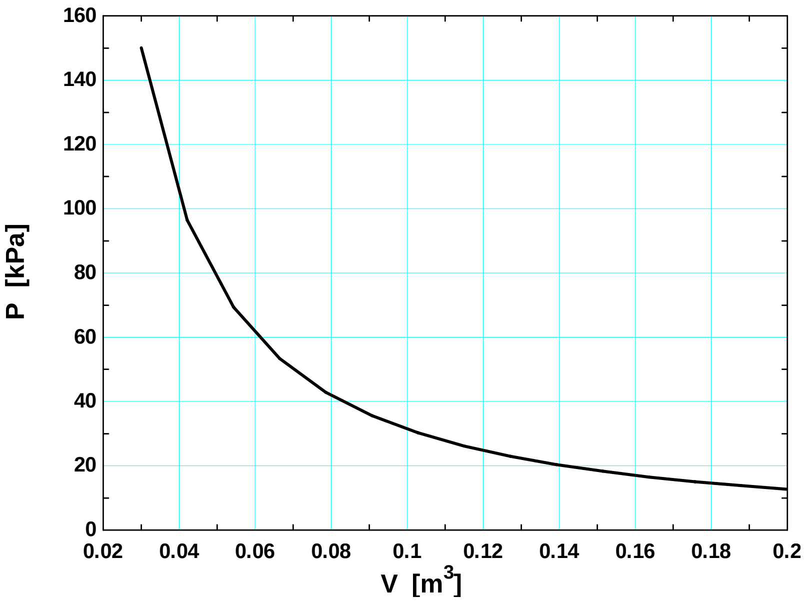
$$W_{b,\text{out}} = \int_1^2 P\,dV = \frac{P_2V_2 - P_1V_1}{1-n}$$
$$= \frac{(12.74\times 0.2 - 150\times 0.03) \text{ kPa}\cdot\text{m}^3}{1-1.3}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$
$$= \mathbf{6.51 \ kJ}$$

Discussion The positive sign indicates that work is done by the system (work output).

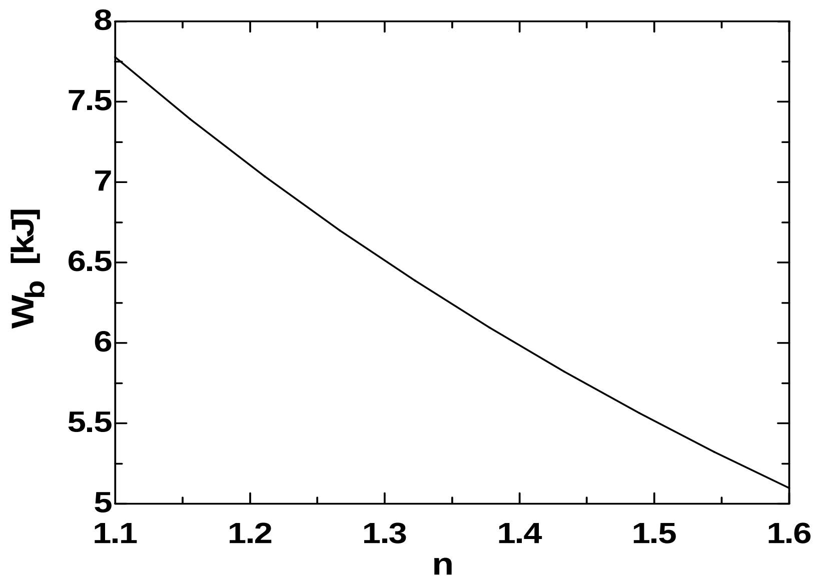
5-18 EES Problem 5-17 is reconsidered. The process described in the problem is to be plotted on a *P*-***V*** diagram, and the effect of the polytropic exponent n on the boundary work as the polytropic exponent varies from 1.1 to 1.6 is to be plotted.

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

```
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 depens on whether n=1 or n<>1"
  If n<>1 then
     BoundWork:=(P[2]*V[2]-P[1]*V[1])/(1-n)"Use Equation 3-22 when n=1"
  else
    BoundWork:= P[1]*V[1]*ln(V[2]/V[1]) "Use Equation 3-20 when n=1"
  endif
end

"Inputs from the diagram window"
{n=1.3
P[1] = 150 [kPa]
V[1] = 0.03 [m^3]
V[2] = 0.2 [m^3]
Gas$='AIR'}
"System:  The gas enclosed in the piston-cylinder device."
"Process: Polytropic expansion or compression, P*V^n = C"
P[2]*V[2]^n=P[1]*V[1]^n
"n = 1.3" "Polytropic exponent"

"Input Data"
W_b = BoundWork(P[1],V[1],P[2],V[2],n)"[kJ]"
"If we modify this problem and specify the mass, then we can calculate the final temperature of
the fluid for compression or expansion"
m[1] = m[2] "Conservation of mass for the closed system"
"Let's solve the problem for m[1] = 0.05 kg"
m[1] = 0.05 [kg]

"Find the temperatures from the pressure and specific volume."
T[1]=temperature(gas$,P=P[1],v=V[1]/m[1])
T[2]=temperature(gas$,P=P[2],v=V[2]/m[2])
```



n	W_b [kJ]
1.1	7.776
1.156	7.393
1.211	7.035
1.267	6.7
1.322	6.387
1.378	6.094
1.433	5.82
1.489	5.564
1.544	5.323
1.6	5.097

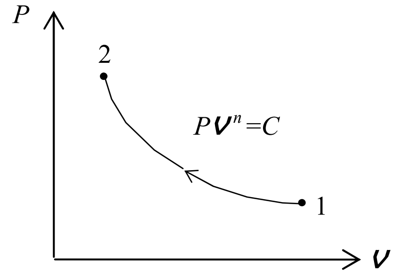


5-19 Nitrogen gas in a cylinder is compressed polytropically until the temperature rises to a specified value. The boundary work done during this process is to be determined.

Assumptions **1** The process is quasi-equilibrium. **2** Nitrogen is an ideal gas.

Properties The gas constant for nitrogen is R = 0.2968 kJ/kg.K (Table A-2a)

Analysis The boundary work for this polytropic process can be determined from



$$W_{b,\text{out}} = \int_1^2 P\,dV = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{mR(T_2 - T_1)}{1-n}$$
$$= \frac{(2\text{ kg})(0.2968\text{ kJ/kg}\cdot\text{K})(360-300)\text{K}}{1-1.4}$$
$$= \mathbf{-89.0\ kJ}$$

Discussion The negative sign indicates that work is done on the system (work input).

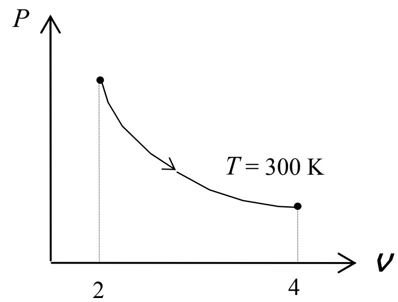
5-20 CD EES A gas whose equation of state is $\bar{v}(P+10/\bar{v}^2) = R_uT$ expands in a cylinder isothermally to a specified volume. The unit of the quantity 10 and the boundary work done during this process are to be determined.

Assumptions The process is quasi-equilibrium.

Analysis (*a*) The term $10/\bar{v}^2$ must have pressure units since it is added to P.

Thus the quantity 10 must have the unit kPa·m^6/kmol^2.

(*b*) The boundary work for this process can be determined from



$$P = \frac{R_uT}{\bar{v}} - \frac{10}{\bar{v}^2} = \frac{R_uT}{V/N} - \frac{10}{(V/N)^2} = \frac{NR_uT}{V} - \frac{10N^2}{V^2}$$

and

$$W_{b,\text{out}} = \int_1^2 P\,dV = \int_1^2 \left(\frac{NR_uT}{V} - \frac{10N^2}{V^2}\right)dV = NR_uT\ln\frac{V_2}{V_1} + 10N^2\left(\frac{1}{V_2} - \frac{1}{V_1}\right)$$
$$= (0.5\text{ kmol})(8.314\text{ kJ/kmol}\cdot\text{K})(300\text{ K})\ln\frac{4\text{ m}^3}{2\text{ m}^3}$$
$$+ (10\text{ kPa}\cdot\text{m}^6/\text{kmol}^2)(0.5\text{kmol})^2\left(\frac{1}{4\text{ m}^3} - \frac{1}{2\text{ m}^3}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$
$$= \mathbf{864\ kJ}$$

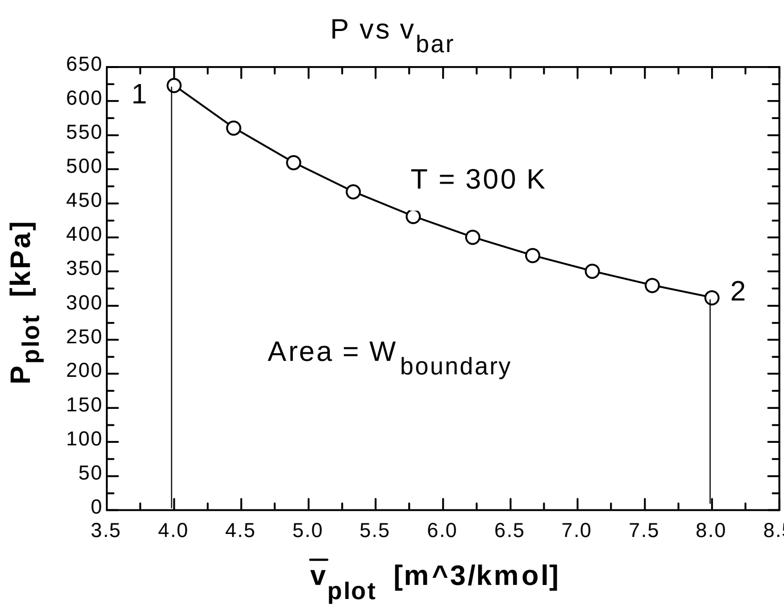
Discussion The positive sign indicates that work is done by the system (work output).

5-21 EES Problem 5-20 is reconsidered. Using the integration feature, the work done is to be calculated and compared, and the process is to be plotted on a *P*-*V* diagram.

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

```
"Input Data"
N=0.5 [kmol]
v1_bar=2/N "[m^3/kmol]"
v2_bar=4/N "[m^3/kmol]"
T=300 [K]
R_u=8.314 [kJ/kmol-K]

"The quation of state is:"
v_bar*(P+10/v_bar^2)=R_u*T "P is in kPa"

"using the EES integral function,  the boundary work, W_bEES, is"
W_b_EES=N*integral(P,v_bar, v1_bar, v2_bar,0.01)

"We can show that W_bhand= integeral of Pdv_bar is
(one should solve for P=F(v_bar) and do the integral 'by hand' for practice)."
W_b_hand = N*(R_u*T*ln(v2_bar/v1_bar) +10*(1/v2_bar-1/v1_bar))

"To plot P vs v_bar, define P_plot =f(v_bar_plot, T) as"

{v_bar_plot*(P_plot+10/v_bar_plot^2)=R_u*T}

" P=P_plot and v_bar=v_bar_plot just to generate the parametric table for plotting purposes.  To
plot P vs v_bar for a new temperature or v_bar_plot range,  remove the '{' and '}' from the above
equation, and reset the v_bar_plot values in the Parametric Table.  Then press F3 or select Solve
Table from the Calculate menu.  Next select New Plot Window under the Plot menu to plot the
new data."
```

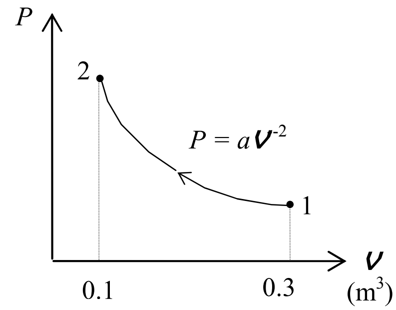
P_{plot}	v_{plot}
622.9	4
560.7	4.444
509.8	4.889
467.3	5.333
431.4	5.778
400.6	6.222
373.9	6.667
350.5	7.111
329.9	7.556
311.6	8



5-22 CO_2 gas in a cylinder is compressed until the volume drops to a specified value. The pressure changes during the process with volume as $P = a\boldsymbol{V}^{-2}$. The boundary work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis The boundary work done during this process is determined from



$$W_{b,\text{out}} = \int_1^2 P d\boldsymbol{V} = \int_1^2 \left(\frac{a}{\boldsymbol{V}^2}\right) d\boldsymbol{V} = -a\left(\frac{1}{\boldsymbol{V}_2} - \frac{1}{\boldsymbol{V}_1}\right)$$

$$= -(8 \text{ kPa}\cdot\text{m}^6)\left(\frac{1}{0.1 \text{ m}^3} - \frac{1}{0.3 \text{ m}^3}\right)\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{-53.3 \text{ kJ}}$$

Discussion The negative sign indicates that work is done on the system (work input).

5-23 Several sets of pressure and volume data are taken as a gas expands. The boundary work done during this process is to be determined using the experimental data.

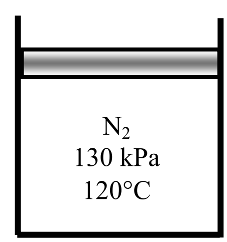
Assumptions The process is quasi-equilibrium.

Analysis Plotting the given data on a P-$\boldsymbol{V}$ diagram on a graph paper and evaluating the area under the process curve, the work done is determined to be **0.25 kJ**.

5-24 A piston-cylinder device contains nitrogen gas at a specified state. The boundary work is to be determined for the isothermal expansion of nitrogen.

Properties The properties of nitrogen are R = 0.2968 kJ/kg.K , k = 1.4 (Table A-2a).

Analysis We first determine initial and final volumes from ideal gas relation, and find the boundary work using the relation for isothermal expansion of an ideal gas



$$\boldsymbol{V}_1 = \frac{mRT}{P_1} = \frac{(0.25 \text{ kg})(0.2968 \text{ kJ/kg.K})(120 + 273 \text{ K})}{(130 \text{ kPa})} = 0.2243 \text{ m}^3$$

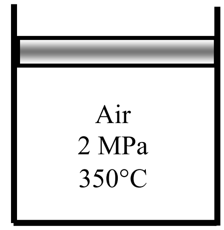
$$\boldsymbol{V}_2 = \frac{mRT}{P_2} = \frac{(0.25 \text{ kg})(0.2968 \text{ kJ/kg.K})(120 + 273 \text{ K})}{(100 \text{ kPa})} = 0.2916 \text{ m}^3$$

$$W_b = P_1\boldsymbol{V}_1 \ln\left(\frac{\boldsymbol{V}_2}{\boldsymbol{V}_1}\right) = (130 \text{ kPa})(0.2243 \text{ m}^3)\ln\left(\frac{0.2916 \text{ m}^3}{0.2243 \text{ m}^3}\right) = \mathbf{7.65 \text{ kJ}}$$

5-25 A piston-cylinder device contains air gas at a specified state. The air undergoes a cycle with three processes. The boundary work for each process and the net work of the cycle are to be determined.

Properties The properties of air are R = 0.287 kJ/kg.K , k = 1.4 (Table A-2a).

Analysis For the isothermal expansion process:



$$V_1 = \frac{mRT}{P_1} = \frac{(0.15\,\text{kg})(0.287\,\text{kJ/kg.K})(350+273\,\text{K})}{(2000\,\text{kPa})} = 0.01341\,\text{m}^3$$

$$V_2 = \frac{mRT}{P_2} = \frac{(0.15\,\text{kg})(0.287\,\text{kJ/kg.K})(350+273\,\text{K})}{(500\,\text{kPa})} = 0.05364\,\text{m}^3$$

$$W_{b,1-2} = P_1V_1\ln\left(\frac{V_2}{V_1}\right) = (2000\,\text{kPa})(0.01341\,\text{m}^3)\ln\left(\frac{0.05364\,\text{m}^3}{0.01341\,\text{m}^3}\right) = \mathbf{37.18\,kJ}$$

For the polytropic compression process:

$$P_2V_2^n = P_3V_3^n \longrightarrow (500\,\text{kPa})(0.05364\,\text{m}^3)^{1.2} = (2000\,\text{kPa})V_3^{1.2} \longrightarrow V_3 = 0.01690\,\text{m}^3$$

$$W_{b,2-3} = \frac{P_3V_3 - P_2V_2}{1-n} = \frac{(2000\,\text{kPa})(0.01690\,\text{m}^3)-(500\,\text{kPa})(0.05364\,\text{m}^3)}{1-1.2} = \mathbf{-34.86\,kJ}$$

For the constant pressure compression process:

$$W_{b,3-1} = P_3(V_1 - V_3) = (2000\,\text{kPa})(0.01341-0.01690)\text{m}^3 = \mathbf{-6.97\,kJ}$$

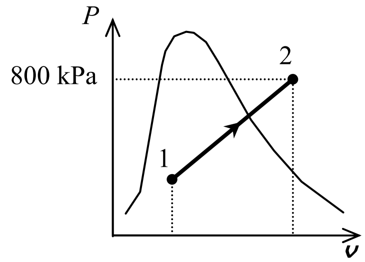
The net work for the cycle is the sum of the works for each process

$$W_{\text{net}} = W_{b,1-2} + W_{b,2-3} + W_{b,3-1} = 37.18 + (-34.86) + (-6.97) = \mathbf{-4.65\,kJ}$$

5-26 A saturated water mixture contained in a spring-loaded piston-cylinder device is heated until the pressure and temperature rises to specified values. The work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis The initial state is saturated mixture at 90°C. The pressure and the specific volume at this state are (Table A-4),



$$P_1 = 70.183\ \text{kPa}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_f + x\boldsymbol{v}_{fg} = 0.001036 + (0.10)(2.3593 - 0.001036) = 0.23686\ \text{m}^3/\text{kg}$$

The final specific volume at 800 kPa and 250°C is (Table A-6)

$$\boldsymbol{v}_2 = 0.29321\ \text{m}^3/\text{kg}$$

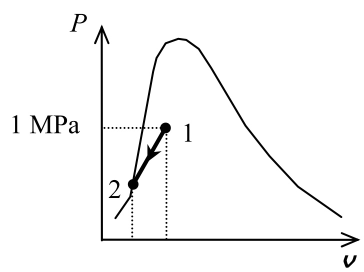
Since this is a linear process, the work done is equal to the area under the process line 1-2:

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2} m(\boldsymbol{v}_2 - \boldsymbol{v}_1) = \frac{(70.183 + 800)\text{kPa}}{2}(1\ \text{kg})(0.29321 - 0.23686)\text{m}^3\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = \mathbf{24.52\ kJ}$$

5-27 A saturated water mixture contained in a spring-loaded piston-cylinder device is cooled until it is saturated liquid at a specified temperature. The work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis The initial state is saturated mixture at 1 MPa. The specific volume at this state is (Table A-5),



$$\boldsymbol{v}_1 = \boldsymbol{v}_f + x\boldsymbol{v}_{fg} = 0.001127 + (0.10)(0.19436 - 0.001127) = 0.020450\ \text{m}^3/\text{kg}$$

The final state is saturated liquid at 100°C (Table A-4)

$$P_2 = 101.42\ \text{kPa}$$
$$\boldsymbol{v}_2 = \boldsymbol{v}_f = 0.001043\ \text{m}^3/\text{kg}$$

Since this is a linear process, the work done is equal to the area under the process line 1-2:

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2} m(\boldsymbol{v}_2 - \boldsymbol{v}_1) = \frac{(1000 + 101.42)\text{kPa}}{2}(0.5\ \text{kg})(0.001043 - 0.020450)\text{m}^3\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = \mathbf{-5.34\ kJ}$$

The negative sign shows that the work is done on the system in the amount of 5.34 kJ.

5-28 Argon is compressed in a polytropic process. The final temperature is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis For a polytropic expansion or compression process,

$$P\boldsymbol{v}^n = \text{Constant}$$

For an ideal gas,

$$P\boldsymbol{v} = RT$$

Combining these equations produces

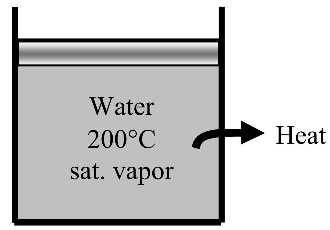
$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(n-1)/n} = (303\text{ K})\left(\frac{1200\text{ kPa}}{120\text{ kPa}}\right)^{0.2/1.2} = \mathbf{444.7\ K}$$

Closed System Energy Analysis

5-29 Saturated water vapor is isothermally condensed to a saturated liquid in a piston-cylinder device. The heat transfer and the work done are to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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

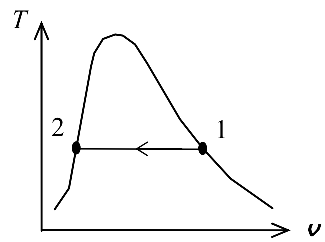


$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

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

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

The properties at the initial and final states are (Table A-4)



$$\left.\begin{array}{l} T_1 = 200°\text{C} \\ x_1 = 1 \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = \boldsymbol{v}_g = 0.12721\ \text{m}^3/\text{kg} \\ u_1 = u_g = 2594.2\ \text{kJ/kg} \end{array}$$

$$P_1 = P_2 = 1554.9\ \text{kPa}$$

$$\left.\begin{array}{l} T_2 = 200°\text{C} \\ x_2 = 0 \end{array}\right\} \begin{array}{l} \boldsymbol{v}_2 = \boldsymbol{v}_f = 0.001157\ \text{m}^3/\text{kg} \\ u_2 = u_f = 850.46\ \text{kJ/kg} \end{array}$$

The work done during this process is

$$w_{b,\text{out}} = \int_1^2 P d\boldsymbol{V} = P(\boldsymbol{v}_2 - \boldsymbol{v}_1) = (1554.9\ \text{kPa})(0.001157 - 0.12721)\ \text{m}^3/\text{kg}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = -196.0\ \text{kJ/kg}$$

That is,

$$w_{b,\text{in}} = \mathbf{196.0\ kJ/kg}$$

Substituting the energy balance equation, we get

$$q_{\text{out}} = w_{b,\text{in}} - (u_2 - u_1) = w_{b,\text{in}} + u_{fg} = 196.0 + 1743.7 = \mathbf{1940\ kJ/kg}$$

5-30E The heat transfer during a process that a closed system undergoes without any internal energy change is to be determined.

Assumptions **1** The system is stationary and thus the kinetic and potential energy changes are zero. **2** The compression or expansion process is quasi-equilibrium.

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

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

$$Q_{\text{in}} - W_{\text{out}} = \Delta U = 0 \quad (\text{since KE = PE = 0})$$

$$Q_{\text{in}} = W_{\text{out}}$$

Then,

$$Q_{\text{in}} = 1.6\times10^6 \text{ lbf}\cdot\text{ft}\left(\frac{1\,\text{Btu}}{778.17\,\text{lbf}\cdot\text{ft}}\right) = \mathbf{2056\ Btu}$$

5-31 The table is to be completed using conservation of energy principle for a closed system.

Analysis The energy balance for a closed system can be expressed as

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

$$Q_{\text{in}} - W_{\text{out}} = E_2 - E_1 = m(e_2 - e_1)$$

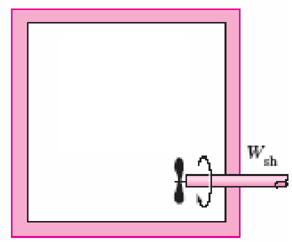
Application of this equation gives the following completed table:

Q_{in} (kJ)	W_{out} (kJ)	E_1 (kJ)	E_2 (kJ)	m (kg)	$e_2 - e_1$ (kJ/kg)
280	**440**	1020	860	3	**-53.3**
-350	130	550	**70**	5	**-96**
-40	260	300	**0**	2	-150
300	**550**	750	500	1	**-250**
-400	-200	**500**	300	2	-100

5-32 A substance is contained in a well-insulated, rigid container that is equipped with a stirring device. The change in the internal energy of this substance for a given work input is to be determined.

Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** The tank is insulated and thus heat transfer is negligible.

Analysis This is a closed system since no mass enters or leaves. The energy balance for this stationary closed system can be expressed as



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

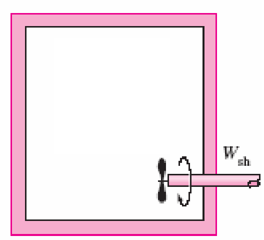
$$W_{sh,in} = \Delta U \quad \text{(since KE = PE = 0)}$$

Then,

$$\Delta U = \mathbf{15\ kJ}$$

5-33 Motor oil is contained in a rigid container that is equipped with a stirring device. The rate of specific energy increase is to be determined.

Analysis This is a closed system since no mass enters or leaves. The energy balance for closed system can be expressed as



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

$$\dot{Q}_{in} + \dot{W}_{sh,in} = \Delta \dot{E}$$

Then,

$$\Delta \dot{E} = \dot{Q}_{in} + \dot{W}_{sh,in} = 1 + 1.5 = 2.5 = 2.5 \text{ W}$$

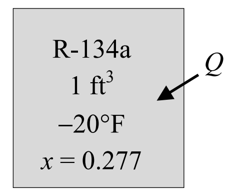
Dividing this by the mass in the system gives

$$\Delta \dot{e} = \frac{\Delta \dot{E}}{m} = \frac{2.5 \text{ J/s}}{1.5 \text{ kg}} = \mathbf{1.67\ J/kg \cdot s}$$

5-34E R-134a contained in a rigid vessel is heated. The heat transfer is to be determined.

Assumptions **1** The system is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved **3** The thermal energy stored in the vessel itself is negligible.

Analysis We take R-134a 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



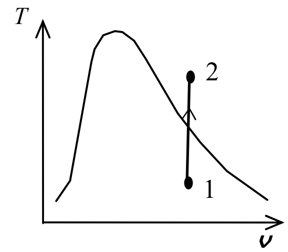
$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

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

The properties at the initial and final states are (Tables A-11E, A-13E)

$$\left.\begin{array}{l} T_1 = -20°\text{F} \\ x_1 = 0.277 \end{array}\right\} \begin{array}{l} \mathbf{v}_1 = \mathbf{v}_f + x\mathbf{v}_{fg} = 0.01156 + (0.277)(3.4426 - 0.01156) = 0.96196 \text{ ft}^3/\text{lbm} \\ u_1 = u_f + xu_{fg} = 6.019 + (0.277)(85.874) = 29.81 \text{ Btu/lbm} \end{array}$$

$$\left.\begin{array}{l} T_2 = 100°\text{F} \\ \mathbf{v}_2 = \mathbf{v}_1 = 0.96196 \text{ ft}^3/\text{lbm} \end{array}\right\} u_2 = 111.30 \text{ Btu/lbm}$$



Note that the final state is superheated vapor and the internal energy at this state should be obtained by interpolation using 50 psia and 60 psia mini tables (100°F line) in Table A-13E. The mass in the system is

$$m = \frac{V_1}{\mathbf{v}_1} = \frac{1 \text{ ft}^3}{0.96196 \text{ ft}^3/\text{lbm}} = 1.0395 \text{ lbm}$$

Substituting,

$$Q_{\text{in}} = m(u_2 - u_1) = (1.0395 \text{ lbm})(111.30 - 29.81) \text{ Btu/lbm} = \mathbf{84.7 \text{ Btu}}$$

5-35 An insulated rigid tank is initially filled with a saturated liquid-vapor mixture of water. An electric heater in the tank is turned on, and the entire liquid in the tank is vaporized. The length of time the heater was kept on is to be determined, and the process is to be shown on a P-v diagram.

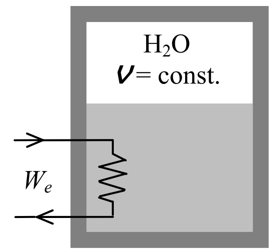
Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** The device is well-insulated and thus heat transfer is negligible. **3** The energy stored in the resistance wires, and the heat transferred to the tank itself is negligible.

Analysis We take the contents of 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

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

$$W_{e,\text{in}} = \Delta U = m(u_2 - u_1) \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$

$$\text{V}I\Delta t = m(u_2 - u_1)$$



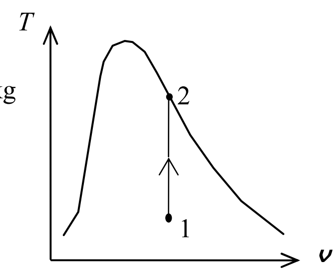
The properties of water are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 100\text{kPa} \\ x_1 = 0.25 \end{array}\right\} \begin{array}{l} v_f = 0.001043, \quad v_g = 1.6941 \text{ m}^3/\text{kg} \\ u_f = 417.40, \quad u_{fg} = 2088.2 \text{ kJ/kg} \end{array}$$

$$v_1 = v_f + x_1 v_{fg} = 0.001043 + [0.25 \times (1.6941 - 0.001043)] = 0.42431 \text{ m}^3/\text{kg}$$

$$u_1 = u_f + x_1 u_{fg} = 417.40 + (0.25 \times 2088.2) = 939.4 \text{ kJ/kg}$$

$$\left.\begin{array}{l} v_2 = v_1 = 0.42431 \text{ m}^3/\text{kg} \\ \text{sat.vapor} \end{array}\right\} u_2 = u_{g@0.42431\text{m}^3/\text{kg}} = 2556.2 \text{ kJ/kg}$$



Substituting,

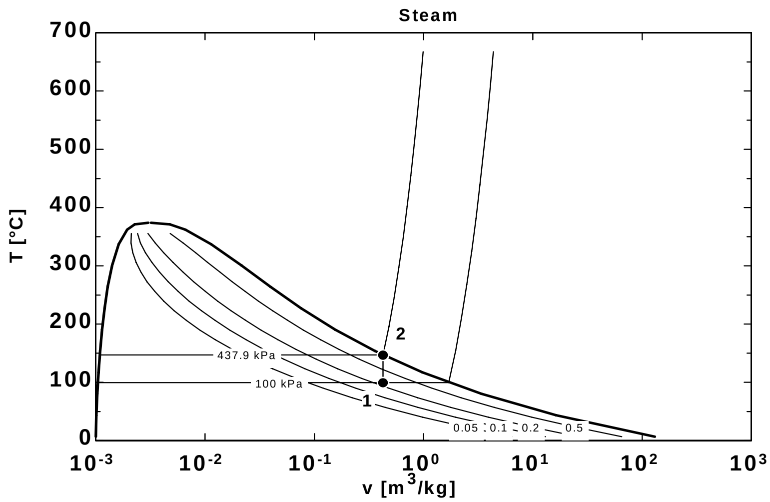
$$(110 \text{ V})(8 \text{ A})\Delta t = (5 \text{ kg})(2556.2 - 939.4)\text{kJ/kg}\left(\frac{1000 \text{ VA}}{1 \text{ kJ/s}}\right)$$

$$\Delta t = 9186 \text{ s} \cong \mathbf{153.1 \text{ min}}$$

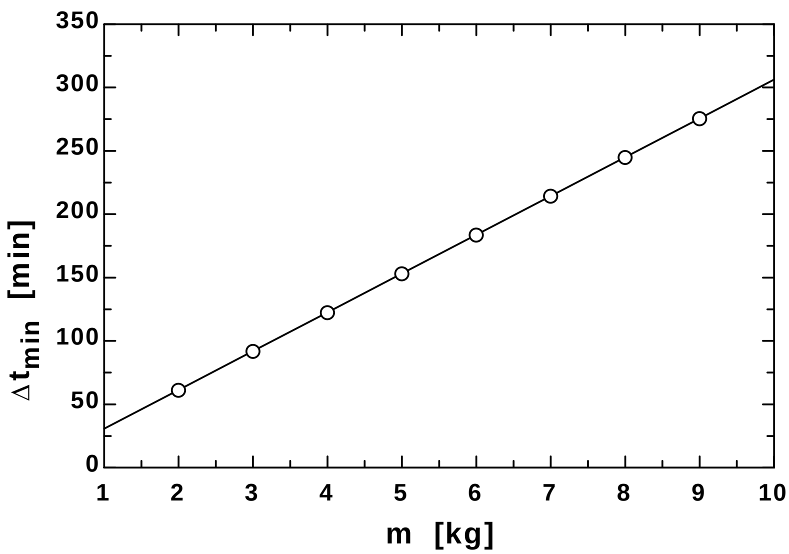
5-36 EES Problem 5-35 is reconsidered. The effect of the initial mass of water on the length of time required to completely vaporize the liquid as the initial mass varies from 1 kg to 10 kg is to be investigated. The vaporization time is to be plotted against the initial mass.

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

```
PROCEDURE P2X2(v[1]:P[2],x[2])
Fluid$='Steam_IAPWS'
If v[1] > V_CRIT(Fluid$) then
P[2]=pressure(Fluid$,v=v[1],x=1)
x[2]=1
else
P[2]=pressure(Fluid$,v=v[1],x=0)
x[2]=0
EndIf
End

"Knowns"
{m=5 [kg]}
P[1]=100 [kPa]
y=0.75 "moisture"
Volts=110 [V]
I=8 [amp]

"Solution"
"Conservation of Energy for the closed tank:"
E_dot_in-E_dot_out=DELTAE_dot
E_dot_in=W_dot_ele  "[kW]"
W_dot_ele=Volts*I*CONVERT(J/s,kW) "[kW]"
E_dot_out=0 "[kW]"
DELTAE_dot=m*(u[2]-u[1])/DELTAt_s "[kW]"
DELTAt_min=DELTAt_s*convert(s,min) "[min]"
"The quality at state 1 is:"
Fluid$='Steam_IAPWS'
x[1]=1-y
u[1]=INTENERGY(Fluid$,P=P[1], x=x[1]) "[kJ/kg]"
v[1]=volume(Fluid$,P=P[1], x=x[1]) "[m^3/kg]"
T[1]=temperature(Fluid$,P=P[1], x=x[1]) "[C]"
"Check to see if state 2 is on the saturated liquid line or saturated vapor line:"
Call P2X2(v[1]:P[2],x[2])
u[2]=INTENERGY(Fluid$,P=P[2], x=x[2]) "[kJ/kg]"
v[2]=volume(Fluid$,P=P[2], x=x[2]) "[m^3/kg]"
T[2]=temperature(Fluid$,P=P[2], x=x[2]) "[C]"
```



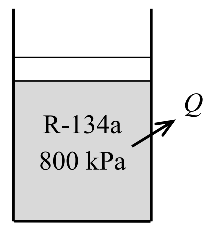
Δt_{min} [min]	m [kg]
30.63	1
61.26	2
91.89	3
122.5	4
153.2	5
183.8	6
214.4	7
245	8
275.7	9
306.3	10



5-37 A cylinder is initially filled with R-134a at a specified state. The refrigerant is cooled at constant pressure. The amount of heat loss is to be determined, and the process is to be shown on a *T*-*v* diagram.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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



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

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

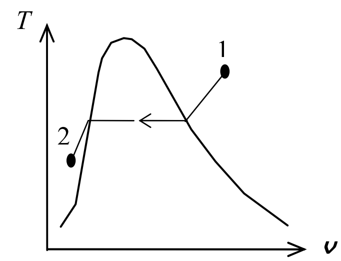
$$-Q_{\text{out}} = m(h_2 - h_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The properties of R-134a are

(Tables A-11 through A-13)

$$\left.\begin{aligned} P_1 &= 800 \text{ kPa} \\ T_1 &= 70°\text{C} \end{aligned}\right\} h_1 = 306.88 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_2 &= 800 \text{ kPa} \\ T_2 &= 15°\text{C} \end{aligned}\right\} h_2 \cong h_{f@15°\text{C}} = 72.34 \text{ kJ/kg}$$



Substituting,

$$Q_{\text{out}} = -\,(5 \text{ kg})(72.34 - 306.88) \text{ kJ/kg} = \mathbf{1173\ kJ}$$

5-38E A cylinder contains water initially at a specified state. The water is heated at constant pressure. The final temperature of the water is to be determined, and the process is to be shown on a T-v diagram.

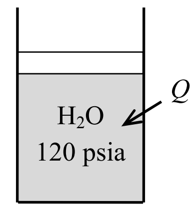
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The thermal energy stored in the cylinder itself is negligible. **3** The compression or expansion process is quasi-equilibrium.

Analysis 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

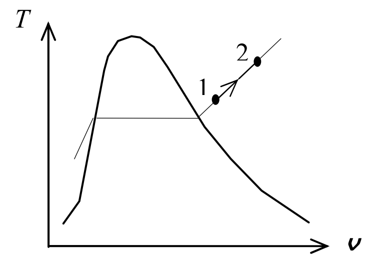
$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

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

$$Q_{in} = m(h_2 - h_1)$$



since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The properties of water are (Tables A-6E)



$$v_1 = \frac{\mathbf{V}_1}{m} = \frac{2\ \text{ft}^3}{0.5\ \text{lbm}} = 4\ \text{ft}^3/\text{lbm}$$

$$\left.\begin{array}{l} P_1 = 120\ \text{psia} \\ v_1 = 4\ \text{ft}^3/\text{lbm} \end{array}\right\} h_1 = 1217.0\ \text{Btu/lbm}$$

Substituting,

$$200\ \text{Btu} = (0.5\ \text{lbm})(h_2 - 1217.0)\text{Btu/lbm}$$

$$h_2 = 1617.0\ \text{Btu/lbm}$$

Then,

$$\left.\begin{array}{l} P_2 = 120\ \text{psia} \\ h_2 = 1617.0\ \text{Btu/lbm} \end{array}\right\} T_2 = \mathbf{1161.4°F}$$

5-39 A cylinder is initially filled with saturated liquid water at a specified pressure. The water is heated electrically as it is stirred by a paddle-wheel at constant pressure. The voltage of the current source is to be determined, and the process is to be shown on a *P*-v diagram.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **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.

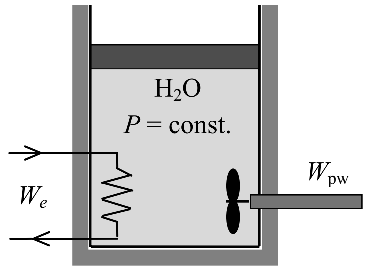
Analysis We take the contents of the cylinder as the system. This is a closed system since no mass enters or leaves. The energy balance for this stationary closed system can be expressed as

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

$$W_{\text{e,in}} + W_{\text{pw,in}} - W_{\text{b,out}} = \Delta U \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$

$$W_{\text{e,in}} + W_{\text{pw,in}} = m(h_2 - h_1)$$

$$(\mathbf{V}I\Delta t) + W_{\text{pw,in}} = m(h_2 - h_1)$$

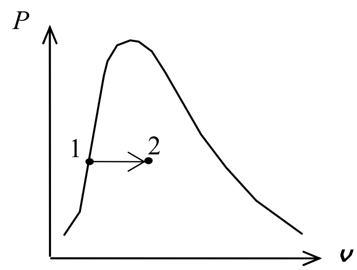


since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The properties of water are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 175 \text{ kPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_1 = h_{f@175\text{ kPa}} = 487.01 \text{ kJ/kg} \\ v_1 = v_{f@175\text{ kPa}} = 0.001057 \text{ m}^3\text{/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 175 \text{ kPa} \\ x_2 = 0.5 \end{array}\right\} h_2 = h_f + x_2 h_{fg} = 487.01 + (0.5 \times 2213.1) = 1593.6 \text{ kJ/kg}$$

$$m = \frac{V_1}{v_1} = \frac{0.005 \text{ m}^3}{0.001057 \text{ m}^3\text{/kg}} = 4.731 \text{ kg}$$



Substituting,

$$\mathbf{V}I\Delta t + (400\text{kJ}) = (4.731 \text{ kg})(1593.6 - 487.01)\text{kJ/kg}$$

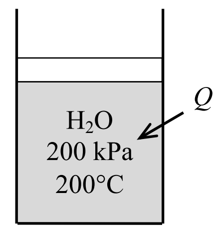
$$\mathbf{V}I\Delta t = 4835 \text{ kJ}$$

$$\mathbf{V} = \frac{4835 \text{ kJ}}{(8 \text{ A})(45 \times 60 \text{ s})}\left(\frac{1000 \text{ VA}}{1 \text{ kJ/s}}\right) = \mathbf{223.9 \text{ V}}$$

5-40 CD EES A cylinder equipped with an external spring is initially filled with steam at a specified state. Heat is transferred to the steam, and both the temperature and pressure rise. The final temperature, the boundary work done by the steam, and the amount of heat transfer are to be determined, and the process is to be shown on a P-v diagram.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The thermal energy stored in the cylinder itself is negligible. **3** The compression or expansion process is quasi-equilibrium. **4** The spring is a linear spring.

Analysis We take the contents of the cylinder as the system. This is a closed system since no mass enters or leaves. Noting that the spring is not part of the system (it is external), the energy balance for this stationary closed system can be expressed as

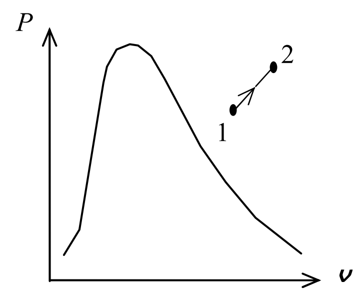


$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

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

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

The properties of steam are (Tables A-4 through A-6)



$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 200°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 1.08049 \text{ m}^3/\text{kg} \\ u_1 = 2654.6 \text{ kJ/kg} \end{array}$$

$$m = \frac{V_1}{v_1} = \frac{0.5 \text{ m}^3}{1.08049 \text{ m}^3/\text{kg}} = 0.4628 \text{ kg}$$

$$v_2 = \frac{V_2}{m} = \frac{0.6 \text{ m}^3}{0.4628 \text{ kg}} = 1.2966 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_2 = 500 \text{ kPa} \\ v_2 = 1.2966 \text{ m}^3/\text{kg} \end{array}\right\} \begin{array}{l} T_2 = \mathbf{1132°C} \\ u_2 = 4325.2 \text{ kJ/kg} \end{array}$$

(b) The pressure of the gas changes linearly with volume, and thus the process curve on a P-V diagram will be a straight line. The boundary work during this process is simply the area under the process curve, which is a trapezoidal. Thus,

$$W_b = Area = \frac{P_1 + P_2}{2}(V_2 - V_1) = \frac{(200+500)\text{kPa}}{2}(0.6 - 0.5)\text{m}^3\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = \mathbf{35 \text{ kJ}}$$

(c) From the energy balance we have

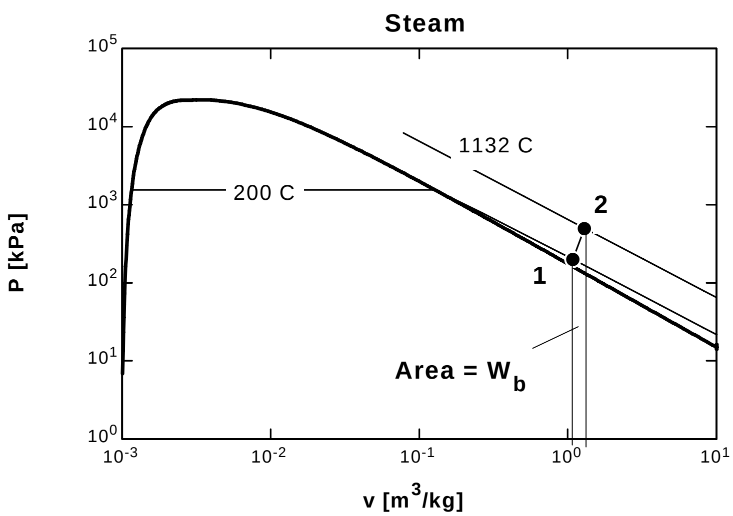
$$Q_{\text{in}} = (0.4628 \text{ kg})(4325.2 - 2654.6)\text{kJ/kg} + 35 \text{ kJ} = \mathbf{808 \text{ kJ}}$$

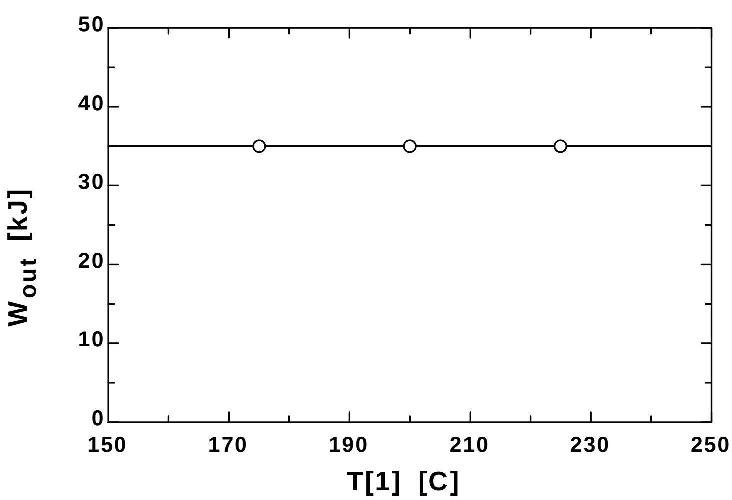
5-41 EES Problem 5-40 is reconsidered. The effect of the initial temperature of steam on the final temperature, the work done, and the total heat transfer as the initial temperature varies from 150°C to 250°C is to be investigated. The final results are to be plotted against the initial temperature.

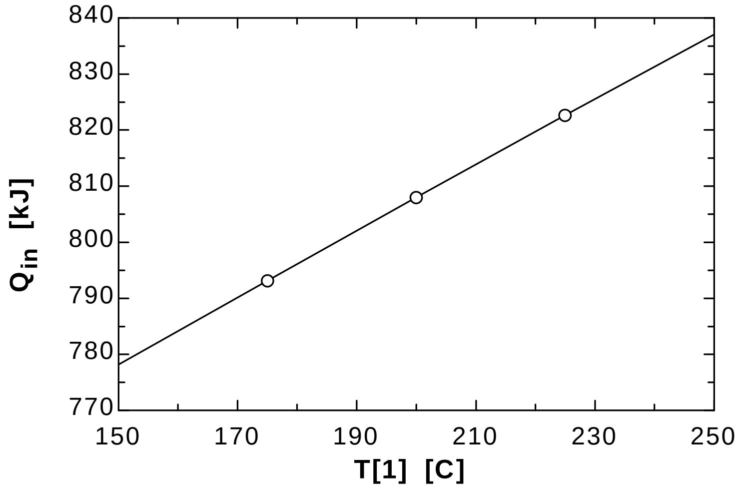
Analysis The problem is solved using EES, and the solution is given below.

```
"The process is given by:"
"P[2]=P[1]+k*x*A/A, and as the spring moves 'x' amount, the volume changes by V[2]-V[1]."
P[2]=P[1]+(Spring_const)*(V[2] - V[1]) "P[2] is a linear function of V[2]"
"where Spring_const = k/A, the actual spring constant divided by the piston face area"

"Conservation of mass for the closed system is:"
m[2]=m[1]

"The conservation of energy for the closed system is"
"E_in - E_out = DeltaE,  neglect DeltaKE and DeltaPE for the system"
Q_in - W_out = m[1]*(u[2]-u[1])
DELTAU=m[1]*(u[2]-u[1])

"Input Data"
P[1]=200 [kPa]
V[1]=0.5 [m^3]
"T[1]=200 [C]"
P[2]=500 [kPa]
V[2]=0.6 [m^3]

Fluid$='Steam_IAPWS'

m[1]=V[1]/spvol[1]
spvol[1]=volume(Fluid$,T=T[1], P=P[1])
u[1]=intenergy(Fluid$, T=T[1], P=P[1])
spvol[2]=V[2]/m[2]

"The final temperature is:"
T[2]=temperature(Fluid$,P=P[2],v=spvol[2])

u[2]=intenergy(Fluid$, P=P[2], T=T[2])
Wnet_other = 0
W_out=Wnet_other + W_b
"W_b = integral of P[2]*dV[2] for 0.5<V[2]<0.6 and is given by:"
 W_b=P[1]*(V[2]-V[1])+Spring_const/2*(V[2]-V[1])^2
```

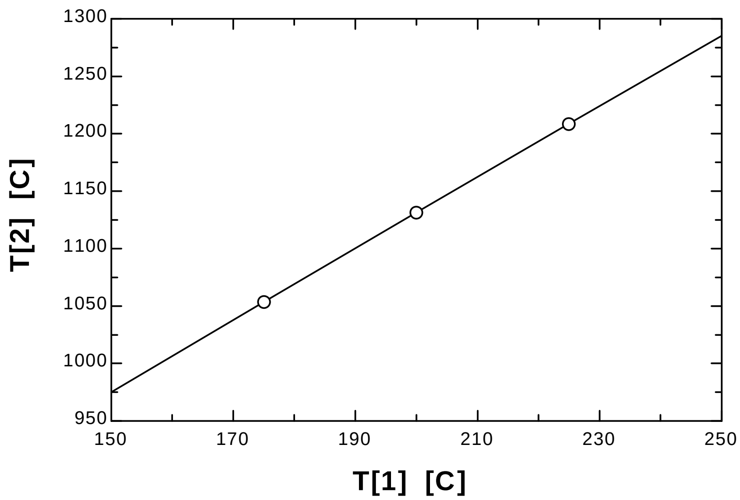
Q_{in} [kJ]	T_1 [C]	T_2 [C]	W_{out} [kJ]
778.2	150	975	35
793.2	175	1054	35
808	200	1131	35
822.7	225	1209	35
837.1	250	1285	35







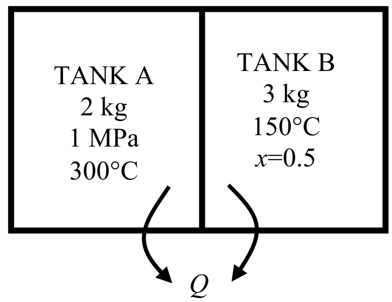
840
830
820
810
800
790
780
770
150
170
190
210
230
250
Q_{in} [kJ]
T[1] [C]



1300
1250
1200
1150
1100
1050
1000
950
150
170
190
210
230
250
T[2] [C]
T[1] [C]

5-42 Two tanks initially separated by a partition contain steam at different states. Now the partition is removed and they are allowed to mix until equilibrium is established. The temperature and quality of the steam at the final state and the amount of heat lost from the tanks 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*) We take the contents of both tanks 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

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

$$-Q_{out} = \Delta U_A + \Delta U_B = [m(u_2 - u_1)]_A + [m(u_2 - u_1)]_B \quad (\text{since } W = \text{KE} = \text{PE} = 0)$$

The properties of steam in both tanks at the initial state are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_{1,A} = 1000 \text{ kPa} \\ T_{1,A} = 300°\text{C} \end{array}\right\} \begin{array}{l} v_{1,A} = 0.25799 \text{ m}^3/\text{kg} \\ u_{1,A} = 2793.7 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} T_{1,B} = 150°\text{C} \\ x_1 = 0.50 \end{array}\right\} \begin{array}{ll} v_f = 0.001091, & v_g = 0.39248 \text{ m}^3/\text{kg} \\ u_f = 631.66, & u_{fg} = 1927.4 \text{ kJ/kg} \end{array}$$

$$v_{1,B} = v_f + x_1 v_{fg} = 0.001091 + [0.50 \times (0.39248 - 0.001091)] = 0.19679 \text{ m}^3/\text{kg}$$

$$u_{1,B} = u_f + x_1 u_{fg} = 631.66 + (0.50 \times 1927.4) = 1595.4 \text{ kJ/kg}$$

The total volume and total mass of the system are

$$V = V_A + V_B = m_A v_{1,A} + m_B v_{1,B} = (2 \text{ kg})(0.25799 \text{ m}^3/\text{kg}) + (3 \text{ kg})(0.19679 \text{ m}^3/\text{kg}) = 1.106 \text{ m}^3$$

$$m = m_A + m_B = 3 + 2 = 5 \text{ kg}$$

Now, the specific volume at the final state may be determined

$$v_2 = \frac{V}{m} = \frac{1.106 \text{ m}^3}{5 \text{ kg}} = 0.22127 \text{ m}^3/\text{kg}$$

which fixes the final state and we can determine other properties

$$\left.\begin{array}{l} P_2 = 300 \text{ kPa} \\ v_2 = 0.22127 \text{ m}^3/\text{kg} \end{array}\right\} \begin{array}{l} T_2 = T_{sat @ 300 \text{ kPa}} = \mathbf{133.5°C} \\ x_2 = \dfrac{v_2 - v_f}{v_g - v_f} = \dfrac{0.22127 - 0.001073}{0.60582 - 0.001073} = \mathbf{0.3641} \\ u_2 = u_f + x_2 u_{fg} = 561.11 + (0.3641 \times 1982.1) = 1282.8 \text{ kJ/kg} \end{array}$$

(*b*) Substituting,

$$\begin{aligned} -Q_{out} &= \Delta U_A + \Delta U_B = [m(u_2 - u_1)]_A + [m(u_2 - u_1)]_B \\ &= (2 \text{ kg})(1282.8 - 2793.7)\text{kJ/kg} + (3 \text{ kg})(1282.8 - 1595.4)\text{kJ/kg} = -3959 \text{ kJ} \end{aligned}$$

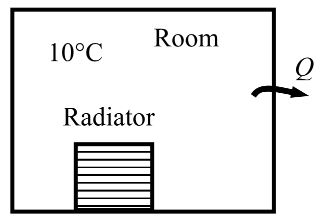
or $\quad Q_{out} = \mathbf{3959\ kJ}$

5-43 A room is heated by an electrical radiator containing heating oil. Heat is lost from the room. The time period during which the heater is on is to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **4** The local atmospheric pressure is 100 kPa. **5** The room is air-tight so that no air leaks in and out during the process.

Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1). Also, c_v = 0.718 kJ/kg.K for air at room temperature (Table A-2). Oil properties are given to be ρ = 950 kg/m^3 and c_p = 2.2 kJ/kg.°C.

Analysis We take the air in the room and the oil in the radiator to be the system. This is a closed system since no mass crosses the system boundary. The energy balance for this stationary constant-volume closed system can be expressed as



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

$$(\dot{W}_{in} - \dot{Q}_{out})\Delta t = \Delta U_{air} + \Delta U_{oil}$$

$$\cong [mc_v(T_2 - T_1)]_{air} + [mc_p(T_2 - T_1)]_{oil} \quad \text{(since KE = PE = 0)}$$

The mass of air and oil are

$$m_{air} = \frac{P V_{air}}{RT_1} = \frac{(100 \text{ kPa})(50 \text{ m}^3)}{(0.287 \text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(10 + 273 \text{ K})} = 62.32 \text{ kg}$$

$$m_{oil} = \rho_{oil} V_{oil} = (950 \text{ kg/m}^3)(0.030 \text{ m}^3) = 28.50 \text{ kg}$$

Substituting,

$$(1.8 - 0.35 \text{ kJ/s})\Delta t = (62.32 \text{ kg})(0.718 \text{ kJ/kg} \cdot °\text{C})(20 - 10)°\text{C} + (28.50 \text{ kg})(2.2 \text{ kJ/kg} \cdot °\text{C})(50 - 10)°\text{C}$$

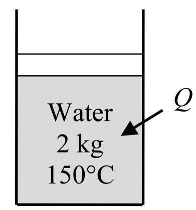
$$\longrightarrow \Delta t = \mathbf{2038\ s = 34.0\ min}$$

Discussion In practice, the pressure in the room will remain constant during this process rather than the volume, and some air will leak out as the air expands. As a result, the air in the room will undergo a constant pressure expansion process. Therefore, it is more proper to be conservative and to using ΔH instead of use ΔU in heating and air-conditioning applications.

5-44 Saturated liquid water is heated at constant pressure to a saturated vapor in a piston-cylinder device. The heat transfer is to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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

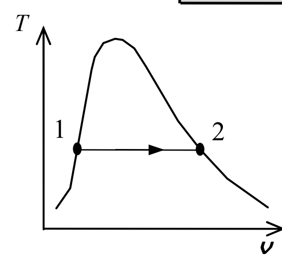


$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

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

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

$$Q_{\text{in}} = m(h_2 - h_1)$$



since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. Since water changes from saturated liquid to saturated vapor, we have

$$Q_{\text{in}} = mh_{fg} = (2\text{ kg})(2113.8\text{ kJ/kg}) = \mathbf{4228\ kJ}$$

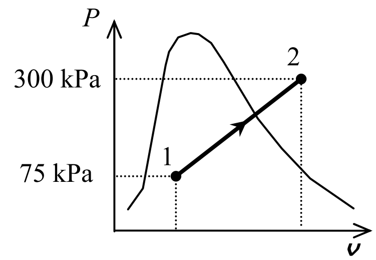
since

$$h_{fg\,@150°\text{C}} = 2113.8\text{ kJ/kg} \qquad \text{(Table A-4)}$$

5-45 A saturated water mixture contained in a spring-loaded piston-cylinder device is heated until the pressure and volume rise to specified values. The heat transfer and the work done are to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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



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

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

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

The initial state is saturated mixture at 75 kPa. The specific volume and internal energy at this state are (Table A-5),

$$v_1 = v_f + xv_{fg} = 0.001037 + (0.13)(2.2172 - 0.001037) = 0.28914 \text{ m}^3/\text{kg}$$

$$u_1 = u_f + xu_{fg} = 384.36 + (0.13)(2111.8) = 658.89 \text{ kJ/kg}$$

The mass of water is

$$m = \frac{V_1}{v_1} = \frac{2 \text{ m}^3}{0.28914 \text{ m}^3/\text{kg}} = 6.9170 \text{ kg}$$

The final specific volume is

$$v_2 = \frac{V_2}{m} = \frac{5 \text{ m}^3}{6.9170 \text{ kg}} = 0.72285 \text{ m}^3/\text{kg}$$

The final state is now fixed. The internal energy at this specific volume and 300 kPa pressure is (Table A-6)

$$u_2 = 2657.2 \text{ kJ/kg}$$

Since this is a linear process, the work done is equal to the area under the process line 1-2:

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1) = \frac{(75 + 300)\text{kPa}}{2}(5 - 2)\text{m}^3 \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = \mathbf{562.5 \text{ kJ}}$$

Substituting into energy balance equation gives

$$Q_{\text{in}} = W_{b,\text{out}} + m(u_2 - u_1) = 562.5 \text{ kJ} + (6.9170 \text{ kg})(2657.2 - 658.89) \text{ kJ/kg} = \mathbf{14{,}385 \text{ kJ}}$$

5-46 R-134a contained in a spring-loaded piston-cylinder device is cooled until the temperature and volume drop to specified values. The heat transfer and the work done are to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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

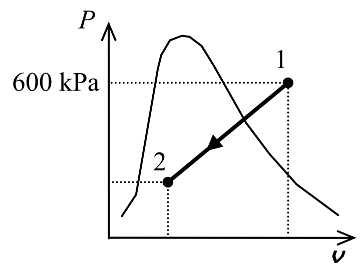
$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

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

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

The initial state properties are (Table A-13)

$$\left.\begin{array}{l} P_1 = 600\ \text{kPa} \\ T_1 = 15°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 0.055522\ \text{m}^3/\text{kg} \\ u_1 = 357.96\ \text{kJ/kg} \end{array}$$



The mass of refrigerant is

$$m = \frac{V_1}{v_1} = \frac{0.3\ \text{m}^3}{0.055522\ \text{m}^3/\text{kg}} = 5.4033\ \text{kg}$$

The final specific volume is

$$v_2 = \frac{V_2}{m} = \frac{0.1\ \text{m}^3}{5.4033\ \text{kg}} = 0.018507\ \text{m}^3/\text{kg}$$

The final state at this specific volume and at -30°C is a saturated mixture. The properties at this state are (Table A-11)

$$x_2 = \frac{v_2 - v_f}{v_g - v_f} = \frac{0.018507 - 0.0007203}{0.22580 - 0.0007203} = 0.079024$$

$$u_2 = u_f + x_2 u_{fg} = 12.59 + (0.079024)(200.52) = 28.44\ \text{kJ/kg}$$

$$P_2 = 84.43\ \text{kPa}$$

Since this is a linear process, the work done is equal to the area under the process line 1-2:

$$W_{b,\text{in}} = \text{Area} = \frac{P_1 + P_2}{2}(V_1 - V_2) = \frac{(600 + 84.43)\text{kPa}}{2}(0.3 - 0.1)\text{m}^3\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = \mathbf{68.44\ kJ}$$

Substituting into energy balance equation gives

$$Q_{\text{out}} = W_{b,\text{in}} - m(u_2 - u_1) = 68.44\ \text{kJ} - (5.4033\ \text{kg})(28.44 - 357.96)\ \text{kJ/kg} = \mathbf{1849\ kJ}$$

5-47E Saturated R-134a vapor is condensed at constant pressure to a saturated liquid in a piston-cylinder device. The heat transfer and the work done are to be determined.

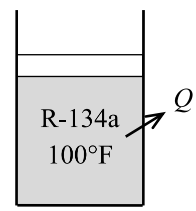
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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

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

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

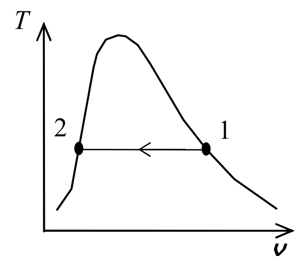
$$Q_{\text{out}} = W_{b,\text{in}} - m(u_2 - u_1)$$



The properties at the initial and final states are (Table A-11E)

$$\left.\begin{array}{l} T_1 = 100°\text{F} \\ x_1 = 1 \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = \boldsymbol{v}_g = 0.34045\ \text{ft}^3/\text{lbm} \\ u_1 = u_g = 107.45\ \text{Btu/lbm} \end{array}$$

$$\left.\begin{array}{l} T_2 = 100°\text{F} \\ x_2 = 0 \end{array}\right\} \begin{array}{l} \boldsymbol{v}_2 = \boldsymbol{v}_f = 0.01386\ \text{ft}^3/\text{lbm} \\ u_2 = u_f = 44.768\ \text{Btu/lbm} \end{array}$$



Also from Table A-11E,

$$P_1 = P_2 = 138.93\ \text{psia}$$
$$u_{fg} = 62.683\ \text{Btu/lbm}$$
$$h_{fg} = 71.080\ \text{Btu/lbm}$$

The work done during this process is

$$w_{b,\text{out}} = \int_1^2 P d\boldsymbol{v} = P(\boldsymbol{v}_2 - \boldsymbol{v}_1) = (138.93\,\text{psia})(0.01386 - 0.34045)\text{ft}^3/\text{lbm}\left(\frac{1\ \text{Btu}}{5.404\ \text{psia}\cdot\text{ft}^3}\right) = -8.396\ \text{Btu/lbm}$$

That is,

$$w_{b,\text{in}} = \mathbf{8.396\ Btu/lbm}$$

Substituting into energy balance equation gives

$$q_{\text{out}} = w_{b,\text{in}} - (u_2 - u_1) = w_{b,\text{in}} + u_{fg} = 8.396 + 62.683 = \mathbf{71.080\ Btu/lbm}$$

Discussion The heat transfer may also be determined from

$$-q_{\text{out}} = h_2 - h_1$$
$$q_{\text{out}} = h_{fg} = 71.080\ \text{Btu/lbm}$$

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

5-48 Saturated R-134a liquid is contained in an insulated piston-cylinder device. Electrical work is supplied to R-134a. The time required for the refrigerant to turn into saturated vapor and the final temperature are to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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

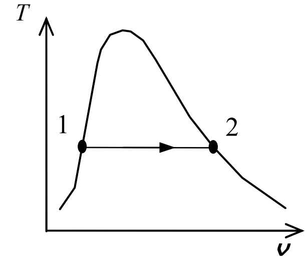
$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

$$W_{e,in} - W_{b,out} = \Delta U = m(u_2 - u_1) \quad \text{(since KE = PE = 0)}$$

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

$$W_{e,in} = H_2 - H_1 = m(h_2 - h_1) = mh_{fg}$$

$$\dot{W}_{e,in}\Delta t = mh_{fg}$$



since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The electrical power and the enthalpy of vaporization of R-134a are

$$\dot{W}_{e,in} = \mathbf{V}I = (10 \text{ V})(2 \text{ A}) = 20 \text{ W}$$

$$h_{fg\,@-10°C} = 205.96 \text{ kJ/kg} \quad \text{(Table A-11)}$$

Substituting,

$$(0.020 \text{ kJ/s})\Delta t = (2 \text{ kg})(205.96 \text{ kJ/kg}) \longrightarrow \Delta t = 20{,}596 \text{ s} = \mathbf{5.72 \text{ h}}$$

The temperature remains constant during this phase change process:

$$T_2 = T_1 = \mathbf{-10°C}$$

Specific Heats, Δu, and Δh of Ideal Gases

5-49C It can be used for any kind of process of an ideal gas.

5-50C It can be used for any kind of process of an ideal gas.

5-51C The desired result is obtained by multiplying the first relation by the molar mass M,

$$Mc_p = Mc_v + MR$$

or

$$\bar{c}_p = \bar{c}_v + R_u$$

5-52C Very close, but no. Because the heat transfer during this process is $Q = mc_p\Delta T$, and c_p varies with temperature.

5-53C It can be either. The difference in temperature in both the K and °C scales is the same.

5-54C The energy required is $mc_p\Delta T$, which will be the same in both cases. This is because the c_p of an ideal gas does not vary with pressure.

5-55C The energy required is $mc_p\Delta T$, which will be the same in both cases. This is because the c_p of an ideal gas does not vary with volume.

5-56C Modeling both gases as ideal gases with constant specific heats, we have

$$\Delta u = c_v \Delta T$$
$$\Delta h = c_p \Delta T$$

Since both gases undergo the same temperature change, the gas with the greatest c_v will experience the largest change in internal energy. Similarly, the gas with the largest c_p will have the greatest enthalpy change. Inspection of Table A-2*a* indicates that air will experience the greatest change in both cases.

5-57 A spring-loaded piston-cylinder device is filled with nitrogen. Nitrogen is now heated until its volume increases by 10%. The changes in the internal energy and enthalpy of the nitrogen are to be determined.

Properties The gas constant of nitrogen is R = 0.2968 kPa·m^3/kg·K. The specific heats of nitrogen at room temperature are c_v = 0.743 kJ/kg·K and c_p = 1.039 kJ/kg·K (Table A-2a).

Analysis The initial volume of nitrogen is

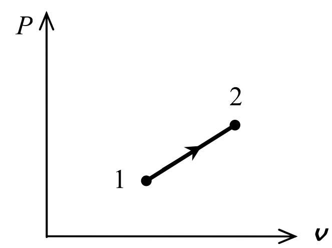
$$V_1 = \frac{mRT_1}{P_1} = \frac{(0.010\text{ kg})(0.2968\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(27+273\text{ K})}{120\text{ kPa}} = 0.00742\text{ m}^3$$

The process experienced by this system is a linear P-v process. The equation for this line is

$$P - P_1 = c(V - V_1)$$

where P_1 is the system pressure when its specific volume is v_1. The spring equation may be written as

$$P - P_1 = \frac{F_s - F_{s,1}}{A} = k\frac{x - x_1}{A} = \frac{kA}{A^2}(x - x_1) = \frac{k}{A^2}(V - V_1)$$



Constant c is hence

$$c = \frac{k}{A^2} = \frac{4^2 k}{\pi^2 D^4} = \frac{(16)(1\text{ kN/m})}{\pi^2(0.1\text{ m})^4} = 16{,}211\text{ kN/m}^5$$

The final pressure is then

$$P_2 = P_1 + c(V_2 - V_1) = P_1 + c(1.1V_1 - V_1) = P_1 + 0.1cV_1$$

$$= 120\text{ kPa} + 0.1(16{,}211\text{ kN/m}^5)(0.00742\text{ m}^3)$$

$$= 132.0\text{ kPa}$$

The final temperature is

$$T_2 = \frac{P_2 V_2}{mR} = \frac{(132.0\text{ kPa})(1.1\times 0.00742\text{ m}^3)}{(0.010\text{ kg})(0.2968\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})} = 363\text{ K}$$

Using the specific heats,

$$\Delta u = c_v \Delta T = (0.743\text{ kJ/kg}\cdot\text{K})(363-300)\text{K} = \mathbf{46.8\ kJ/kg}$$

$$\Delta h = c_p \Delta T = (1.039\text{ kJ/kg}\cdot\text{K})(363-300)\text{K} = \mathbf{65.5\ kJ/kg}$$

5-58E The internal energy change of air is to be determined for two cases of specified temperature changes.

Assumptions At specified conditions, air behaves as an ideal gas.

Properties The constant-volume specific heat of air at room temperature is c_v = 0.171 Btu/lbm·R (Table A-2Ea).

Analysis Using the specific heat at constant volume,

$$\Delta u = c_v \Delta T = (0.171\,\text{Btu/lbm}\cdot\text{R})(200-100)\text{R} = \mathbf{17.1\,Btu/lbm}$$

If we use the same room temperature specific heat value, the internal energy change will be the same for the second case. However, if we consider the variation of specific heat with temperature and use the specific heat values from Table A-2Eb, we have c_v = 0.1725 Btu/lbm·R at 150°F and c_v = 0.1712 Btu/lbm·R at 50°F. Then,

$$\Delta u_1 = c_v \Delta T_1 = (0.1725\,\text{Btu/lbm}\cdot\text{R})(200-100)\text{R} = \mathbf{17.25\,Btu/lbm}$$

$$\Delta u_2 = c_v \Delta T_2 = (0.1712\,\text{Btu/lbm}\cdot\text{R})(100-0)\text{R} = \mathbf{17.12\,Btu/lbm}$$

The two results differ from each other by about 0.8%.

5-59 The total internal energy changes for neon and argon are to be determined for a given temperature change.

Assumptions At specified conditions, neon and argon behave as an ideal gas.

Properties The constant-volume specific heats of neon and argon are 0.6179 kJ/kg·K and 0.3122 kJ/kg·K, respectively (Table A-2*a*).

Analysis The total internal energy changes are

$$\Delta U_{\text{neon}} = mc_v \Delta T = (2\,\text{kg})(0.6179\,\text{kJ/kg}\cdot\text{K})(180-20)\text{K} = \mathbf{129.7\,kJ}$$

$$\Delta U_{\text{argon}} = mc_v \Delta T = (2\,\text{kg})(0.3122\,\text{kJ/kg}\cdot\text{K})(180-20)\text{K} = \mathbf{99.9\,kJ}$$

5-60 The enthalpy changes for neon and argon are to be determined for a given temperature change.

Assumptions At specified conditions, neon and argon behave as an ideal gas.

Properties The constant-pressure specific heats of argon and neon are 0.5203 kJ/kg·K and 1.0299 kJ/kg·K, respectively (Table A-2*a*).

Analysis The enthalpy changes are

$$\Delta h_{\text{argon}} = c_p \Delta T = (0.5203\,\text{kJ/kg}\cdot\text{K})(400-100)\text{K} = \mathbf{156.1\,kJ/kg}$$

$$\Delta h_{\text{neon}} = c_p \Delta T = (1.0299\,\text{kJ/kg}\cdot\text{K})(400-100)\text{K} = \mathbf{309.0\,kJ/kg}$$

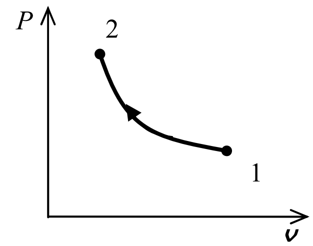
5-61 Neon is compressed isothermally in a compressor. The specific volume and enthalpy changes are to be determined.

Assumptions At specified conditions, neon behaves as an ideal gas.

Properties The gas constant of neon is R = 0.4119 kJ/kg·K and the constant-pressure specific heat of neon is 1.0299 kJ/kg·K (Table A-2*a*).

Analysis At the compressor inlet, the specific volume is

$$\boldsymbol{v}_1 = \frac{RT}{P_1} = \frac{(0.4119\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(20+273\ \text{K})}{100\ \text{kPa}} = 1.207\ \text{m}^3/\text{kg}$$



Similarly, at the compressor exit,

$$\boldsymbol{v}_2 = \frac{RT}{P_2} = \frac{(0.4119\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(20+273\ \text{K})}{500\ \text{kPa}} = 0.2414\ \text{m}^3/\text{kg}$$

The change in the specific volume caused by the compressor is

$$\Delta\boldsymbol{v} = \boldsymbol{v}_2 - \boldsymbol{v}_1 = 0.2414 - 1.207 = \mathbf{-0.966\ m^3/kg}$$

Since the process is isothermal,

$$\Delta h = c_p \Delta T = \mathbf{0\ kJ/kg}$$

5-62E The enthalpy change of oxygen gas during a heating process is to be determined using an empirical specific heat relation, constant specific heat at average temperature, and constant specific heat at room temperature.

Analysis (*a*) Using the empirical relation for $\bar{c}_p(T)$ from Table A-2Ec,

$$\bar{c}_p = a + bT + cT^2 + dT^3$$

where a = 6.085, b = 0.2017×10^{-2}, c = -0.05275×10^{-5}, and d = 0.05372×10^{-9}. Then,

$$\begin{aligned}
\Delta\bar{h} &= \int_1^2 \bar{c}_p(T)dT = \int_1^2 \left[a + bT + cT^2 + dT^3\right]dT \\
&= a(T_2 - T_1) + \tfrac{1}{2}b(T_2^2 + T_1^2) + \tfrac{1}{3}c(T_2^3 - T_1^3) + \tfrac{1}{4}d(T_2^4 - T_1^4) \\
&= 6.085(1500 - 800) + \tfrac{1}{2}(0.2017\times10^{-2})(1500^2 - 800^2) \\
&\quad - \tfrac{1}{3}(0.05275\times10^{-5})(1500^3 - 800^3) + \tfrac{1}{4}(0.05372\times10^{-9})(1500^4 - 800^4) \\
&= 5442.3 \text{ Btu/lbmol}
\end{aligned}$$

$$\Delta h = \frac{\Delta\bar{h}}{M} = \frac{5442.3 \text{ Btu/lbmol}}{31.999 \text{ lbm/lbmol}} = \mathbf{170.1\ Btu/lbm}$$

(*b*) Using the constant c_p value from Table A-2Eb at the average temperature of 1150 R,

$$c_{p,\text{avg}} = c_{p@1150\text{ R}} = 0.255 \text{ Btu/lbm}\cdot\text{R}$$

$$\Delta h = c_{p,\text{avg}}(T_2 - T_1) = (0.255 \text{ Btu/lbm}\cdot\text{R})(1500 - 800)\text{ R} = \mathbf{178.5\ \ Btu/lbm}$$

(*c*) Using the constant c_p value from Table A-2Ea at room temperature,

$$c_{p,\text{avg}} = c_{p@537\text{ R}} = 0.219 \text{ Btu/lbm}\cdot\text{R}$$

$$\Delta h = c_{p,\text{avg}}(T_2 - T_1) = (0.219 \text{ Btu/lbm}\cdot\text{R})(1500 - 800)\text{R} = \mathbf{153.3\ Btu/lbm}$$

5-63 The internal energy change of hydrogen gas during a heating process is to be determined using an empirical specific heat relation, constant specific heat at average temperature, and constant specific heat at room temperature.

Analysis (*a*) Using the empirical relation for $\bar{c}_p(T)$ from Table A-2c and relating it to $\bar{c}_v(T)$,

$$\bar{c}_v(T) = \bar{c}_p - R_u = (a - R_u) + bT + cT^2 + dT^3$$

where a = 29.11, b = -0.1916×10^{-2}, c = 0.4003×10^{-5}, and d = -0.8704×10^{-9}. Then,

$$\begin{aligned}
\Delta\bar{u} &= \int_1^2 \bar{c}_v(T)dT = \int_1^2 \left[(a - R_u) + bT + cT^2 + dT^3\right]dT \\
&= (a - R_u)(T_2 - T_1) + \tfrac{1}{2}b(T_2^2 + T_1^2) + \tfrac{1}{3}c(T_2^3 - T_1^3) + \tfrac{1}{4}d(T_2^4 - T_1^4) \\
&= (29.11 - 8.314)(800 - 200) - \tfrac{1}{2}(0.1961\times10^{-2})(800^2 - 200^2) \\
&\quad + \tfrac{1}{3}(0.4003\times10^{-5})(800^3 - 200^3) - \tfrac{1}{4}(0.8704\times10^{-9})(800^4 - 200^4) \\
&= 12{,}487 \text{ kJ/kmol}
\end{aligned}$$

$$\Delta u = \frac{\Delta\bar{u}}{M} = \frac{12{,}487 \text{ kJ/kmol}}{2.016 \text{ kg/kmol}} = \mathbf{6194\ kJ/kg}$$

(*b*) Using a constant c_p value from Table A-2b at the average temperature of 500 K,

$$c_{v,\text{avg}} = c_{v@500\text{ K}} = 10.389 \text{ kJ/kg}\cdot\text{K}$$

$$\Delta u = c_{v,\text{avg}}(T_2 - T_1) = (10.389 \text{ kJ/kg}\cdot\text{K})(800 - 200)\text{K} = \mathbf{6233\ kJ/kg}$$

(*c*) Using a constant c_p value from Table A-2a at room temperature,

$$c_{v,\text{avg}} = c_{v@300\text{ K}} = 10.183 \text{ kJ/kg}\cdot\text{K}$$

$$\Delta u = c_{v,\text{avg}}(T_2 - T_1) = (10.183 \text{ kJ/kg}\cdot\text{K})(800 - 200)\text{K} = \mathbf{6110\ kJ/kg}$$

Closed System Energy Analysis: Ideal Gases

5-64C No, it isn't. This is because the first law relation $Q - W = \Delta U$ reduces to $W = 0$ in this case since the system is adiabatic ($Q = 0$) and $\Delta U = 0$ for the isothermal processes of ideal gases. Therefore, this adiabatic system cannot receive any net work at constant temperature.

5-65E The air in a rigid tank is heated until its pressure doubles. The volume of the tank and the amount of heat transfer are to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -221°F and 547 psia. **2** The kinetic and potential energy changes are negligible, $\Delta pe \cong \Delta ke \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications.

Properties The gas constant of air is $R = 0.3704$ psia.ft^3/lbm.R (Table A-1E).

Analysis (*a*) The volume of the tank can be determined from the ideal gas relation,

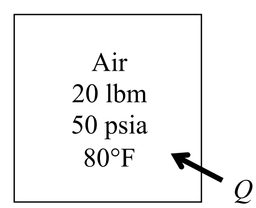
$$\mathbf{V} = \frac{mRT_1}{P_1} = \frac{(20\text{ lbm})(0.3704\text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(540\text{ R})}{50\text{ psia}} = \mathbf{80.0\ ft^3}$$

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

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

$$Q_{\text{in}} = \Delta U$$

$$Q_{\text{in}} = m(u_2 - u_1) \cong mc_v(T_2 - T_1)$$



The final temperature of air is

$$\frac{P_1\mathbf{V}}{T_1} = \frac{P_2\mathbf{V}}{T_2} \longrightarrow T_2 = \frac{P_2}{P_1}T_1 = 2 \times (540\text{ R}) = 1080\text{ R}$$

The internal energies are (Table A-21E)

$$u_1 = u_{@\,540\text{ R}} = 92.04\text{ Btu/lbm}$$

$$u_2 = u_{@\,1080\text{ R}} = 186.93\text{ Btu/lbm}$$

Substituting,

Q_{in} = (20 lbm)(186.93 - 92.04)Btu/lbm = **1898 Btu**

Alternative solutions The specific heat of air at the average temperature of T_{avg} = (540+1080)/2= 810 R = 350°F is, from Table A-2Eb, $c_{v,\text{avg}}$ = 0.175 Btu/lbm.R. Substituting,

Q_{in} = (20 lbm)(0.175 Btu/lbm.R)(1080 - 540) R = **1890 Btu**

Discussion Both approaches resulted in almost the same solution in this case.

5-66 A resistance heater is to raise the air temperature in the room from 7 to 23°C within 15 min. The required power rating of the resistance heater is to be determined.

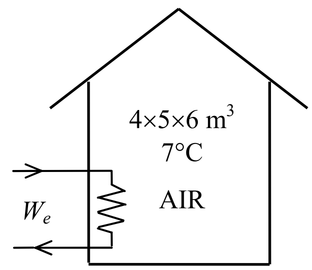
Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **4** Heat losses from the room are negligible. **5** The room is air-tight so that no air leaks in and out during the process.

Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1). Also, c_v = 0.718 kJ/kg.K for air at room temperature (Table A-2).

Analysis We take the air in the room to be the system. This is a closed system since no mass crosses the system boundary. The energy balance for this stationary constant-volume closed system can be expressed as

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

$$W_{\text{e,in}} = \Delta U \cong mc_{v,\text{avg}}(T_2 - T_1) \ \ (\text{since } Q = \text{KE} = \text{PE} = 0)$$



or,

$$\dot{W}_{e,\text{in}}\Delta t = mc_{v,\text{avg}}(T_2 - T_1)$$

The mass of air is

$$V = 4 \times 5 \times 6 = 120 \text{ m}^3$$

$$m = \frac{P_1 V}{RT_1} = \frac{(100 \text{ kPa})(120 \text{ m}^3)}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(280 \text{ K})} = 149.3 \text{ kg}$$

Substituting, the power rating of the heater becomes

$$\dot{W}_{e,\text{in}} = \frac{(149.3 \text{ kg})(0.718 \text{ kJ/kg}\cdot^\circ\text{C})(23 - 7)^\circ\text{C}}{15 \times 60 \text{ s}} = \mathbf{1.91 \text{ kW}}$$

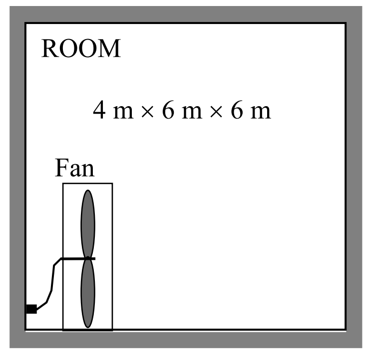
Discussion In practice, the pressure in the room will remain constant during this process rather than the volume, and some air will leak out as the air expands. As a result, the air in the room will undergo a constant pressure expansion process. Therefore, it is more proper to be conservative and to use ΔH instead of using ΔU in heating and air-conditioning applications.

5-67 A student living in a room turns her 150-W fan on in the morning. The temperature in the room when she comes back 10 h later is to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **4** All the doors and windows are tightly closed, and heat transfer through the walls and the windows is disregarded.

Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1). Also, c_v = 0.718 kJ/kg.K for air at room temperature (Table A-2).

Analysis We take the room as the system. This is a *closed system* since the doors and the windows are said to be tightly closed, and thus no mass crosses the system boundary during the process. The energy balance for this system can be expressed as



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

$$W_{e,in} = \Delta U$$

$$W_{e,in} = m(u_2 - u_1) \cong mc_v(T_2 - T_1)$$

The mass of air is

$$V = 4 \times 6 \times 6 = 144 \text{ m}^3$$

$$m = \frac{P_1 V}{RT_1} = \frac{(100 \text{ kPa})(144 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(288 \text{ K})} = 174.2 \text{ kg}$$

The electrical work done by the fan is

$$W_e = \dot{W}_e \Delta t = (0.15 \text{ kJ / s})(10 \times 3600 \text{ s}) = 5400 \text{ kJ}$$

Substituting and using the c_v value at room temperature,

$$5400 \text{ kJ} = (174.2 \text{ kg})(0.718 \text{ kJ/kg·°C})(T_2 - 15)\text{°C}$$

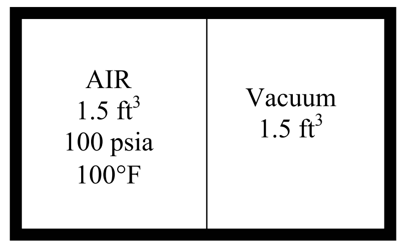
$$T_2 = \mathbf{58.2°C}$$

Discussion Note that a fan actually causes the internal temperature of a confined space to rise. In fact, a 100-W fan supplies a room with as much energy as a 100-W resistance heater.

5-68E One part of an insulated rigid tank contains air while the other side is evacuated. The internal energy change of the air and the final air pressure are to be determined when the partition is removed.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of –221.5°F and 547 psia. **2** The kinetic and potential energy changes are negligible, $\Delta\text{ke} \cong \Delta\text{pe} \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **3** The tank is insulated and thus heat transfer is negligible.

Analysis We take the entire tank as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as



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

$$\mathbf{0} = \Delta U = mc_v(T_2 - T_1)$$

Since the internal energy does not change, the temperature of the air will also not change. Applying the ideal gas equation gives

$$P_1\mathbf{V}_1 = P_2\mathbf{V}_2 \longrightarrow P_2 = P_1\frac{\mathbf{V}_1}{\mathbf{V}_2} = P_1\frac{\mathbf{V}_2/2}{\mathbf{V}_2} = \frac{P_1}{2} = \frac{100\text{ psia}}{2} = \mathbf{50\ psia}$$

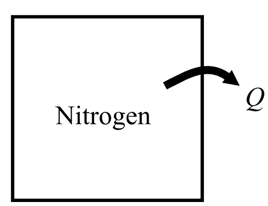
5-69 Nitrogen in a rigid vessel is cooled by rejecting heat. The internal energy change of the nitrogen is to be determined.

Assumptions **1** Nitrogen is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 126.2 K and 3.39 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta\text{ke} \cong \Delta\text{pe} \cong 0$. **3** Constant specific heats at room temperature can be used for nitrogen.

Analysis We take the nitrogen as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as

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

$$-Q_{\text{out}} = \Delta U = mc_v(T_2 - T_1)$$



Thus,

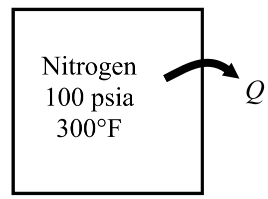
$$\Delta u = -q_{\text{out}} = \mathbf{-100\ kJ/kg}$$

5-70E Nitrogen in a rigid vessel is cooled. The work done and heat transfer are to be determined.

Assumptions **1** Nitrogen is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 126.2 K (227.1 R) and 3.39 MPa (492 psia). **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for nitrogen.

Properties For nitrogen, c_v = 0.177 Btu/lbm·R at room temperature (Table A-2E*a*).

Analysis We take the nitrogen as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as



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

$$-Q_{out} = \Delta U = mc_v(T_2 - T_1)$$

There is no work done since the vessel is rigid:

$$w = \mathbf{0\ Btu/lbm}$$

Since the specific volume is constant during the process, the final temperature is determined from ideal gas equation to be

$$T_2 = T_1 \frac{P_2}{P_1} = (760\text{ R})\frac{50\text{ psia}}{100\text{ psia}} = 380\text{ R}$$

Substituting,

$$q_{out} = c_v(T_1 - T_2) = (0.177\text{ Btu/lbm}\cdot\text{R})(760 - 380)\text{R} = \mathbf{67.3\ Btu/lbm}$$

5-71 Oxygen is heated to experience a specified temperature change. The heat transfer is to be determined for two cases.

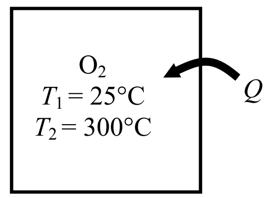
Assumptions **1** Oxygen is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 154.8 K and 5.08 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats can be used for oxygen.

Properties The specific heats of oxygen at the average temperature of (25+300)/2=162.5°C=436 K are c_p = 0.952 kJ/kg·K and c_v = 0.692 kJ/kg·K (Table A-2*b*).

Analysis We take the oxygen as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for a constant-volume process can be expressed as

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

$$Q_{in} = \Delta U = mc_v(T_2 - T_1)$$



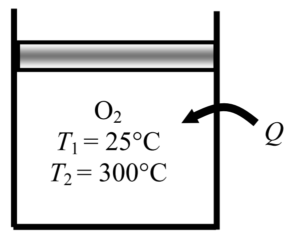
The energy balance during a constant-pressure process (such as in a piston-cylinder device) can be expressed as

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

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

$$Q_{in} = W_{b,out} + \Delta U$$

$$Q_{in} = \Delta H = mc_p(T_2 - T_1)$$



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

$$Q_{in,V=const} = mc_v(T_2 - T_1) = (1\ \text{kg})(0.692\ \text{kJ/kg}\cdot\text{K})(300-25)\text{K} = \mathbf{190.3\ kJ}$$

$$Q_{in,P=const} = mc_p(T_2 - T_1) = (1\ \text{kg})(0.952\ \text{kJ/kg}\cdot\text{K})(300-25)\text{K} = \mathbf{261.8\ kJ}$$

5-72 Air in a closed system undergoes an isothermal process. The initial volume, the work done, and the heat transfer are to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 132.5 K and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta\text{ke} \cong \Delta\text{pe} \cong 0$. **3** Constant specific heats can be used for air.

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

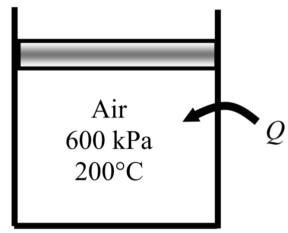
Analysis We take the air as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as

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

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U = mc_{v}(T_2 - T_1)$$

$$Q_{\text{in}} - W_{b,\text{out}} = 0 \quad (\text{since } T_1 = T_2)$$

$$Q_{\text{in}} = W_{b,\text{out}}$$



The initial volume is

$$V_1 = \frac{mRT_1}{P_1} = \frac{(2\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(473\text{ K})}{600\text{ kPa}} = \mathbf{0.4525\ m^3}$$

Using the boundary work relation for the isothermal process of an ideal gas gives

$$W_{b,\text{out}} = m\int_1^2 P\,dv = mRT\int_1^2 \frac{dv}{v} = mRT\ln\frac{v_2}{v_1} = mRT\ln\frac{P_1}{P_2}$$

$$= (2\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(473\text{ K})\ln\frac{600\text{ kPa}}{80\text{ kPa}} = \mathbf{547.1\,kJ}$$

From energy balance equation,

$$Q_{\text{in}} = W_{b,\text{out}} = \mathbf{547.1\,kJ}$$

5-73 Argon in a piston-cylinder device undergoes an isothermal process. The mass of argon and the work done are to be determined.

Assumptions **1** Argon is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 151 K and 4.86 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta\text{ke} \cong \Delta\text{pe} \cong 0$.

Properties The gas constant of argon is $R = 0.2081\text{kJ/kg·K}$ (Table A-1).

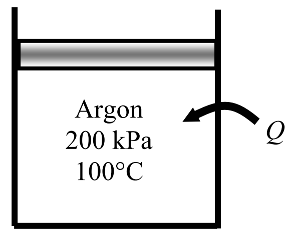
Analysis We take argon as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as

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

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U = mc_v(T_2 - T_1)$$

$$Q_{\text{in}} - W_{b,\text{out}} = 0 \quad (\text{since } T_1 = T_2)$$

$$Q_{\text{in}} = W_{b,\text{out}}$$



Thus,

$$W_{b,\text{out}} = Q_{\text{in}} = \mathbf{1500\ kJ}$$

Using the boundary work relation for the isothermal process of an ideal gas gives

$$W_{b,\text{out}} = m\int_1^2 P\,dv = mRT\int_1^2 \frac{dv}{v} = mRT\ln\frac{v_2}{v_1} = mRT\ln\frac{P_1}{P_2}$$

Solving for the mass of the system,

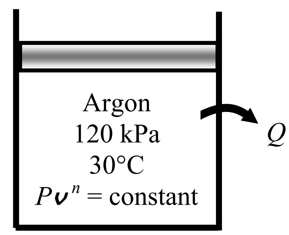
$$m = \frac{W_{b,\text{out}}}{RT\ln\dfrac{P_1}{P_2}} = \frac{1500\ \text{kJ}}{(0.2081\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(373\ \text{K})\ln\dfrac{200\ \text{kPa}}{50\ \text{kPa}}} = \mathbf{13.94\ kg}$$

5-74 Argon is compressed in a polytropic process. The work done and the heat transfer are to be determined.

Assumptions **1** Argon is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 151 K and 4.86 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$.

Properties The properties of argon are R = 0.2081kJ/kg·K and c_v = 0.3122 kJ/kg·K (Table A-2*a*).

Analysis We take argon as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as



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

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U = mc_v(T_2 - T_1)$$

Using the boundary work relation for the polytropic process of an ideal gas gives

$$w_{b,\text{out}} = \frac{RT_1}{1-n}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right] = \frac{(0.2081\,\text{kJ/kg}\cdot\text{K})(303\,\text{K})}{1\text{-}1.2}\left[\left(\frac{1200}{120}\right)^{0.2/1.2} - 1\right] = -147.5\,\text{kJ/kg}$$

Thus,

$$w_{b,\text{in}} = \mathbf{147.5\ kJ/kg}$$

The temperature at the final state is

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(n\text{-}1)/n} = (303\,\text{K})\left(\frac{1200\,\text{kPa}}{120\,\text{kPa}}\right)^{0.2/1.2} = 444.7\,\text{K}$$

From the energy balance equation,

$$q_{\text{in}} = w_{b,\text{out}} + c_v(T_2 - T_1) = -147.5\,\text{kJ/kg} + (0.3122\,\text{kJ/kg}\cdot\text{K})(444.7 - 303)\text{K} = -103.3\,\text{kJ/kg}$$

Thus,

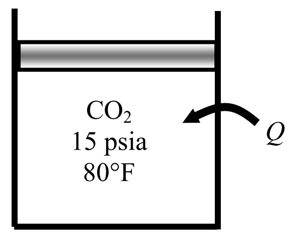
$$q_{\text{out}} = \mathbf{103.3\ kJ/kg}$$

5-75E Carbon dioxide contained in a piston-cylinder device undergoes a constant-pressure process. The work done and the heat transfer are to be determined.

Assumptions **1** Carbon dioxide is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 547.5 R and 1071 psia. **2** The kinetic and potential energy changes are negligible, $\Delta \text{ke} \cong \Delta \text{pe} \cong 0$. **3** Constant specific heats at room temperature can be used for CO_2.

Properties The properties of CO_2 at room temperature are R = 0.04513 Btu/lbm·R and c_v = 0.158 Btu/lbm·R (Table A-2E*a*).

Analysis We take CO_2 as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as



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

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U = mc_v(T_2 - T_1)$$

Using the boundary work relation for the isobaric process of an ideal gas gives

$$w_{b,\text{out}} = P(v_2 - v_1) = R(T_2 - T_1) = (0.04513\ \text{Btu/lbm}\cdot\text{R})(200-80)\text{R} = \mathbf{5.416\ Btu/lbm}$$

Substituting into energy balance equation,

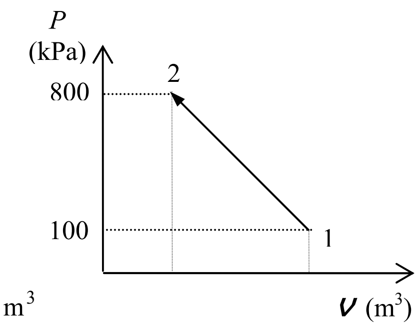
$$q_{\text{in}} = w_{b,\text{out}} + c_v(T_2 - T_1) = 5.416\ \text{Btu/lbm} + (0.158\ \text{Btu/lbm}\cdot\text{R})(200-80)\text{R} = \mathbf{24.38\ Btu/lbm}$$

5-76 Helium contained in a spring-loaded piston-cylinder device is heated. The work done and the heat transfer are to be determined.

Assumptions **1** Helium is an ideal gas since it is at a high temperature relative to its critical temperature of 5.3 K. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$.

Properties The properties of helium are R = 2.0769kJ/kg·K and c_v = 3.1156 kJ/kg·K (Table A-2*a*).

Analysis We take helium as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as



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

$$Q_{in} - W_{b,out} = \Delta U = mc_v(T_2 - T_1)$$

The initial and final specific volumes are

$$V_1 = \frac{mRT_1}{P_1} = \frac{(5\text{ kg})(2.0769\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\text{ K})}{100\text{ kPa}} = 30.427\text{ m}^3$$

$$V_2 = \frac{mRT_2}{P_2} = \frac{(5\text{ kg})(2.0769\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(160+273\text{ K})}{800\text{ kPa}} = 5.621\text{ m}^3$$

Pressure changes linearly with volume and the work done is equal to the area under the process line 1-2:

$$\begin{aligned} W_{b,out} &= \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1) \\ &= \frac{(100+800)\text{kPa}}{2}(5.621 - 30.427)\text{m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= -11{,}163\text{ kJ} \end{aligned}$$

Thus,

$$W_{b,in} = \mathbf{11.163\ kJ}$$

Using the energy balance equation,

$$Q_{in} = W_{b,out} + mc_v(T_2 - T_1) = -11{,}163\text{ kJ} + (5\text{ kg})(3.1156\text{ kJ/kg}\cdot\text{K})(160-20)\text{K} = -8982\text{ kJ}$$

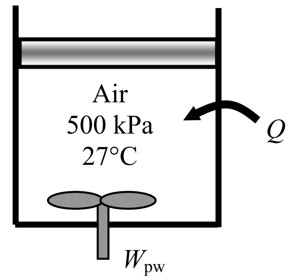
Thus,

$$Q_{out} = \mathbf{8982\ kJ}$$

5-77 A piston-cylinder device contains air. A paddle wheel supplies a given amount of work to the air. The heat transfer is to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 132.5 K and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats can be used for air.

Analysis We take the air as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as



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

$$W_{pw,in} - W_{b,out} + Q_{in} = \Delta U = mc_v(T_2 - T_1)$$

$$W_{pw,in} - W_{b,out} + Q_{in} = 0 \quad (\text{since } T_1 = T_2)$$

$$Q_{in} = W_{b,out} - W_{pw,in}$$

Using the boundary work relation on a unit mass basis for the isothermal process of an ideal gas gives

$$w_{b,out} = RT \ln\frac{v_2}{v_1} = RT \ln 3 = (0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})\ln 3 = 94.6 \text{ kJ/kg}$$

Substituting into the energy balance equation (expressed on a unit mass basis) gives

$$q_{in} = w_{b,out} - w_{pw,in} = 94.6 - 50 = \mathbf{44.6 \ kJ/kg}$$

Discussion Note that the energy content of the system remains constant in this case, and thus the total energy transfer output via boundary work must equal the total energy input via shaft work and heat transfer.

5-78 A cylinder equipped with a set of stops for the piston to rest on is initially filled with helium gas at a specified state. The amount of heat that must be transferred to raise the piston is to be determined.

Assumptions **1** Helium is an ideal gas with constant specific heats. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** There are no work interactions involved. **4** The thermal energy stored in the cylinder itself is negligible.

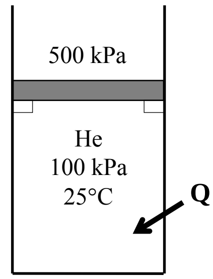
Properties The specific heat of helium at room temperature is c_v = 3.1156 kJ/kg.K (Table A-2).

Analysis We take the helium gas in the cylinder as the system. This is a closed system since no mass crosses the boundary of the system. The energy balance for this constant volume closed system can be expressed as

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

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

$$Q_{in} = m(u_2 - u_1) = mc_v(T_2 - T_1)$$



The final temperature of helium can be determined from the ideal gas relation to be

$$\frac{P_1 V}{T_1} = \frac{P_2 V}{T_2} \longrightarrow T_2 = \frac{P_2}{P_1} T_1 = \frac{500 \text{ kPa}}{100 \text{ kPa}}(298 \text{ K}) = 1490 \text{ K}$$

Substituting into the energy balance relation gives

Q_{in} = (0.5 kg)(3.1156 kJ/kg·K)(1490 - 298)K = **1857 kJ**

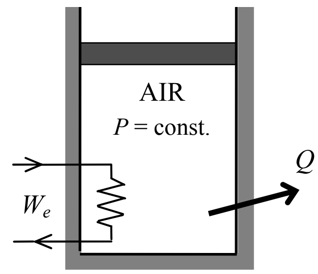
5-79 A cylinder is initially filled with air at a specified state. Air is heated electrically at constant pressure, and some heat is lost in the process. The amount of electrical energy supplied is to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** Air is an ideal gas with variable specific heats. **3** The thermal energy stored in the cylinder itself and the resistance wires is negligible. **4** The compression or expansion process is quasi-equilibrium.

Properties The initial and final enthalpies of air are (Table A-21)

$$h_1 = h_{@\,298\text{ K}} = 298.18\text{ kJ/kg}$$

$$h_2 = h_{@\,350\text{ K}} = 350.49\text{ kJ/kg}$$



Analysis 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

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

$$W_{\text{e,in}} - Q_{\text{out}} - W_{\text{b,out}} = \Delta U \longrightarrow W_{\text{e,in}} = m(h_2 - h_1) + Q_{\text{out}}$$

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

$$W_{\text{e,in}} = (15\text{ kg})(350.49 - 298.18)\text{kJ/kg} + (60\text{ kJ}) = 845\text{ kJ}$$

or,

$$W_{e,in} = (845\text{kJ})\left(\frac{1\text{ kWh}}{3600\text{ kJ}}\right) = \mathbf{0.235\ kWh}$$

Alternative solution The specific heat of air at the average temperature of T_{avg} = (25+ 77)/2 = 51°C = 324 K is, from Table A-2b, $c_{p,\text{avg}}$ = 1.0065 kJ/kg.°C. Substituting,

$$W_{\text{e,in}} = mc_p(T_2 - T_1) + Q_{\text{out}} = (15\text{ kg})(1.0065\text{ kJ/kg.°C})(77 - 25)\text{°C} + 60\text{ kJ} = 845\text{ kJ}$$

or,

$$W_{\text{e,in}} = (845\text{ kJ})\left(\frac{1\text{ kWh}}{3600\text{ kJ}}\right) = \mathbf{0.235\ kWh}$$

Discussion Note that for small temperature differences, both approaches give the same result.

5-80 An insulated cylinder initially contains CO_2 at a specified state. The CO_2 is heated electrically for 10 min at constant pressure until the volume doubles. The electric current is to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The CO_2 is an ideal gas with constant specific heats. **3** The thermal energy stored in the cylinder itself and the resistance wires is negligible. **4** The compression or expansion process is quasi-equilibrium.

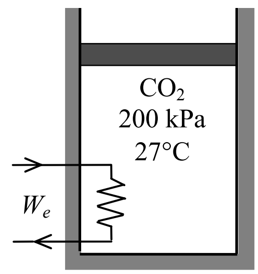
Properties The gas constant and molar mass of CO_2 are R = 0.1889 kPa.m^3/kg.K and M = 44 kg/kmol (Table A-1). The specific heat of CO_2 at the average temperature of T_{avg} = (300 + 600)/2 = 450 K is $c_{p,avg}$ = 0.978 kJ/kg.°C (Table A-2b).

Analysis 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

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

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

$$W_{\text{e,in}} = m(h_2 - h_1) \cong mc_p(T_2 - T_1)$$



since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The final temperature of CO_2 is

$$\frac{P_1 \boldsymbol{V}_1}{T_1} = \frac{P_2 \boldsymbol{V}_2}{T_2} \longrightarrow T_2 = \frac{P_2}{P_1}\frac{\boldsymbol{V}_2}{\boldsymbol{V}_1} T_1 = 1 \times 2 \times (300 \text{ K}) = 600 \text{ K}$$

The mass of CO_2 is

$$m = \frac{P_1 \boldsymbol{V}_1}{RT_1} = \frac{(200 \text{ kPa})(0.3 \text{ m}^3)}{(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(300 \text{ K})} = 1.059 \text{ kg}$$

Substituting,

$$W_{\text{e,in}} = (1.059 \text{ kg})(0.978 \text{ kJ/kg.K})(600 - 300)\text{K} = 311 \text{ kJ}$$

Then,

$$I = \frac{W_{\text{e,in}}}{\mathbf{V}\Delta t} = \frac{311 \text{ kJ}}{(110\text{V})(10 \times 60 \text{ s})}\left(\frac{1000 \text{ VA}}{1 \text{ kJ/s}}\right) = \mathbf{4.71 \text{ A}}$$

5-81 A cylinder initially contains nitrogen gas at a specified state. The gas is compressed polytropically until the volume is reduced by one-half. The work done and the heat transfer are to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The N_2 is an ideal gas with constant specific heats. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

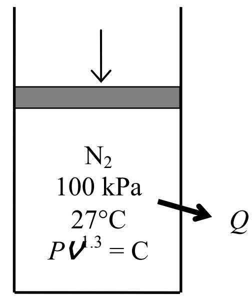
Properties The gas constant of N_2 is R = 0.2968 kPa.m^3/kg.K (Table A-1). The c_v value of N_2 at the average temperature (369+300)/2 = 335 K is 0.744 kJ/kg.K (Table A-2b).

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

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

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

$$W_{\text{b,in}} - Q_{\text{out}} = mc_v(T_2 - T_1)$$



The final pressure and temperature of nitrogen are

$$P_2 V_2^{1.3} = P_1 V_1^{1.3} \longrightarrow P_2 = \left(\frac{V_1}{V_2}\right)^{1.3} P_1 = 2^{1.3}(100\text{ kPa}) = 246.2\text{ kPa}$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \longrightarrow T_2 = \frac{P_2}{P_1}\frac{V_2}{V_1} T_1 = \frac{246.2\text{ kPa}}{100\text{ kPa}} \times 0.5 \times (300\text{ K}) = 369.3\text{ K}$$

Then the boundary work for this polytropic process can be determined from

$$W_{\text{b,in}} = -\int_1^2 P\,dV = -\frac{P_2 V_2 - P_1 V_1}{1-n} = -\frac{mR(T_2 - T_1)}{1-n}$$

$$= -\frac{(0.8\text{ kg})(0.2968\text{ kJ/kg}\cdot\text{K})(369.3 - 300)\text{K}}{1 - 1.3} = \mathbf{54.8\ kJ}$$

Substituting into the energy balance gives

$$Q_{\text{out}} = W_{\text{b,in}} - mc_v(T_2 - T_1)$$

$$= 54.8\text{ kJ} - (0.8\text{ kg})(0.744\text{ kJ/kg.K})(369.3 - 360)\text{K}$$

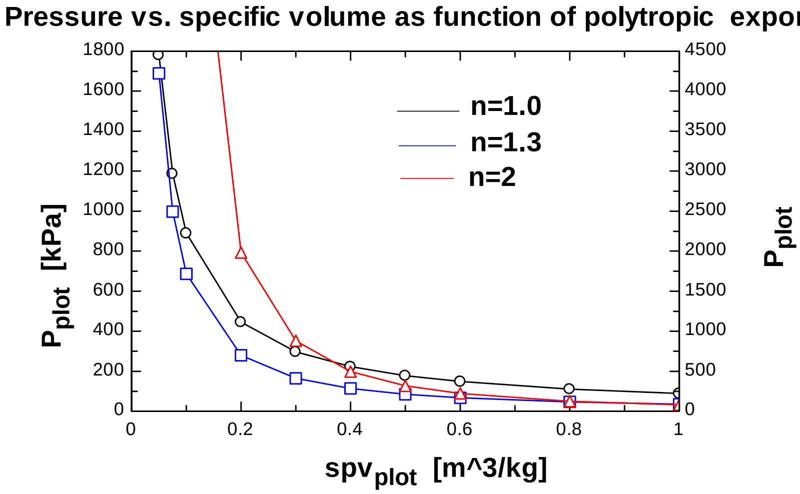
$$= \mathbf{13.6\ kJ}$$

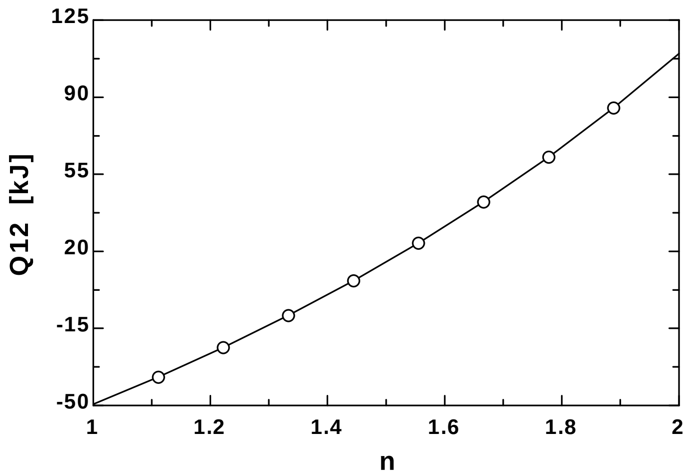
5-82 EES Problem 5-81 is reconsidered. The process is to be plotted on a *P*-***V*** diagram, and the effect of the polytropic exponent n on the boundary work and heat transfer as the polytropic exponent varies from 1.1 to 1.6 is to be investigated. The boundary work and the heat transfer are to be plotted versus the polytropic exponent.

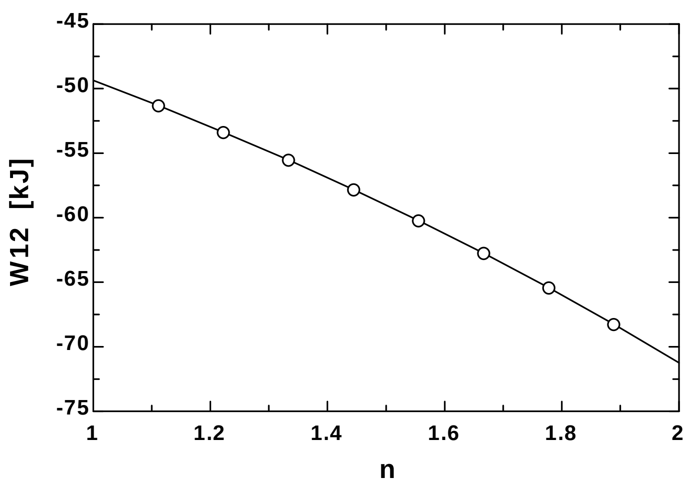
Analysis The problem is solved using EES, and the solution is given below.

```
Procedure      Work(P[2],V[2],P[1],V[1],n:W12)
If n=1 then
W12=P[1]*V[1]*ln(V[2]/V[1])
Else
W12=(P[2]*V[2]-P[1]*V[1])/(1-n)
endif
End

"Input Data"
Vratio=0.5 "V[2]/V[1] = Vratio"
n=1.3 "Polytropic exponent"
P[1] = 100 [kPa]
T[1] = (27+273) [K]
m=0.8 [kg]
MM=molarmass(nitrogen)
R_u=8.314 [kJ/kmol-K]
R=R_u/MM
V[1]=m*R*T[1]/P[1]
"Process equations"
V[2]=Vratio*V[1]
P[2]*V[2]/T[2]=P[1]*V[1]/T[1]"The combined ideal gas law for
states 1 and 2 plus the polytropic process relation give P[2] and T[2]"
P[2]*V[2]^n=P[1]*V[1]^n
"Conservation of Energy for the closed system:"
"E_in - E_out = DeltaE,  we neglect Delta KE and Delta PE for the system, the nitrogen."
Q12 - W12 = m*(u[2]-u[1])
u[1]=intenergy(N2, T=T[1])  "internal energy for nitrogen as an ideal gas, kJ/kg"
u[2]=intenergy(N2, T=T[2])
Call Work(P[2],V[2],P[1],V[1],n:W12)
"The following is required for the P-v plots"
{P_plot*spv_plot/T_plot=P[1]*V[1]/m/T[1]"The combined ideal gas law for
states 1 and 2 plus the polytropic process relation give P[2] and T[2]"
P_plot*spv_plot^n=P[1]*(V[1]/m)^n}
{spV_plot=R*T_plot/P_plot"[m^3]"}
```

n	Q12 [kJ]	W12 [kJ]
1	-49.37	-49.37
1.111	-37	-51.32
1.222	-23.59	-53.38
1.333	-9.067	-55.54
1.444	6.685	-57.82
1.556	23.81	-60.23
1.667	42.48	-62.76
1.778	62.89	-65.43
1.889	85.27	-68.25
2	109.9	-71.23


Pressure vs. specific volume as function of polytropic exponent
n=1.0
n=1.3
n=2
P_plot [kPa]
P_plot
spv_plot [m^3/kg]
1800
1600
1400
1200
1000
800
600
400
200
0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0.2
0.4
0.6
0.8
1

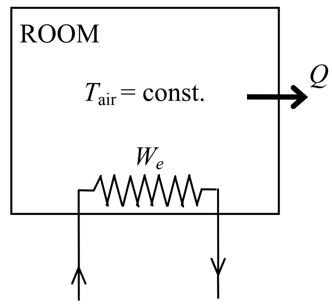

Q12 [kJ]
n
125
90
55
20
-15
-50
1
1.2
1.4
1.6
1.8
2


W12 [kJ]
n
-45
-50
-55
-60
-65
-70
-75
1
1.2
1.4
1.6
1.8
2

5-83 It is observed that the air temperature in a room heated by electric baseboard heaters remains constant even though the heater operates continuously when the heat losses from the room amount to 6500 kJ/h. The power rating of the heater is to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** The temperature of the room is said to remain constant during this process.

Analysis We take the room as the system. This is a closed system since no mass crosses the boundary of the system. The energy balance for this system reduces to



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

$$W_{e,in} - Q_{out} = \Delta U = 0 \longrightarrow W_{e,in} = Q_{out}$$

since $\Delta U = mc_v\Delta T = 0$ for isothermal processes of ideal gases. Thus,

$$\dot{W}_{e,in} = \dot{Q}_{out} = (6500 \text{ kJ/h})\left(\frac{1 \text{ kW}}{3600 \text{ kJ/h}}\right) = \mathbf{1.81\ kW}$$

5-84 A cylinder equipped with a set of stops for the piston is initially filled with air at a specified state. Heat is transferred to the air until the volume doubled. The work done by the air and the amount of heat transfer are to be determined, and the process is to be shown on a P-v diagram.

Assumptions **1** Air is an ideal gas with variable specific heats. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

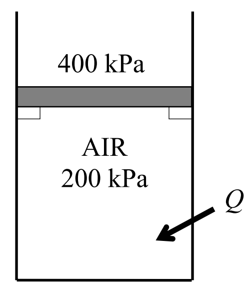
Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1).

Analysis We take the air in the cylinder as the system. This is a closed system since no mass crosses the boundary of the system. The energy balance for this closed system can be expressed as

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

$$Q_{in} - W_{b,out} = \Delta U = m(u_3 - u_1)$$

$$Q_{in} = m(u_3 - u_1) + W_{b,out}$$

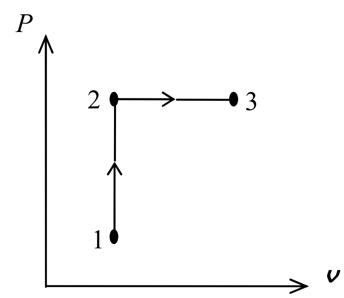


The initial and the final volumes and the final temperature of air are

$$V_1 = \frac{mRT_1}{P_1} = \frac{(3\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})}{200\text{ kPa}} = 1.29\text{ m}^3$$

$$V_3 = 2V_1 = 2\times 1.29 = 2.58\text{ m}^3$$

$$\frac{P_1V_1}{T_1} = \frac{P_3V_3}{T_3} \longrightarrow T_3 = \frac{P_3}{P_1}\frac{V_3}{V_1}T_1 = \frac{400\text{ kPa}}{200\text{ kPa}}\times 2\times(300\text{ K}) = 1200\text{ K}$$



No work is done during process 1-2 since $V_1 = V_2$. The pressure remains constant during process 2-3 and the work done during this process is

$$W_{b,out} = \int_1^2 P\,dV = P_2(V_3 - V_2) = (400\text{ kPa})(2.58 - 1.29)\text{m}^3 = \mathbf{516\ kJ}$$

The initial and final internal energies of air are (Table A-21)

$$u_1 = u_{@300\text{ K}} = 214.07\text{ kJ/kg}$$

$$u_3 = u_{@1200\text{ K}} = 933.33\text{ kJ/kg}$$

Then from the energy balance,

$$Q_{in} = (3\text{ kg})(933.33 - 214.07)\text{kJ/kg} + 516\text{ kJ} = \mathbf{2674\ kJ}$$

Alternative solution The specific heat of air at the average temperature of T_{avg} = (300 + 1200)/2 = 750 K is, from Table A-2b, $c_{v,avg}$ = 0.800 kJ/kg.K. Substituting,

$$Q_{in} = m(u_3 - u_1) + W_{b,out} \cong mc_v(T_3 - T_1) + W_{b,out}$$

$$Q_{in} = (3\text{ kg})(0.800\text{ kJ/kg.K})(1200 - 300)\text{ K} + 516\text{ kJ} = \mathbf{2676\ kJ}$$

5-85 CD EES A cylinder equipped with a set of stops on the top is initially filled with air at a specified state. Heat is transferred to the air until the piston hits the stops, and then the pressure doubles. The work done by the air and the amount of heat transfer are to be determined, and the process is to be shown on a *P*-*v* diagram.

Assumptions **1** Air is an ideal gas with variable specific heats. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** The thermal energy stored in the cylinder itself is negligible.

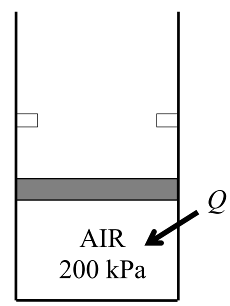
Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1).

Analysis We take the air in the cylinder to be the system. This is a closed system since no mass crosses the boundary of the system. The energy balance for this closed system can be expressed as

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

$$Q_{\text{in}} - W_{\text{b,out}} = \Delta U = m(u_3 - u_1)$$

$$Q_{\text{in}} = m(u_3 - u_1) + W_{\text{b,out}}$$

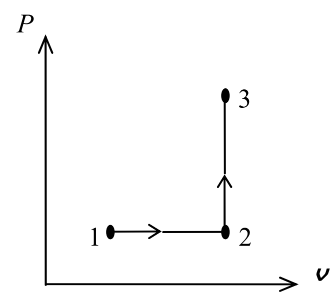


The initial and the final volumes and the final temperature of air are determined from

$$V_1 = \frac{mRT_1}{P_1} = \frac{(3\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})}{200\text{ kPa}} = 1.29\text{ m}^3$$

$$V_3 = 2V_1 = 2\times 1.29 = 2.58\text{ m}^3$$

$$\frac{P_1V_1}{T_1} = \frac{P_3V_3}{T_3} \longrightarrow T_3 = \frac{P_3}{P_1}\frac{V_3}{V_1}T_1 = \frac{400\text{ kPa}}{200\text{ kPa}}\times 2\times(300\text{ K}) = 1200\text{ K}$$



No work is done during process 2-3 since $V_2 = V_3$. The pressure remains constant during process 1-2 and the work done during this process is

$$W_b = \int_1^2 P dV = P_2(V_2 - V_1)$$

$$= (200\text{ kPa})(2.58 - 1.29)\text{ m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = \mathbf{258\text{ kJ}}$$

The initial and final internal energies of air are (Table A-21)

$$u_1 = u_{@300\text{ K}} = 214.07\text{ kJ/kg}$$

$$u_3 = u_{@1200\text{ K}} = 933.33\text{ kJ/kg}$$

Substituting,

$$Q_{\text{in}} = (3\text{ kg})(933.33 - 214.07)\text{kJ/kg} + 258\text{ kJ} = \mathbf{2416\text{ kJ}}$$

Alternative solution The specific heat of air at the average temperature of T_{avg} = (300 + 1200)/2 = 750 K is, from Table A-2b, $c_{v\text{avg}}$ = 0.800 kJ/kg.K. Substituting

$$Q_{\text{in}} = m(u_3 - u_1) + W_{\text{b,out}} \cong mc_v(T_3 - T_1) + W_{\text{b,out}}$$

$$= (3\text{ kg})(0.800\text{ kJ/kg.K})(1200 - 300)\text{ K} + 258\text{ kJ} = \mathbf{2418\text{ kJ}}$$

Closed System Energy Analysis: Solids and Liquids

5-86 An iron block is heated. The internal energy and enthalpy changes are to be determined for a given temperature change.

Assumptions Iron is an incompressible substance with a constant specific heat.

Properties The specific heat of iron is 0.45 kJ/kg·K (Table A-3*b*).

Analysis The internal energy and enthalpy changes are equal for a solid. Then,

$$\Delta H = \Delta U = mc\Delta T = (1\,\text{kg})(0.45\,\text{kJ/kg}\cdot\text{K})(80-20)\text{K} = \mathbf{27\ kJ}$$

5-87E Liquid water experiences a process from one state to another. The internal energy and enthalpy changes are to be determined under different assumptions.

Analysis (a) Using the properties from compressed liquid tables

$$u_1 \cong u_{f@\,50°\text{F}} = 18.07\ \text{Btu/lbm} \quad (\text{Table A-4E})$$

$$\begin{aligned} h_1 &= h_{f\,@\,50°\text{F}} + v_f(P - P_{\text{sat}\,@\,T}) \\ &= 18.07\ \text{Btu/lbm} + (0.01602\ \text{ft}^3/\text{lbm})(50 - 0.17812)\ \text{psia} = 18.87\ \text{Btu/lbm} \end{aligned}$$

$$\left.\begin{array}{l} P_2 = 2000\ \text{psia} \\ T_2 = 100°\text{F} \end{array}\right\} \begin{array}{l} u_2 = 67.36\ \text{Btu/lbm} \\ h_2 = 73.30\ \text{Btu/lbm} \end{array} \quad (\text{Table A-7E})$$

$$\Delta u = u_2 - u_1 = 67.36 - 18.07 = \mathbf{49.29\ Btu/lbm}$$
$$\Delta h = h_2 - h_1 = 73.30 - 18.87 = \mathbf{54.43\ Btu/lbm}$$

(b) Using incompressible substance approximation and property tables (Table A-4E),

$$\begin{aligned} u_1 &\cong u_{f@\,50°\text{F}} = 18.07\ \text{Btu/lbm} \\ h_1 &\cong h_{f@\,50°\text{F}} = 18.07\ \text{Btu/lbm} \\ u_2 &\cong u_{f@\,100°\text{F}} = 68.03\ \text{Btu/lbm} \\ h_2 &\cong h_{f@\,100°\text{F}} = 68.03\ \text{Btu/lbm} \end{aligned}$$

$$\Delta u = u_2 - u_1 = 68.03 - 18.07 = \mathbf{49.96\ Btu/lbm}$$
$$\Delta h = h_2 - h_1 = 68.03 - 18.07 = \mathbf{49.96\ Btu/lbm}$$

(c) Using specific heats and taking the specific heat of water to be 1.00 Btu/lbm·R (Table A-3E*a*),

$$\Delta h = \Delta u = c\Delta T = (1.00\ \text{Btu/lbm}\cdot\text{R})(100-50)\text{R} = \mathbf{50\ Btu/lbm}$$

5-88E A person shakes a canned of drink in a iced water to cool it. The mass of the ice that will melt by the time the canned drink is cooled to a specified temperature is to be determined.

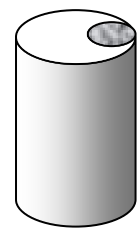
Assumptions **1** The thermal properties of the drink are constant, and are taken to be the same as those of water. **2** The effect of agitation on the amount of ice melting is negligible. **3** The thermal energy capacity of the can itself is negligible, and thus it does not need to be considered in the analysis.

Properties The density and specific heat of water at the average temperature of (75+45)/2 = 60°F are ρ = 62.3 lbm/ft^3, and c_p = 1.0 Btu/lbm.°F (Table A-3E). The heat of fusion of water is 143.5 Btu/lbm.

Analysis We take a canned drink as the system. The energy balance for this closed system can be expressed as

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

$$-Q_{out} = \Delta U_{\text{canned drink}} = m(u_2 - u_1) \longrightarrow Q_{out} = mc(T_1 - T_2)$$



Noting that 1 gal = 128 oz and 1 ft^3 = 7.48 gal = 957.5 oz, the total amount of heat transfer from a ball is

$$m = \rho \boldsymbol{V} = (62.3\ \text{lbm/ft}^3)(12\ \text{oz/can})\left(\frac{1\ \text{ft}^3}{7.48\ \text{gal}}\right)\left(\frac{1\ \text{gal}}{128\ \text{fluid oz}}\right) = 0.781\ \text{lbm/can}$$

$$Q_{out} = mc(T_1 - T_2) = (0.781\ \text{lbm/can})(1.0\ \text{Btu/lbm.°F})(75 - 45)\text{°F} = 23.4\ \text{Btu/can}$$

Noting that the heat of fusion of water is 143.5 Btu/lbm, the amount of ice that will melt to cool the drink is

$$m_{ice} = \frac{Q_{out}}{h_{if}} = \frac{23.4\ \text{Btu/can}}{143.5\ \text{Btu/lbm}} = \mathbf{0.163\ lbm} \quad \text{(per can of drink)}$$

since heat transfer to the ice must be equal to heat transfer from the can.

Discussion The actual amount of ice melted will be greater since agitation will also cause some ice to melt.

5-89 An iron whose base plate is made of an aluminum alloy is turned on. The minimum time for the plate to reach a specified temperature is to be determined.

Assumptions **1** It is given that 85 percent of the heat generated in the resistance wires is transferred to the plate. **2** The thermal properties of the plate are constant. **3** Heat loss from the plate during heating is disregarded since the minimum heating time is to be determined. **4** There are no changes in kinetic and potential energies. **5** The plate is at a uniform temperature at the end of the process.

Properties The density and specific heat of the aluminum alloy plate are given to be ρ = 2770 kg/m^3 and c_p = 875 kJ/kg.°C.

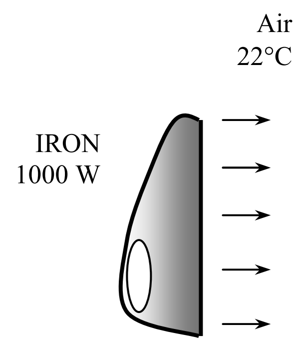
Analysis The mass of the iron's base plate is

$$m = \rho V = \rho LA = (2770\ \text{kg/m}^3)(0.005\ \text{m})(0.03\ \text{m}^2) = 0.4155\ \text{kg}$$

Noting that only 85 percent of the heat generated is transferred to the plate, the rate of heat transfer to the iron's base plate is

$$\dot{Q}_{\text{in}} = 0.85 \times 1000\ \text{W} = 850\ \text{W}$$

We take plate to be the system. The energy balance for this closed system can be expressed as



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

$$Q_{\text{in}} = \Delta U_{\text{plate}} = m(u_2 - u_1) \longrightarrow \dot{Q}_{\text{in}}\Delta t = mc(T_2 - T_1)$$

Solving for Δt and substituting,

$$\Delta t = \frac{mc\Delta T_{\text{plate}}}{\dot{Q}_{\text{in}}} = \frac{(0.4155\ \text{kg})(875\ \text{J/kg.°C})(140 - 22)\text{°C}}{850\ \text{J/s}} = \mathbf{50.5\ s}$$

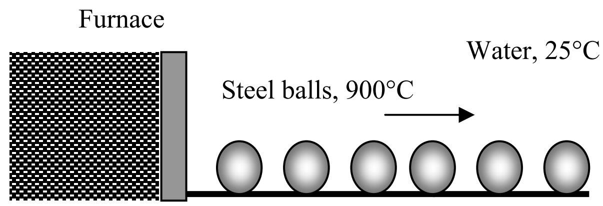
which is the time required for the plate temperature to reach the specified temperature.

5-90 Stainless steel ball bearings leaving the oven at a specified uniform temperature at a specified rate are exposed to air and are cooled before they are dropped into the water for quenching. The rate of heat transfer from the ball bearing to the air is 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 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

$$\dot{Q}_{\text{total}} = \dot{n}_{\text{ball}} Q_{\text{out (per ball)}} = (800\ \text{balls/min}) \times (0.1756\ \text{kJ/ball}) = \mathbf{140.5\ \ kJ/min} = \mathbf{2.34\ \ kW}$$

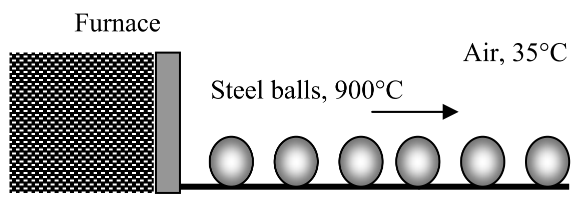
Therefore, heat is lost to the air at a rate of 2.34 kW.

5-91 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 is 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 We take a single ball as the system. The energy balance for this closed system can be expressed as



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

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

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

(b) The amount of heat transfer from a single ball is

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

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

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

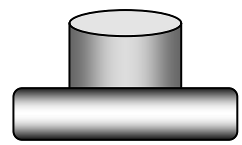
$$\dot{Q}_{out} = \dot{n}_{ball} Q_{out} = (2500 \text{ balls/h}) \times (0.781 \text{ kJ/ball}) = 1{,}953 \text{ kJ/h} = \mathbf{542 \text{ W}}$$

5-92 An electronic device is on for 5 minutes, and off for several hours. The temperature of the device at the end of the 5-min operating period is to be determined for the cases of operation with and without a heat sink.

Assumptions **1** The device and the heat sink are isothermal. **2** The thermal properties of the device and of the sink are constant. **3** Heat loss from the device during on time is disregarded since the highest possible temperature is to be determined.

Properties The specific heat of the device is given to be c_p = 850 J/kg.°C. The specific heat of aluminum at room temperature of 300 K is 902 J/kg.°C (Table A-3).

Analysis We take the device to be the system. Noting that electrical energy is supplied, the energy balance for this closed system can be expressed as



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

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

$$\dot{W}_{e,in}\Delta t = mc(T_2 - T_1)$$

Substituting, the temperature of the device at the end of the process is determined to be

$$(30 \text{ J/s})(5 \times 60 \text{ s}) = (0.020 \text{ kg})(850 \text{ J/kg.°C})(T_2 - 25)\text{°C} \quad \to \quad T_2 = \mathbf{554°C} \text{ (without the heat sink)}$$

Case 2 When a heat sink is attached, the energy balance can be expressed as

$$W_{e,in} = \Delta U_{device} + \Delta U_{heat\,sink}$$

$$\dot{W}_{e,in}\Delta t = mc(T_2 - T_1)_{device} + mc(T_2 - T_1)_{heat\,sink}$$

Substituting, the temperature of the device-heat sink combination is determined to be

$$(30 \text{ J/s})(5 \times 60 \text{ s}) = (0.020 \text{ kg})(850 \text{ J/kg.°C})(T_2 - 25)\text{°C} + (0.200 \text{ kg})(902 \text{ J/kg.°C})(T_2 - 25)\text{°C}$$

$$T_2 = \mathbf{70.6°C} \quad \text{(with heat sink)}$$

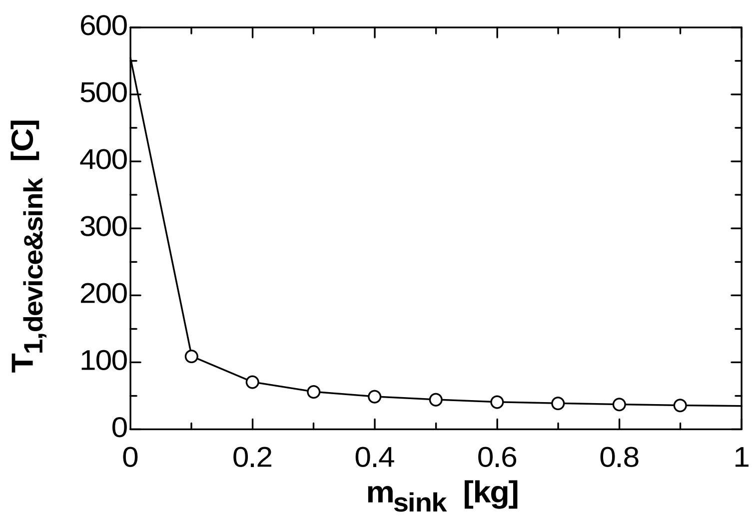
Discussion These are the maximum temperatures. In reality, the temperatures will be lower because of the heat losses to the surroundings.

5-93 EES Problem 5-92 is reconsidered. The effect of the mass of the heat sink on the maximum device temperature as the mass of heat sink varies from 0 kg to 1 kg is to be investigated. The maximum temperature is to be plotted against the mass of heat sink.

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

```
"Knowns:"
"T_1 is the maximum temperature of the device"
Q_dot_out = 30 [W]
m_device=20 [g]
Cp_device=850 [J/kg-C]
A=5 [cm^2]
DELTAt=5 [min]
T_amb=25 [C]
{m_sink=0.2 [kg]}
"Cp_al taken from Table A-3(b) at 300K"
Cp_al=0.902 [kJ/kg-C]
T_2=T_amb

"Solution:"
"The device without the heat sink is considered to be a closed system."
"Conservation of Energy for the closed system:"
"E_dot_in - E_dot_out = DELTAE_dot,  we neglect DELTA KE and DELTA PE for the system, the
device."
E_dot_in - E_dot_out = DELTAE_dot
E_dot_in =0
E_dot_out = Q_dot_out
"Use the solid material approximation to find the energy change of the device."
DELTAE_dot= m_device*convert(g,kg)*Cp_device*(T_2-T_1_device)/(DELTAt*convert(min,s))
"The device with the heat sink is considered to be a closed system."
"Conservation of Energy for the closed system:"
"E_dot_in - E_dot_out = DELTAE_dot,  we neglect DELTA KE and DELTA PE for the device with the
heat sink."
E_dot_in - E_dot_out = DELTAE_dot_combined
"Use the solid material approximation to find the energy change of the device."
DELTAE_dot_combined= (m_device*convert(g,kg)*Cp_device*(T_2-
T_1_device&sink)+m_sink*Cp_al*(T_2-T_1_device&sink)*convert(kJ,J))/(DELTAt*convert(min,s))
```

m_{sink} [kg]	$T_{1,device\&sink}$ [C]
0	554.4
0.1	109
0.2	70.59
0.3	56.29
0.4	48.82
0.5	44.23
0.6	41.12
0.7	38.88
0.8	37.19
0.9	35.86
1	34.79

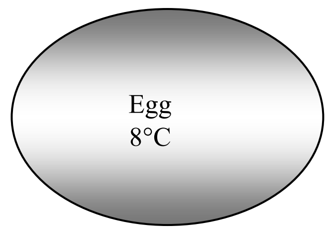


5-94 An egg is dropped into boiling water. The amount of heat transfer to the egg by the time it is cooked is to be determined.

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 ρ = 1020 kg/m³ and c_p = 3.32 kJ/kg.°C.

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



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

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

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

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

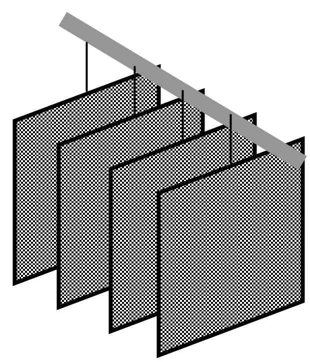
$$Q_{in} = mc_p(T_2 - T_1) = (0.0889\ \text{kg})(3.32\ \text{kJ/kg.°C})(80 - 8)\text{°C} = \mathbf{21.2\ kJ}$$

5-95E Large brass plates are heated in an oven at a rate of 300/min. The rate of heat transfer to the plates in the oven is 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 ρ = 532.5 lbm/ft³ and c_p = 0.091 Btu/lbm.°F.

Analysis We take the plate to be the system. The energy balance for this closed system can be expressed as



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

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

The mass of each plate and the amount of heat transfer to each plate is

$$m = \rho V = \rho LA = (532.5\ \text{lbm/ft}^3)[(1.2/12\ \text{ft})(2\ \text{ft})(2\ \text{ft})] = 213\ \text{lbm}$$

$$Q_{in} = mc(T_2 - T_1) = (213\ \text{lbm/plate})(0.091\ \text{Btu/lbm.°F})(1000 - 75)\text{°F} = 17{,}930\ \text{Btu/plate}$$

Then the total rate of heat transfer to the plates becomes

$$\dot{Q}_{total} = \dot{n}_{plate} Q_{in,\ per\ plate} = (300\ \text{plates/min}) \times (17{,}930\ \text{Btu/plate}) = \mathbf{5{,}379{,}000\ Btu/min = 89{,}650\ Btu/s}$$

5-96 Long cylindrical steel rods are heat-treated in an oven. The rate of heat transfer to the rods in the oven is to be determined.

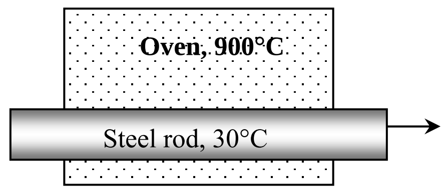
Assumptions **1** The thermal properties of the rods are constant. **2** The changes in kinetic and potential energies are negligible.

Properties The density and specific heat of the steel rods are given to be ρ = 7833 kg/m^3 and c_p = 0.465 kJ/kg.°C.

Analysis 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

$$m = \rho \boldsymbol{V} = \rho LA = \rho L(\pi D^2 / 4) = (7833 \text{ kg/m}^3)(3 \text{ m})[\pi(0.1 \text{ m})^2 / 4] = 184.6 \text{ kg}$$

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



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

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

Substituting,

$$Q_{in} = mc(T_2 - T_1) = (184.6 \text{ kg})(0.465 \text{ kJ/kg.°C})(700 - 30)\text{°C} = 57{,}512 \text{ kJ}$$

Noting that this much heat is transferred in 1 min, the rate of heat transfer to the rod becomes

$$\dot{Q}_{in} = Q_{in} / \Delta t = (57{,}512 \text{ kJ})/(1 \text{ min}) = 57{,}512 \text{ kJ/min} = \mathbf{958.5 \text{ kW}}$$

Review Problems

5-97 The compression work from P_1 to P_2 using a polytropic process is to be compared for neon and air.

Assumptions The process is quasi-equilibrium.

Properties The gas constants for neon and air R = 0.4119 and 0.287 kJ/kg·K, respectively (Table A-2*a*).

Analysis For a polytropic process,

$$P\boldsymbol{v}^n = \text{Constant}$$

The boundary work during a polytropic process of an ideal gas is

$$w_{b,\text{out}} = \int_1^2 P d\boldsymbol{v} = \text{Constant}\int_1^2 \boldsymbol{v}^{-n} d\boldsymbol{v} = \frac{P_1\boldsymbol{v}_1}{1-n}\left[\left(\frac{\boldsymbol{v}_2}{\boldsymbol{v}_1}\right)^{1-n} - 1\right] = \frac{RT_1}{1-n}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right]$$

The negative of this expression gives the compression work during a polytropic process. Inspection of this equation reveals that the gas with the smallest gas constant (i.e., largest molecular weight) requires the least work for compression. In this problem, air will require the least amount of work.

5-98 Nitrogen is heated to experience a specified temperature change. The heat transfer is to be determined for two cases.

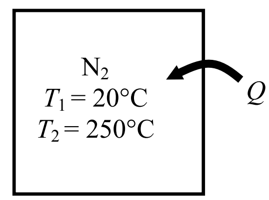
Assumptions **1** Nitrogen is an ideal gas since it is at a high temperature and probably low pressure relative to its critical point values of 126.2 K and 3.39 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats can be used for nitrogen.

Properties The specific heats of nitrogen at the average temperature of (20+250)/2=135°C=408 K are c_p = 1.045 kJ/kg·K and c_v = 0.748 kJ/kg·K (Table A-2*b*).

Analysis We take the nitrogen as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for a constant-volume process can be expressed as

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

$$Q_{in} = \Delta U = mc_v(T_2 - T_1)$$



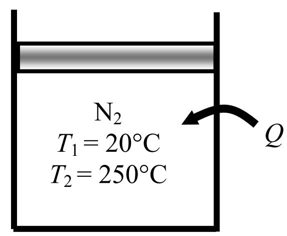
The energy balance during a constant-pressure process (such as in a piston-cylinder device) can be expressed as

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

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

$$Q_{in} = W_{b,out} + \Delta U$$

$$Q_{in} = \Delta H = mc_p(T_2 - T_1)$$



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

$$Q_{in,V=const} = mc_v(T_2 - T_1) = (10\text{ kg})(0.748\text{ kJ/kg}\cdot\text{K})(250-20)\text{K} = \mathbf{1720 kJ}$$

$$Q_{in,P=const} = mc_p(T_2 - T_1) = (10\text{ kg})(1.045\text{ kJ/kg}\cdot\text{K})(250-20)\text{K} = \mathbf{2404\ kJ}$$

5-99E An insulated rigid vessel contains air. A paddle wheel supplies work to the air. The work supplied and final temperature are to be determined.

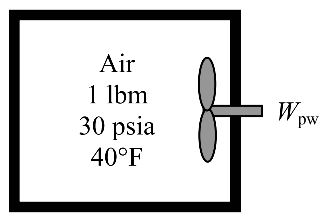
Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 238.5 R and 547 psia. **2** The kinetic and potential energy changes are negligible, $\Delta \mathrm{ke} \cong \Delta \mathrm{pe} \cong 0$. **3** Constant specific heats can be used for air.

Properties The specific heats of air at room temperature are c_p = 0.240 Btu/lbm·R and c_v = 0.171 Btu/lbm·R (Table A-2E*a*).

Analysis We take the air as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as

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

$$W_{\mathrm{pw,in}} = \Delta U = mc_v (T_2 - T_1)$$



As the specific volume remains constant during this process, the ideal gas equation gives

$$T_2 = T_1 \frac{P_2}{P_1} = (500\ \mathrm{R}) \frac{50\ \mathrm{psia}}{30\ \mathrm{psia}} = 833.3\ \mathrm{R} = \mathbf{373.3°F}$$

Substituting,

$$W_{\mathrm{pw,in}} = mc_v (T_2 - T_1) = (1\ \mathrm{lbm})(0.171\ \mathrm{Btu/lbm \cdot R})(833.3 - 500)\mathrm{R} = \mathbf{57.0\ Btu}$$

5-100 During a phase change, a constant pressure process becomes a constant temperature process. Hence,

$$c_p = \left. \frac{\partial h}{\partial T} \right|_T = \frac{\text{finite}}{0} = \text{infinite}$$

and the specific heat at constant pressure has no meaning. The specific heat at constant volume does have a meaning since

$$c_v = \left. \frac{\partial u}{\partial T} \right|_v = \frac{\text{finite}}{\text{finite}} = \text{finite}$$

5-101 A gas mixture contained in a rigid tank is cooled. The heat transfer is to be determined.

Assumptions **1** The gas mixture is an ideal gas. **2** The kinetic and potential energy changes are negligible, $\Delta\text{ke} \cong \Delta\text{pe} \cong 0$. **3** Constant specific heats can be used.

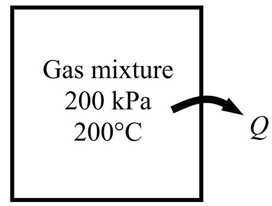
Properties The specific heat of gas mixture is given to be c_v = 0.748 kJ/kg·K.

Analysis We take the contents of the tank as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as

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

$$-Q_{\text{out}} = \Delta U = mc_v(T_2 - T_1)$$

$$q_{\text{out}} = c_v(T_1 - T_2)$$



As the specific volume remains constant during this process, the ideal gas equation gives

$$T_2 = T_1 \frac{P_2}{P_1} = (473\text{ K})\frac{100\text{ kPa}}{200\text{ kPa}} = 236.5\text{ K}$$

Substituting,

$$q_{\text{out}} = c_v(T_1 - T_2) = (0.748\text{ kJ/kg}\cdot\text{K})(473 - 236.5)\text{K} = \mathbf{177\ kJ/kg}$$

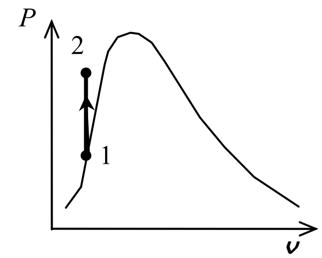
5-102 A well-insulated rigid vessel contains saturated liquid water. Electrical work is done on water. The final temperature is to be determined.

Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** The thermal energy stored in the tank itself is negligible.

Analysis We take the contents of the tank 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

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

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



The amount of electrical work added during 30 minutes period is

$$W_{e,in} = \mathbf{V}I\Delta t = (50\text{ V})(10\text{ A})(30\times 60\text{ s})\left(\frac{1\text{ W}}{1\text{ VA}}\right) = 900{,}000\text{ J} = 900\text{ kJ}$$

The properties at the initial state are (Table A-4)

$$u_1 = u_{f\,@40°C} = 167.53\text{ kJ/kg}$$

$$v_1 = v_{f\,@40°C} = 0.001008\text{ m}^3\text{/kg..}$$

Substituting,

$$W_{e,in} = m(u_2 - u_1) \longrightarrow u_2 = u_1 + \frac{W_{e,in}}{m} = 167.53\text{ kJ/kg} + \frac{900\text{ kJ}}{3\text{ kg}} = 467.53\text{ kJ/kg}$$

The final state is compressed liquid. Noting that the specific volume is constant during the process, the final temperature is determined using EES to be

$$\left.\begin{array}{l} u_2 = 467.53\text{ kJ/kg} \\ v_1 = v_1 = 0.001008\text{ m}^3\text{/kg} \end{array}\right\} T_2 = \mathbf{118.9°C} \quad \text{(from EES)}$$

Discussion We cannot find this temperature directly from steam tables at the end of the book. Approximating the final compressed liquid state as saturated liquid at the given internal energy, the final temperature is determined from Table A-4 to be

$$T_2 \cong T_{sat@\,u=467.53\text{ kJ/kg}} = 111.5°C$$

Note that this approximation resulted in an answer, which is not very close to the exact answer determined using EES.

5-103 The boundary work expression during a polytropic process of an ideal gas is to be derived.

Assumptions The process is quasi-equilibrium.

Analysis For a polytropic process,

$$P_1 \boldsymbol{v}_1^n = P_2 \boldsymbol{v}_2^n = \text{Constant}$$

Substituting this into the boundary work expression gives

$$\begin{aligned} w_{b,\text{out}} &= \int_1^2 P d\boldsymbol{v} = P_1 \boldsymbol{v}_1^n \int_1^2 \boldsymbol{v}^{-n} d\boldsymbol{v} = \frac{P_1 \boldsymbol{v}_1}{1-n}(\boldsymbol{v}_2^{1-n} - \boldsymbol{v}_1^{1-n}) \\ &= \frac{P_1}{1-n}\left(\frac{\boldsymbol{v}_2}{\boldsymbol{v}_2^n}\boldsymbol{v}_1^n - \frac{\boldsymbol{v}_1}{\boldsymbol{v}_1^n}\boldsymbol{v}_1^n\right) \\ &= \frac{P_1 \boldsymbol{v}_1}{1-n}(\boldsymbol{v}_2^{1-n}\boldsymbol{v}_1^{n-1} - 1) \\ &= \frac{RT_1}{1-n}\left[\left(\frac{\boldsymbol{v}_2}{\boldsymbol{v}_1}\right)^{1-n} - 1\right] \end{aligned}$$

When the specific volume ratio is eliminated with the expression for the constant,

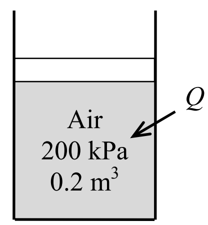
$$w_{b,\text{out}} = \frac{RT_1}{1-n}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right]$$

where $n \neq 1$

5-104 A cylinder equipped with an external spring is initially filled with air at a specified state. Heat is transferred to the air, and both the temperature and pressure rise. The total boundary work done by the air, and the amount of work done against the spring are to be determined, and the process is to be shown on a *P*-V diagram.

Assumptions **1** The process is quasi-equilibrium. **2** The spring is a linear spring.

Analysis (*a*) The pressure of the gas changes linearly with volume during this process, and thus the process curve on a *P-V* diagram will be a straight line. Then the boundary work during this process is simply the area under the process curve, which is a trapezoidal. Thus,

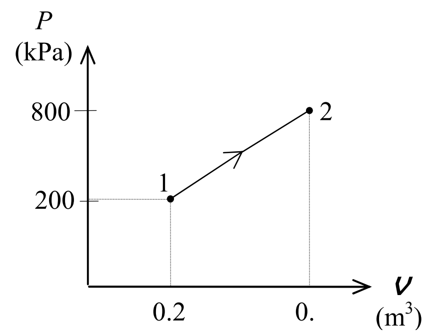


$$W_{b,out} = \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1)$$

$$= \frac{(200+800)\text{kPa}}{2}(0.5-0.2)\text{m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{150\ kJ}$$

(*b*) If there were no spring, we would have a constant pressure process at P = 200 kPa. The work done during this process is



$$W_{b,out,no\ spring} = \int_1^2 P\,dV = P(V_2 - V_1)$$

$$= (200\text{ kPa})(0.5-0.2)\text{m}^3/\text{kg}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

$$= 60\text{ kJ}$$

Thus,

$$W_{spring} = W_b - W_{b,no\ spring} = 150 - 60 = \mathbf{90\ kJ}$$

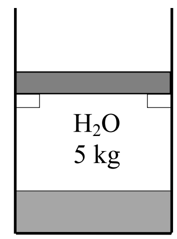
5-105 A cylinder equipped with a set of stops for the piston is initially filled with saturated liquid-vapor mixture of water a specified pressure. Heat is transferred to the water until the volume increases by 20%. The initial and final temperature, the mass of the liquid when the piston starts moving, and the work done during the process are to be determined, and the process is to be shown on a *P-v* diagram.

Assumptions The process is quasi-equilibrium.

Analysis (*a*) Initially the system is a saturated mixture at 125 kPa pressure, and thus the initial temperature is

$$T_1 = T_{\text{sat@125 kPa}} = \mathbf{106.0°C}$$

The total initial volume is



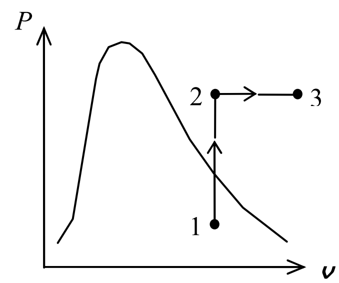
$$\mathbf{V}_1 = m_f v_f + m_g v_g = 2\times 0.001048 + 3\times 1.3750 = 4.127 \text{ m}^3$$

Then the total and specific volumes at the final state are

$$\mathbf{V}_3 = 1.2\mathbf{V}_1 = 1.2\times 4.127 = 4.953 \text{ m}^3$$

$$v_3 = \frac{\mathbf{V}_3}{m} = \frac{4.953 \text{ m}^3}{5 \text{ kg}} = 0.9905 \text{ m}^3/\text{kg}$$

Thus,



$$\left.\begin{aligned} P_3 &= 300 \text{ kPa} \\ v_3 &= 0.9905 \text{ m}^3/\text{kg} \end{aligned}\right\} T_3 = \mathbf{373.6°C}$$

(*b*) When the piston first starts moving, P_2 = 300 kPa and $\mathbf{V}_2 = \mathbf{V}_1$ = 4.127 m^3. The specific volume at this state is

$$v_2 = \frac{\mathbf{V}_2}{m} = \frac{4.127 \text{ m}^3}{5 \text{ kg}} = 0.8254 \text{ m}^3/\text{kg}$$

which is greater than v_g = 0.60582 m^3/kg at 300 kPa. Thus **no liquid** is left in the cylinder when the piston starts moving.

(*c*) No work is done during process 1-2 since $\mathbf{V}_1 = \mathbf{V}_2$. The pressure remains constant during process 2-3 and the work done during this process is

$$W_b = \int_2^3 P\,d\mathbf{V} = P_2(\mathbf{V}_3 - \mathbf{V}_2) = (300 \text{ kPa})(4.953 - 4.127)\text{m}^3\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = \mathbf{247.6 \text{ kJ}}$$

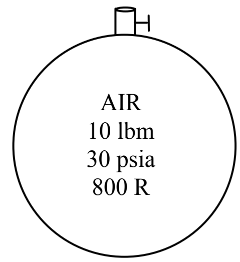
5-106E A spherical balloon is initially filled with air at a specified state. The pressure inside is proportional to the square of the diameter. Heat is transferred to the air until the volume doubles. The work done is to be determined.

Assumptions **1** Air is an ideal gas. **2** The process is quasi-equilibrium.

Properties The gas constant of air is R = 0.06855 Btu/lbm.R (Table A-1E).

Analysis The dependence of pressure on volume can be expressed as

$$V = \frac{1}{6}\pi D^3 \longrightarrow D = \left(\frac{6V}{\pi}\right)^{1/3}$$



$$P \propto D^2 \longrightarrow P = kD^2 = k\left(\frac{6V}{\pi}\right)^{2/3}$$

or, $$k\left(\frac{6}{\pi}\right)^{2/3} = P_1 V_1^{-2/3} = P_2 V_2^{-2/3}$$

Also, $$\frac{P_2}{P_1} = \left(\frac{V_2}{V_1}\right)^{2/3} = 2^{2/3} = 1.587$$

and $$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \longrightarrow T_2 = \frac{P_2 V_2}{P_1 V_1} T_1 = 1.587 \times 2 \times (800 \text{ R}) = 2539 \text{ R}$$

Thus,

$$W_b = \int_1^2 P dV = \int_1^2 k\left(\frac{6V}{\pi}\right)^{2/3} dV = \frac{3k}{5}\left(\frac{6}{\pi}\right)^{2/3}\left(V_2^{5/3} - V_1^{5/3}\right) = \frac{3}{5}(P_2 V_2 - P_1 V_1)$$

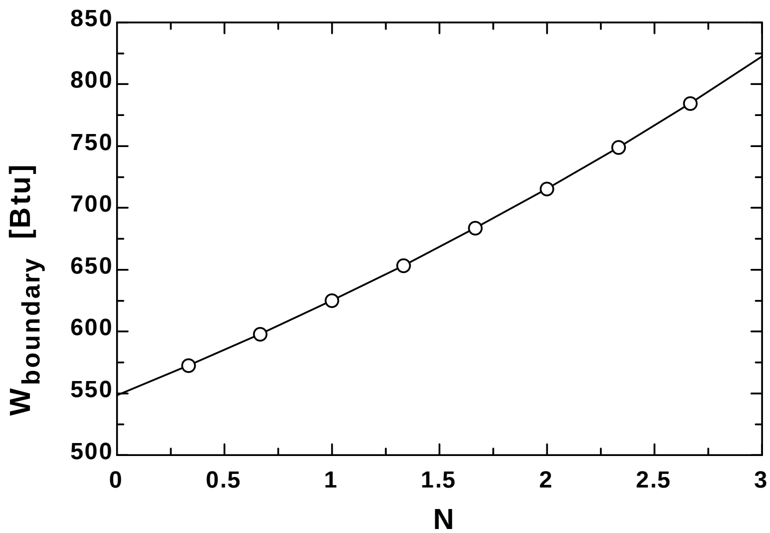
$$= \frac{3}{5} mR(T_2 - T_1) = \frac{3}{5}(10 \text{ lbm})(0.06855 \text{ Btu/lbm}\cdot\text{R})(2539 - 800)\text{R} = \mathbf{715\ \ Btu}$$

5-107E EES Problem 5-106E is reconsidered. Using the integration feature, the work done is to be determined and compared to the 'hand calculated' result.

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

```
N=2
m=10 [lbm]
P_1=30 [psia]
T_1=800 [R]
V_2=2*V_1
R=1545"[ft-lbf/lbmol-R]"/molarmass(air)"[ft-lbf/lbm-R]"
P_1*Convert(psia,lbf/ft^2)*V_1=m*R*T_1
V_1=4*pi*(D_1/2)^3/3"[ft^3]"
C=P_1/D_1^N
(D_1/D_2)^3=V_1/V_2
P_2=C*D_2^N"[psia]"
P_2*Convert(psia,lbf/ft^2)*V_2=m*R*T_2
P=C*D^N*Convert(psia,lbf/ft^2)"[ft^2]"
V=4*pi*(D/2)^3/3"[ft^3]"
W_boundary_EES=integral(P,V,V_1,V_2)*convert(ft-lbf,Btu)"[Btu]"
W_boundary_HAND=pi*C/(2*(N+3))*(D_2^(N+3)-D_1^(N+3))*convert(ft-
lbf,Btu)*convert(ft^2,in^2)"[Btu]"
```

N	$W_{boundary}$ [Btu]
0	548.3
0.3333	572.5
0.6667	598.1
1	625
1.333	653.5
1.667	683.7
2	715.5
2.333	749.2
2.667	784.8
3	822.5



5-108 A cylinder is initially filled with saturated R-134a vapor at a specified pressure. The refrigerant is heated both electrically and by heat transfer at constant pressure for 6 min. The electric current is to be determined, and the process is to be shown on a T-v diagram.

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

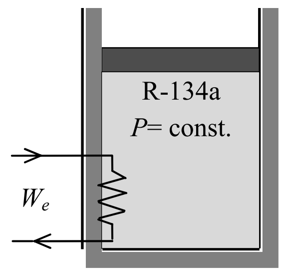
Analysis We take the contents of the cylinder as the system. This is a closed system since no mass enters or leaves. The energy balance for this stationary closed system can be expressed as

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

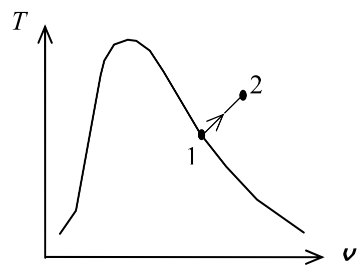
$$Q_{in} + W_{e,in} - W_{b,out} = \Delta U \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$

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

$$Q_{in} + (\text{V}I\Delta t) = m(h_2 - h_1)$$



since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The properties of R-134a are (Tables A-11 through A-13)



$$\left.\begin{array}{l} P_1 = 240 \text{ kPa} \\ \text{sat. vapor} \end{array}\right\} h_1 = h_{g@240\text{kPa}} = 247.28 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 240 \text{ kPa} \\ T_1 = 70°\text{C} \end{array}\right\} h_2 = 314.51 \text{ kJ/kg}$$

Substituting,

$$300{,}000 \text{ VAs} + (110 \text{ V})(I)(6 \times 60 \text{ s}) = (12 \text{ kg})(314.51 - 247.28)\text{kJ/kg}\left(\frac{1000 \text{ VA}}{1 \text{ kJ/s}}\right)$$

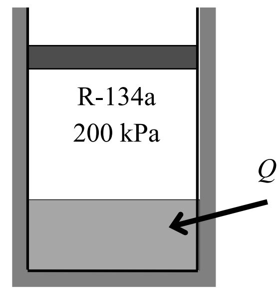
$$I = \mathbf{12.8\ A}$$

5-109 A cylinder is initially filled with saturated liquid-vapor mixture of R-134a at a specified pressure. Heat is transferred to the cylinder until the refrigerant vaporizes completely at constant pressure. The initial volume, the work done, and the total heat transfer are to be determined, and the process is to be shown on a P-v diagram.

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

Analysis (a) Using property data from R-134a tables (Tables A-11 through A-13), the initial volume of the refrigerant is determined to be

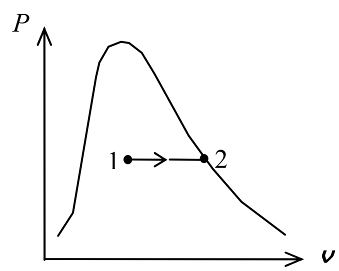
$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ x_1 = 0.25 \end{array}\right\} \begin{array}{ll} v_f = 0.0007533, & v_g = 0.099867 \text{ m}^3/\text{kg} \\ u_f = 38.28, & u_{fg} = 186.21 \text{ kJ/kg} \end{array}$$



$$v_1 = v_f + x_1 v_{fg}$$
$$= 0.0007533 + 0.25 \times (0.099867 - 0.0007533) = 0.02553 \text{ m}^3/\text{kg}$$
$$u_1 = u_f + x_1 u_{fg} = 38.28 + 0.25 \times 186.21 = 84.83 \text{ kJ/kg}$$

$$V_1 = m v_1 = (0.2 \text{ kg})(0.02553 \text{ m}^3/\text{kg}) = \mathbf{0.005106\ m^3}$$

(b) The work done during this constant pressure process is



$$\left.\begin{array}{l} P_2 = 200 \text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} v_2 = v_{g@200 \text{ kPa}} = 0.09987 \text{ m}^3/\text{kg} \\ u_2 = u_{g@200 \text{ kPa}} = 224.48 \text{ kJ/kg} \end{array}$$

$$W_{b,\text{out}} = \int_1^2 P\,dV = P(V_2 - V_1) = mP(v_2 - v_1)$$
$$= (0.2 \text{ kg})(200 \text{ kPa})(0.09987 - 0.02553)\text{m}^3/\text{kg}\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right)$$
$$= \mathbf{2.97\ kJ}$$

(c) 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

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

Substituting,

$$Q_{\text{in}} = (0.2 \text{ kg})(224.48 - 84.83)\text{kJ/kg} + 2.97 = \mathbf{30.9\ kJ}$$

5-110 A cylinder is initially filled with helium gas at a specified state. Helium is compressed polytropically to a specified temperature and pressure. The heat transfer during the process is to be determined.

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 = 2.0769 kPa.m^3/kg.K (Table A-1). Also, c_v = 3.1156 kJ/kg.K (Table A-2).

Analysis The mass of helium and the exponent n are determined to be

$$m = \frac{P_1 V_1}{RT_1} = \frac{(150\text{ kPa})(0.5\text{ m}^3)}{(2.0769\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\text{ K})} = 0.123\text{ kg}$$

$$\frac{P_1 V_1}{RT_1} = \frac{P_2 V_2}{RT_2} \longrightarrow V_2 = \frac{T_2 P_1}{T_1 P_2} V_1 = \frac{413\text{ K}}{293\text{ K}} \times \frac{150\text{ kPa}}{400\text{ kPa}} \times 0.5\text{ m}^3 = 0.264\text{ m}^3$$

$$P_2 V_2^n = P_1 V_1^n \longrightarrow \left(\frac{P_2}{P_1}\right) = \left(\frac{V_1}{V_2}\right)^n \longrightarrow \frac{400}{150} = \left(\frac{0.5}{0.264}\right)^n \longrightarrow n = 1.536$$

Then the boundary work for this polytropic process can be determined from

$$W_{\text{b,in}} = -\int_1^2 P\,dV = -\frac{P_2 V_2 - P_1 V_1}{1-n} = -\frac{mR(T_2 - T_1)}{1-n}$$

$$= -\frac{(0.123\text{ kg})(2.0769\text{ kJ/kg}\cdot\text{K})(413-293)\text{K}}{1-1.536} = 57.2\text{ kJ}$$

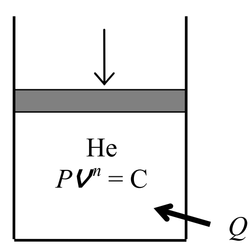
We take the contents of the cylinder as the system. This is a closed system since no mass enters or leaves. Taking the direction of heat transfer to be to the cylinder, the energy balance for this stationary closed system can be expressed as

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

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

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

$$= mc_v(T_2 - T_1) - W_{\text{b,in}}$$



Substituting,

Q_{in} = (0.123 kg)(3.1156 kJ/kg·K)(413 - 293)K - (57.2 kJ) = **-11.2 kJ**

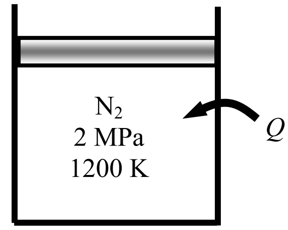
The negative sign indicates that heat is lost from the system.

5-111 Nitrogen gas is expanded in a polytropic process. The work done and the heat transfer are to be determined.

Assumptions **1** Nitrogen is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 126.2 K and 3.39 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats can be used.

Properties The properties of nitrogen are R = 0.2968 kJ/kg·K and c_v = 0.743 kJ/kg·K (Table A-2*a*).

Analysis We take nitrogen in the cylinder as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as



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

$$Q_{in} - W_{b,out} = \Delta U = mc_v(T_2 - T_1)$$

Using the boundary work relation for the polytropic process of an ideal gas gives

$$w_{b,out} = \frac{RT_1}{1-n}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right] = \frac{(0.2968\ \text{kJ/kg}\cdot\text{K})(1200\ \text{K})}{1\text{-}1.35}\left[\left(\frac{120}{2000}\right)^{0.35/1.35} - 1\right] = \mathbf{526.9\ kJ/kg}$$

The temperature at the final state is

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(n\text{-}1)/n} = (1200\ \text{K})\left(\frac{120\ \text{kPa}}{2000\ \text{kPa}}\right)^{0.35/1.35} = 578.6\ \text{K}$$

Substituting into the energy balance equation,

$$q_{in} = w_{b,out} + c_v(T_2 - T_1) = 526.9\ \text{kJ/kg} + (0.743\ \text{kJ/kg}\cdot\text{K})(578.6 - 1200)\text{K} = \mathbf{65.2\ kJ/kg}$$

5-112 The expansion work from P_1 to P_2 in a closed system polytropic process is to be compared for neon and air.

Assumptions The process is quasi-equilibrium.

Properties The gas constants for neon and air are R = 0.4119 and 0.287 kJ/kg·K, respectively (Table A-2*a*).

Analysis For a polytropic process,

$$P\boldsymbol{v}^n = \text{Constant}$$

The boundary work during a polytropic process of an ideal gas is

$$w_{b,out} = \int_1^2 Pd\boldsymbol{v} = \text{Constant}\int_1^2 \boldsymbol{v}^{-n}d\boldsymbol{v} = \frac{P_1\boldsymbol{v}_1}{1-n}\left[\left(\frac{\boldsymbol{v}_2}{\boldsymbol{v}_1}\right)^{1-n} - 1\right] = \frac{RT_1}{1-n}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right]$$

Inspection of this equation reveals that the gas with the largest gas constant (i.e., smallest molecular weight) will produce the greatest amount of work. Hence, the neon gas will produce the greatest amount of work.

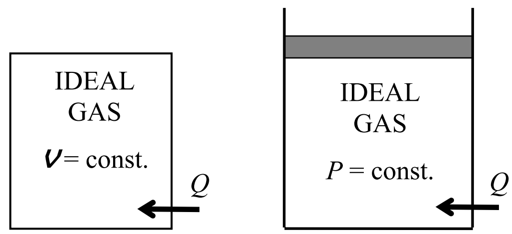
5-113 A cylinder and a rigid tank initially contain the same amount of an ideal gas at the same state. The temperature of both systems is to be raised by the same amount. The amount of extra heat that must be transferred to the cylinder is to be determined.

Analysis In the absence of any work interactions, other than the boundary work, the ΔH and ΔU represent the heat transfer for ideal gases for constant pressure and constant volume processes, respectively. Thus the extra heat that must be supplied to the air maintained at constant pressure is

$$Q_{\text{in, extra}} = \Delta H - \Delta U = mc_p\Delta T - mc_v\Delta T = m(c_p - c_v)\Delta T = mR\Delta T$$

where

$$R = \frac{R_u}{M} = \frac{8.314 \text{ kJ/kmol}\cdot\text{K}}{25 \text{ kg/kmol}} = 0.3326 \text{ kJ/kg}\cdot\text{K}$$



Substituting,

$$Q_{\text{in, extra}} = (12 \text{ kg})(0.3326 \text{ kJ/kg·K})(15 \text{ K}) = \mathbf{59.9 \text{ kJ}}$$

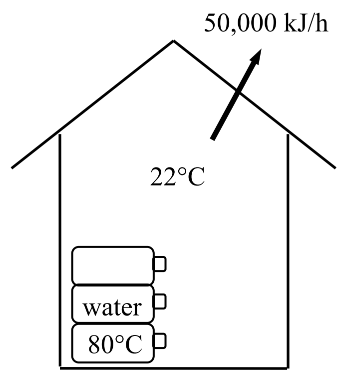
5-114 The heating of a passive solar house at night is to be assisted by solar heated water. The length of time that the electric heating system would run that night with or without solar heating are to be determined.

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 ρ = 1 kg/L and c = 4.18 kJ/kg·°C (Table A-3).

Analysis (a) 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

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

$$W_{\text{e,in}} - Q_{\text{out}} = \Delta U = (\Delta U)_{\text{water}} + (\Delta U)_{\text{air}}$$

$$= (\Delta U)_{\text{water}} = mc(T_2 - T_1)_{\text{water}}$$

or, $\dot{W}_{\text{e,in}}\Delta t - Q_{\text{out}} = [mc(T_2 - T_1)]_{\text{water}}$

Substituting,

(15 kJ/s)Δt - (50,000 kJ/h)(10 h) = (1000 kg)(4.18 kJ/kg·°C)(22 - 80)°C

It gives Δt = 17,170 s = **4.77 h**

(b) If the house incorporated no solar heating, the energy balance relation above would simplify further to

$$\dot{W}_{\text{e,in}}\Delta t - Q_{\text{out}} = 0$$

Substituting,

(15 kJ/s)Δt - (50,000 kJ/h)(10 h) = 0

It gives

Δt = 33,333 s = **9.26 h**

5-115 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 is 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.

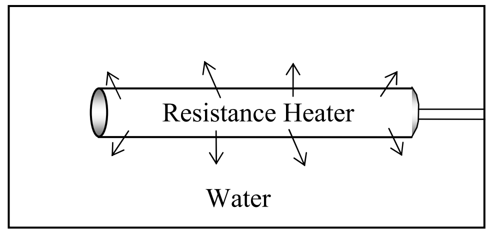
Properties The specific heat of water at room temperature is c = 4.18 kJ/kg·°C (Table A-3).

Analysis Taking the water in the container as the system, the energy balance can be expressed as

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

$$W_{e,in} = (\Delta U)_{water}$$

$$\dot{W}_{e,in}\Delta t = mc(T_2 - T_1)_{water}$$



Substituting,

(1800 J/s)Δt = (40 kg)(4180 J/kg·°C)(80 - 20)°C

Solving for Δt gives

Δt = **5573 s = 92.9 min = 1.55 h**

5-116 One ton of liquid water at 80°C is brought into a room. The final equilibrium temperature in the room is to be determined.

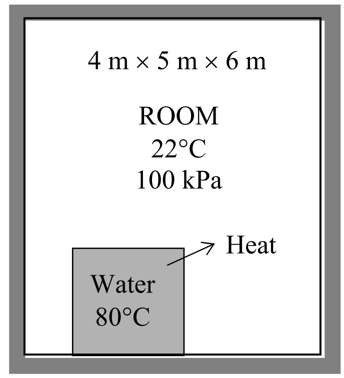
Assumptions **1** The room is well insulated and well sealed. **2** The thermal properties of water and air are constant.

Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1). The specific heat of water at room temperature is c = 4.18 kJ/kg·°C (Table A-3).

Analysis The volume and the mass of the air in the room are

$$V = 4\text{x}5\text{x}6 = 120 \text{ m}^3$$

$$m_{\text{air}} = \frac{P_1 V_1}{RT_1} = \frac{(100 \text{ kPa})(120 \text{ m}^3)}{(0.2870 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(295 \text{ K})} = 141.7 \text{ kg}$$



Taking the contents of the room, including the water, as our system, the energy balance can be written as

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

$$0 = \Delta U = (\Delta U)_{\text{water}} + (\Delta U)_{\text{air}}$$

or

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

Substituting,

$$(1000 \text{ kg})(4.180 \text{ kJ/kg}\cdot^\circ\text{C})(T_f - 80)^\circ\text{C} + (141.7 \text{ kg})(0.718 \text{ kJ/kg}\cdot^\circ\text{C})(T_f - 22)^\circ\text{C} = 0$$

It gives

T_f = **78.6°C**

where T_f is the final equilibrium temperature in the room.

5-117 A room is to be heated by 1 ton of hot water contained in a tank placed in the room. The minimum initial temperature of the water is to be determined if it to meet the heating requirements of this room for a 25-h period.

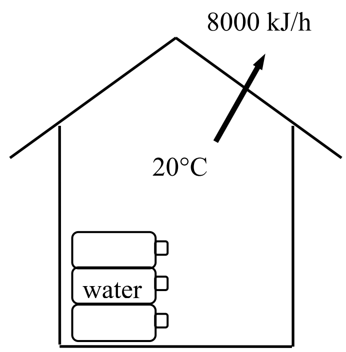
Assumptions **1** Water is an incompressible substance with constant specific heats. **2** Air is an ideal gas with constant specific heats. **3** The energy stored in the container itself is negligible relative to the energy stored in water. **4** The room is maintained at 20°C at all times. **5** The hot water is to meet the heating requirements of this room for a 25-h period.

Properties The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C (Table A-3).

Analysis Heat loss from the room during a 25-h period is

$$Q_{\text{loss}} = (8000 \text{ kJ/h})(24 \text{ h}) = 192{,}000 \text{ kJ}$$

Taking the contents of the room, including the water, as our system, the energy balance can be written as



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

$$-Q_{\text{out}} = \Delta U = (\Delta U)_{\text{water}} + (\Delta U)_{\text{air}}^{\nearrow 0}$$

or

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

Substituting,

$$-192{,}000 \text{ kJ} = (1000 \text{ kg})(4.18 \text{ kJ/kg·°C})(20 - T_1)$$

It gives

$$T_1 = \mathbf{65.9°C}$$

where T_1 is the temperature of the water when it is first brought into the room.

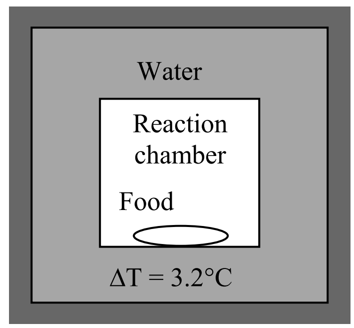
5-118 A sample of a food is burned in a bomb calorimeter, and the water temperature rises by 3.2°C when equilibrium is established. The energy content of the food is to be determined.

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 reaction chamber is negligible relative to the energy stored in water. **4** The energy supplied by the mixer is negligible.

Properties The specific heat of water at room temperature is c = 4.18 kJ/kg·°C (Table A-3). The constant volume specific heat of air at room temperature is c_v = 0.718 kJ/kg·°C (Table A-2).

Analysis The chemical energy released during the combustion of the sample is transferred to the water as heat. Therefore, disregarding the change in the sensible energy of the reaction chamber, the energy content of the food is simply the heat transferred to the water. Taking the water as our system, the energy balance can be written as

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



or

$$Q_{in} = (\Delta U)_{\text{water}} = [mc(T_2 - T_1)]_{\text{water}}$$

Substituting,

$$Q_{\text{in}} = (3\text{ kg})(4.18\text{ kJ/kg·°C})(3.2\text{°C}) = 40.13\text{ kJ}$$

for a 2-g sample. Then the energy content of the food per unit mass is

$$\frac{40.13\text{ kJ}}{2\text{ g}}\left(\frac{1000\text{ g}}{1\text{ kg}}\right) = \mathbf{20{,}060\ \ kJ/kg}$$

To make a rough estimate of the error involved in neglecting the thermal energy stored in the reaction chamber, we treat the entire mass within the chamber as air and determine the change in sensible internal energy:

$$(\Delta U)_{\text{chamber}} = [mc_v(T_2 - T_1)]_{\text{chamber}} = (0.102\text{ kg})(0.718\text{ kJ/kg·}^\circ\text{C})(3.2^\circ\text{C}) = 0.23\text{ kJ}$$

which is less than 1% of the internal energy change of water. Therefore, it is reasonable to disregard the change in the sensible energy content of the reaction chamber in the analysis.

5-119 A man drinks one liter of cold water at 3°C in an effort to cool down. The drop in the average body temperature of the person under the influence of this cold water is to be determined.

Assumptions **1** Thermal properties of the body and water are constant. **2** The effect of metabolic heat generation and the heat loss from the body during that time period are negligible.

Properties The density of water is very nearly 1 kg/L, and the specific heat of water at room temperature is c = 4.18 kJ/kg·°C (Table A-3). The average specific heat of human body is given to be 3.6 kJ/kg.°C.

Analysis. The mass of the water is

$$m_w = \rho \boldsymbol{V} = (1 \text{ kg/L})(1 \text{ L}) = 1 \text{ kg}$$

We take the man and the water as our system, and disregard any heat and mass transfer and chemical reactions. Of course these assumptions may be acceptable only for very short time periods, such as the time it takes to drink the water. Then the energy balance can be written as

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

$$0 = \Delta U = \Delta U_{\text{body}} + \Delta U_{\text{water}}$$

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

Substituting $$(68 \text{ kg})(3.6 \text{ kJ/kg}\cdot^\circ\text{C})(T_f - 39)^\circ\text{C} + (1 \text{ kg})(4.18 \text{ kJ/kg}\cdot^\circ\text{C})(T_f - 3)^\circ\text{C} = 0$$

It gives

T_f = 38.4°C

Then

ΔT=39 – 38.4 = **0.6°C**

Therefore, the average body temperature of this person should drop about half a degree celsius.

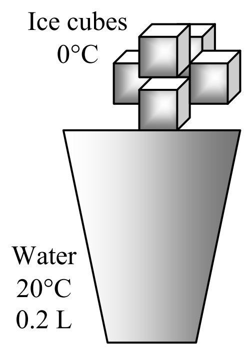
5-120 A 0.2-L glass of water at 20°C is to be cooled with ice to 5°C. The amount of ice or cold water that needs to be added to the water is to be determined.

Assumptions **1** Thermal properties of the ice and water are constant. **2** Heat transfer to the glass is negligible. **3** There is no stirring by hand or a mechanical device (it will add energy).

Properties The density of water is 1 kg/L, and the specific heat of water at room temperature is c = 4.18 kJ/kg·°C (Table A-3). The specific heat of ice at about 0°C is c = 2.11 kJ/kg·°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*) The mass of the water is

$$m_w = \rho V = (1\ \text{kg/L})(0.2\ \text{L}) = 0.2\ \text{kg}$$



We take the ice and the water as our system, and disregard any heat and mass transfer. This is a reasonable assumption since the time period of the process is very short. Then the energy balance can be written as

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

$$0 = \Delta U$$

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

$$[mc(0^\circ\text{C} - T_1)_{\text{solid}} + mh_{if} + mc(T_2 - 0^\circ\text{C})_{\text{liquid}}]_{\text{ice}} + [mc(T_2 - T_1)]_{\text{water}} = 0$$

Noting that $T_{1,\text{ ice}}$ = 0°C and T_2 = 5°C and substituting gives

$$m[0 + 333.7\ \text{kJ/kg} + (4.18\ \text{kJ/kg·°C})(5\text{-}0)\text{°C}] + (0.2\ \text{kg})(4.18\ \text{kJ/kg·°C})(5\text{-}20)\text{°C} = 0$$

$$m = 0.0364\ \text{kg} = \mathbf{36.4\ g}$$

(*b*) When $T_{1,\text{ ice}}$ = -8°C instead of 0°C, substituting gives

$$m[(2.11\ \text{kJ/kg·°C})[0\text{-}(\text{-}8)]\text{°C} + 333.7\ \text{kJ/kg} + (4.18\ \text{kJ/kg·°C})(5\text{-}0)\text{°C}]$$
$$+ (0.2\ \text{kg})(4.18\ \text{kJ/kg·°C})(5\text{-}20)\text{°C} = 0$$

$$m = 0.0347\ \text{kg} = \mathbf{34.7\ g}$$

Cooling with cold water can be handled the same way. All we need to do is replace the terms for ice by a term for cold water at 0°C:

$$(\Delta U)_{\text{cold water}} + (\Delta U)_{\text{water}} = 0$$

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

Substituting,

$$[m_{\text{cold water}}(4.18\ \text{kJ/kg·°C})(5 - 0)\text{°C}] + (0.2\ \text{kg})(4.18\ \text{kJ/kg·°C})(5\text{-}20)\text{°C} = 0$$

It gives

$$m = 0.6\ \text{kg} = \mathbf{600\ g}$$

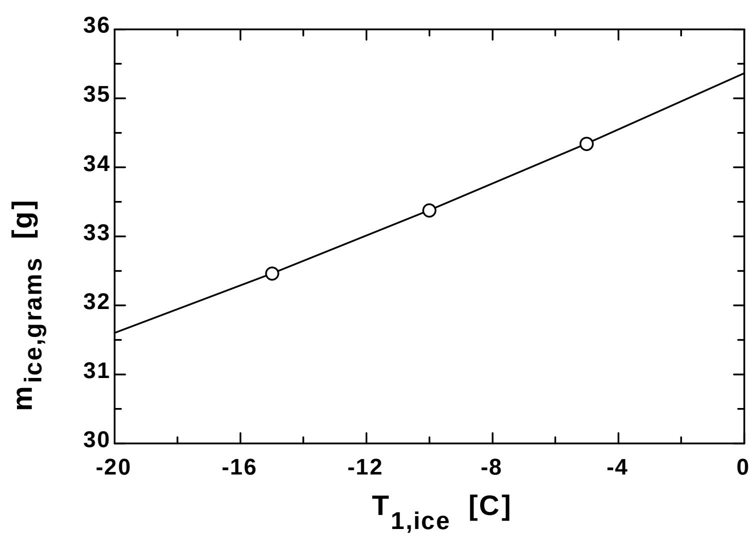
Discussion Note that this is 17 times the amount of ice needed, and it explains why we use ice instead of water to cool drinks. Also, the temperature of ice does not seem to make a significant difference.

5-121 EES Problem 5-120 is reconsidered. The effect of the initial temperature of the ice on the final mass of ice required as the ice temperature varies from -20°C to 0°C is to be investigated. The mass of ice is to be plotted against the initial temperature of ice.

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

```
"Knowns"
rho_water = 1 [kg/L]
V = 0.2 [L]
T_1_ice = 0 [C]
T_1 = 20 [C]
T_2 = 5 [C]
C_ice = 2.11 [kJ/kg-C]
C_water = 4.18 [kJ/kg-C]
h_if = 333.7 [kJ/kg]
T_1_ColdWater = 0 [C]

"The mass of the water is:"
m_water = rho_water*V "[kg]"
"The system is the water plus the ice.  Assume a short time period and neglect
any heat  and mass transfer.  The energy balance becomes:"
E_in - E_out = DELTAE_sys "[kJ]"
E_in = 0 "[kJ]"
E_out = 0"[kJ]"
DELTAE_sys = DELTAU_water+DELTAU_ice"[kJ]"
DELTAU_water = m_water*C_water*(T_2 - T_1)"[kJ]"
DELTAU_ice = DELTAU_solid_ice+DELTAU_melted_ice"[kJ]"
DELTAU_solid_ice =m_ice*C_ice*(0-T_1_ice) + m_ice*h_if"[kJ]"
DELTAU_melted_ice=m_ice*C_water*(T_2 - 0)"[kJ]"
m_ice_grams=m_ice*convert(kg,g)"[g]"
"Cooling with Cold Water:"
DELTAE_sys = DELTAU_water+DELTAU_ColdWater"[kJ]"
DELTAU_water = m_water*C_water*(T_2_ColdWater - T_1)"[kJ]"
DELTAU_ColdWater = m_ColdWater*C_water*(T_2_ColdWater - T_1_ColdWater)"[kJ]"
m_ColdWater_grams=m_ColdWater*convert(kg,g)"[g]"
```

$m_{ice,grams}$ [g]	$T_{1,ice}$ [C]
31.6	-20
32.47	-15
33.38	-10
34.34	-5
35.36	0



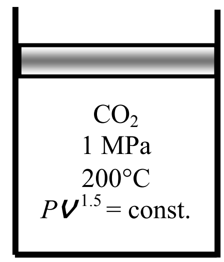
5-122 Carbon dioxide is compressed polytropically in a piston-cylinder device. The final temperature is to be determined treating the carbon dioxide as an ideal gas and a van der Waals gas.

Assumptions The process is quasi-equilibrium.

Properties The gas constant of carbon dioxide is R = 0.1889 kJ/kg·K (Table A-1).

Analysis (a) The initial specific volume is

$$\boldsymbol{v}_1 = \frac{RT_1}{P_1} = \frac{(0.1889\ \text{kJ/kg}\cdot\text{K})(473\ \text{K})}{1000\ \text{kPa}} = 0.08935\ \text{m}^3/\text{kg}$$



From polytropic process expression,

$$\boldsymbol{v}_2 = \boldsymbol{v}_1\left(\frac{P_1}{P_2}\right)^{1/n} = (0.08935\ \text{m}^3/\text{kg})\left(\frac{1000}{3000}\right)^{1/1.5} = 0.04295\ \text{m}^3/\text{kg}$$

The final temperature is then

$$T_2 = \frac{P_2\boldsymbol{v}_2}{R} = \frac{(3000\ \text{kPa})(0.04295\ \text{m}^3/\text{kg})}{0.1889\ \text{kJ/kg}\cdot\text{K}} = \mathbf{682.1 K}$$

(b) The van der Waals equation of state for carbon dioxide is

$$\left(P + \frac{365.8}{\bar{\boldsymbol{v}}^2}\right)(\bar{\boldsymbol{v}} - 0.0428) = R_u T$$

When this is applied to the initial state, the result is

$$\left(1000 + \frac{365.8}{\bar{\boldsymbol{v}}_1^2}\right)(\bar{\boldsymbol{v}}_1 - 0.0428) = (8.314)(473)$$

whose solution by iteration or by EES is

$$\bar{\boldsymbol{v}}_1 = 3.882\ \text{m}^3/\text{kmol}$$

The final molar specific volume is then

$$\bar{\boldsymbol{v}}_2 = \bar{\boldsymbol{v}}_1\left(\frac{P_1}{P_2}\right)^{1/n} = (3.882\ \text{m}^3/\text{kmol})\left(\frac{1000}{3000}\right)^{1/1.5} = 1.866\ \text{m}^3/\text{kmol}$$

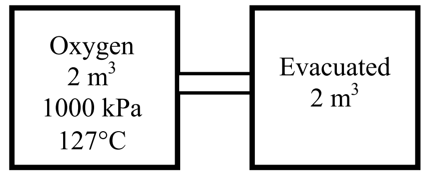
Substitution of the final molar specific volume into the van der Waals equation of state produces

$$T_2 = \frac{1}{R_u}\left(P + \frac{365.8}{\bar{\boldsymbol{v}}^2}\right)(\bar{\boldsymbol{v}} - 0.0428) = \frac{1}{8.314}\left(3000 + \frac{365.8}{(1.866)^2}\right)(1.866 - 0.0428) = \mathbf{680.9\ K}$$

5-123 Two adiabatic chambers are connected by a valve. One chamber contains oxygen while the other one is evacuated. The valve is now opened until the oxygen fills both chambers and both tanks have the same pressure. The total internal energy change and the final pressure in the tanks are to be determined.

Assumptions **1** Oxygen is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 154.8 K and 5.08 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta\text{ke} \cong \Delta\text{pe} \cong 0$. **3** Constant specific heats at room temperature can be used. **4** Both chambers are insulated and thus heat transfer is negligible.

Analysis We take both chambers as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as



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

$$\mathbf{0} = \Delta U = mc_v(T_2 - T_1)$$

Since the internal energy does not change, the temperature of the air will also not change. Applying the ideal gas equation gives

$$P_1 V_1 = P_2 V_2 \longrightarrow P_2 = P_1 \frac{V_1}{V_2} = (1000\text{ kPa})\frac{2\text{ m}^3}{4\text{ m}^3} = \mathbf{500\ kPa}$$

5-124 … 5-129 Design and Essay Problems

5-128 A claim that fruits and vegetables are cooled by 6°C for each percentage point of weight loss as moisture during vacuum cooling is to be evaluated.

Analysis Assuming the fruits and vegetables are cooled from 30ºC and 0ºC, the average heat of vaporization can be taken to be 2466 kJ/kg, which is the value at 15ºC, and the specific heat of products can be taken to be 4 kJ/kg.ºC. Then the vaporization of 0.01 kg water will lower the temperature of 1 kg of produce by 24.66/4 = 6ºC. Therefore, the vacuum cooled products will lose 1 percent moisture for each 6ºC drop in temperature. Thus the claim is **reasonable**.