Chapter 4
ENERGY ANALYSIS OF CLOSED SYSTEMS

Moving Boundary Work

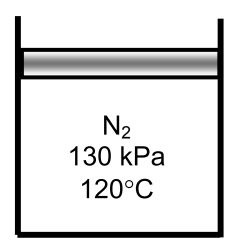
4-1C It represents the boundary work for quasi-equilibrium processes.

4-2C Yes.

4-3C The area under the process curve, and thus the boundary work done, is greater in the constant pressure case.

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

4-5 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

$$m = \frac{P_1 V_1}{RT_1} = \frac{(130\ \text{kPa})(0.07\ \text{m}^3)}{(0.2968\ \text{kJ/kg.K})(120+273\ \text{K})} = 0.07802\ \text{kg}$$

$$V_2 = \frac{mRT_2}{P_2} = \frac{(0.07802\ \text{kg})(0.2968\ \text{kPa.m}^3/\text{kg.K})(100+273\ \text{K})}{100\ \text{kPa}} = 0.08637\ \text{m}^3$$

The polytropic index is determined from

$$P_1 V_1^n = P_2 V_2^n \longrightarrow (130\ \text{kPa})(0.07\ \text{m}^3)^n = (100\ \text{kPa})(0.08637\ \text{m}^3)^n \longrightarrow n = 1.249$$

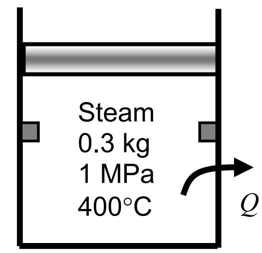
The boundary work is determined from

$$W_b = \frac{P_2 V_2 - P_1 V_1}{1-n} = \frac{(100\ \text{kPa})(0.08637\ \text{m}^3) - (130\ \text{kPa})(0.07\ \text{m}^3)}{1-1.249} = \mathbf{1.86\ kJ}$$

4-6 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

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

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

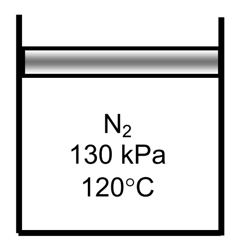
$$W_b = mP(\boldsymbol{v}_1 - 0.60\boldsymbol{v}_1) = (0.3\text{ kg})(1000\text{ kPa})(0.30661 - 0.60 \times 0.30661)\text{m}^3/\text{kg} = \mathbf{36.79\text{ kJ}}$$

The temperature at the final state is

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

4-7 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

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

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

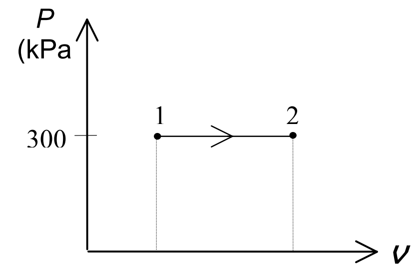
4-8 Saturated water vapor in a cylinder is heated at constant pressure until its temperature rises to a specified value. The boundary work done during this process is to be determined.

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)

$$\left.\begin{array}{l} P_1 = 300 \text{ kPa} \\ \text{Sat. vapor} \end{array}\right\} v_1 = v_{g@300 \text{ kPa}} = 0.60582 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_2 = 300 \text{ kPa} \\ T_2 = 200°\text{C} \end{array}\right\} v_2 = 0.71643 \text{ m}^3/\text{kg}$$



Analysis The boundary work is determined from its definition to be

$$W_{b,\text{out}} = \int_1^2 P\,d\mathbf{V} = P(\mathbf{V}_2 - \mathbf{V}_1) = mP(v_2 - v_1)$$

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

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

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

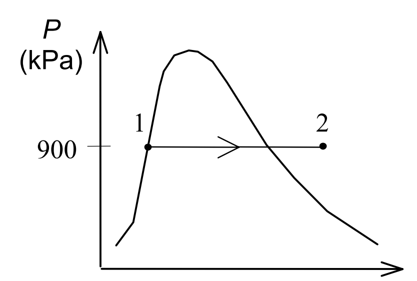
4-9 Refrigerant-134a in a cylinder is heated at constant pressure until its temperature rises to a specified value. The boundary work done during this process is to be determined.

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)

$$\left.\begin{array}{l} P_1 = 900 \text{ kPa} \\ \text{Sat. liquid} \end{array}\right\} v_1 = v_{f@900 \text{ kPa}} = 0.0008580 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_2 = 900 \text{ kPa} \\ T_2 = 70°\text{C} \end{array}\right\} v_2 = 0.027413 \text{ m}^3/\text{kg}$$



Analysis The boundary work is determined from its definition to be

$$m = \frac{\mathbf{V}_1}{v_1} = \frac{0.2 \text{ m}^3}{0.0008580 \text{ m}^3/\text{kg}} = 233.1 \text{ kg}$$

and

$$W_{b,\text{out}} = \int_1^2 P\,d\mathbf{V} = P(\mathbf{V}_2 - \mathbf{V}_1) = mP(v_2 - v_1)$$

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

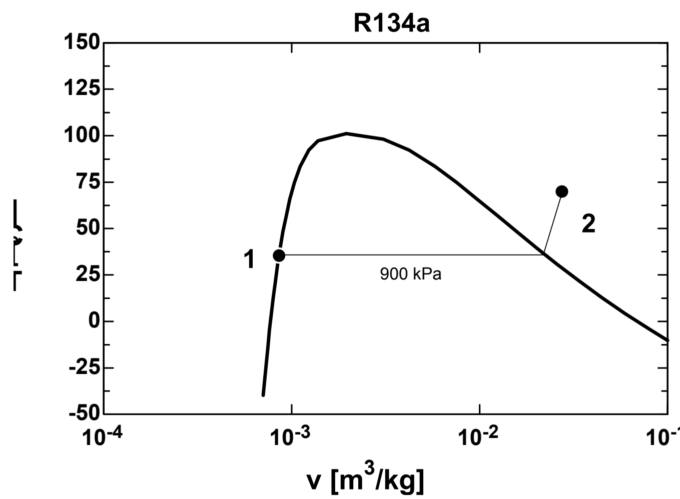
$$= \mathbf{5571\ kJ}$$

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

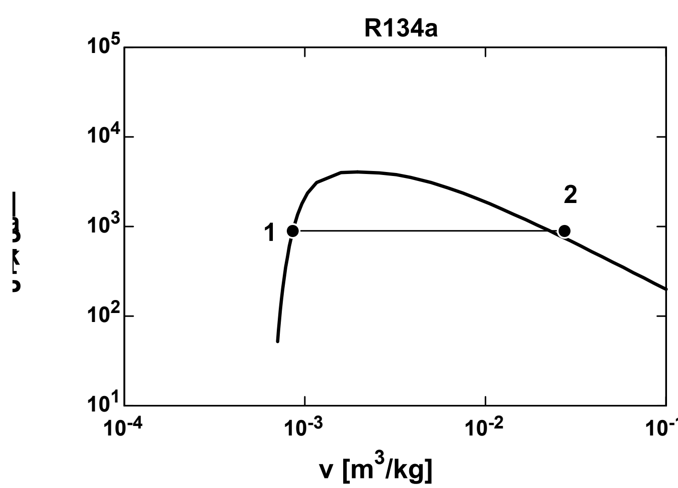
4-10 EES Problem 4-9 is reconsidered. The effect of pressure on the work done as the pressure varies from 400 kPa to 1200 kPa is to be investigated. The work done is to be plotted versus the pressure.

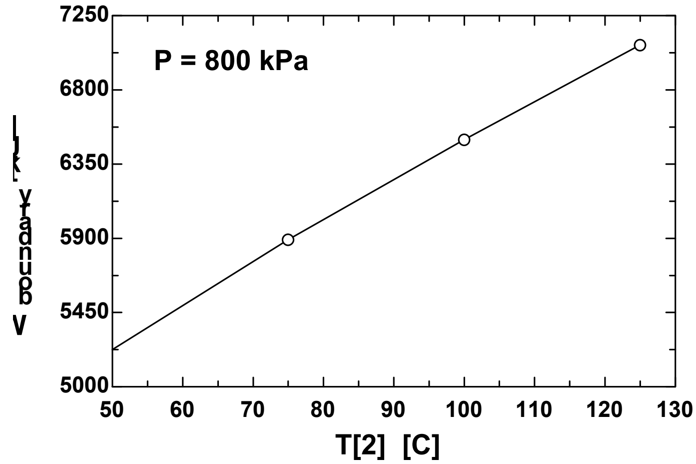
Analysis The problem is solved using EES, and the solution is given below.

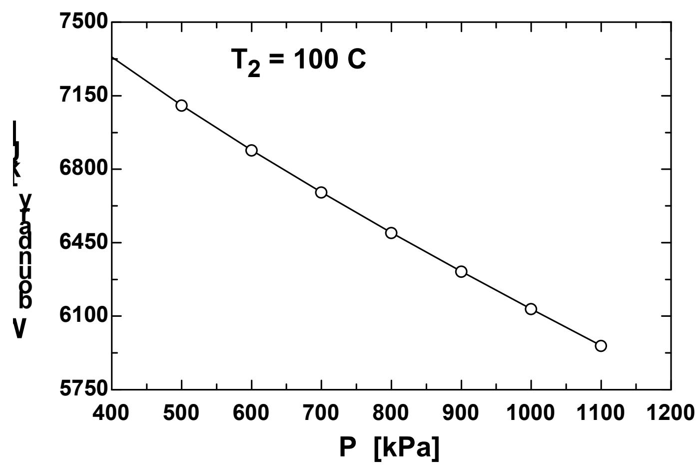
```
"Knowns"
Vol_1L=200 [L]
x_1=0 "saturated liquid state"
P=900 [kPa]
T_2=70 [C]

"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
```

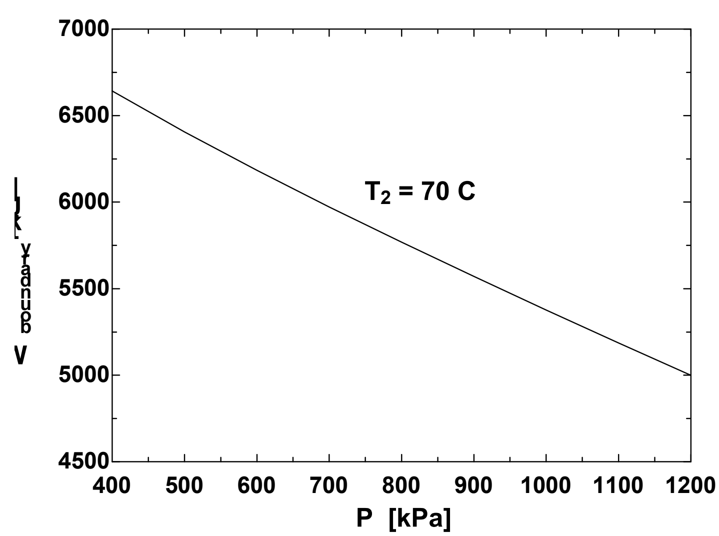


P [kPa]	$W_{boundary}$ [kJ]
400	6643
500	6405
600	6183
700	5972
800	5769
900	5571
1000	5377
1100	5187
1200	4999




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


T_2 = 100 C
7500
7150
6800
6450
6100
5750
400
500
600
700
800
900
1000
1100
1200
P [kPa]


T_2 = 70 C
7000
6500
6000
5500
5000
4500
400
500
600
700
800
900
1000
1100
1200
P [kPa]

4-11E 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.

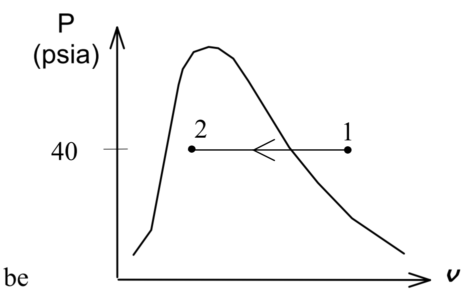
Properties Noting that the pressure remains constant during this process, the specific volumes at the initial and the final states are (Table A-4E through A-6E)

$$\left.\begin{array}{l} P_1 = 40 \text{ psia} \\ T_1 = 600°\text{F} \end{array}\right\} v_1 = 15.686 \text{ ft}^3/\text{lbm}$$

$$\left.\begin{array}{l} P_2 = 40 \text{ psia} \\ x_2 = 0.3 \end{array}\right\} v_2 = v_f + x_2 v_{fg}$$

$$= 0.01715 + 0.3(10.501 - 0.01715)$$

$$= 3.1623 \text{ ft}^3/\text{lbm}$$



Analysis The boundary work is determined from its definition to be

$$W_{b,\text{out}} = \int_1^2 P\,dV = P(V_2 - V_1) = mP(v_2 - v_1)$$

$$= (16 \text{ lbm})(40 \text{ psia})(3.1623 - 15.686)\text{ft}^3/\text{lbm}\left(\frac{1 \text{ Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right)$$

$$= \mathbf{-1483\ Btu}$$

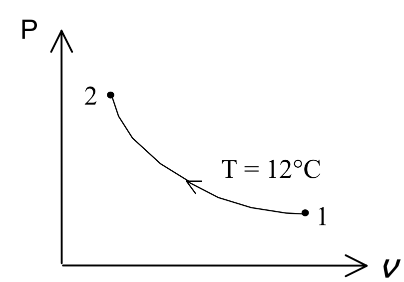
Discussion The negative sign indicates that work is done on the system (work input).

4-12 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



$$W_{b,\text{out}} = \int_1^2 P\,dV = P_1V_1 \ln\frac{V_2}{V_1} = mRT\ln\frac{P_1}{P_2}$$

$$= (2.4 \text{ kg})(0.287 \text{ kJ/kg}\cdot\text{K})(285 \text{ K})\ln\frac{150 \text{ kPa}}{600 \text{ kPa}}$$

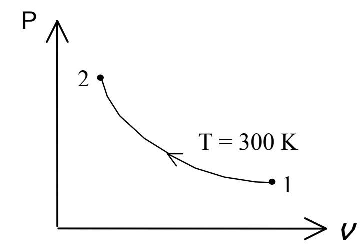
$$= \mathbf{-272\ \ kJ}$$

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

4-13 Nitrogen gas 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** Nitrogen is an ideal gas.

Analysis The boundary work is determined from its definition to be



$$W_{b,\text{out}} = \int_1^2 P\,dV = P_1V_1 \ln\frac{V_2}{V_1} = P_1V_1 \ln\frac{P_1}{P_2}$$

$$= (150\text{ kPa})(0.2\text{ m}^3)\left(\ln\frac{150\text{ kPa}}{800\text{ kPa}}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

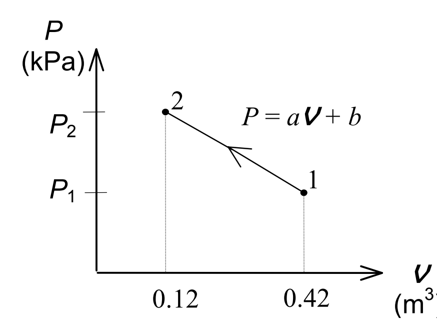
$$= \mathbf{-50.2\ kJ}$$

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

4-14 A gas in a cylinder is compressed to a specified volume in a process during which the pressure changes linearly with volume. The boundary work done during this process is to be determined by plotting the process on a P-V diagram and also by integration.

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,



$$P_1 = aV_1 + b = (-1200\text{ kPa/m}^3)(0.42\text{ m}^3) + (600\text{ kPa}) = 96\text{ kPa}$$

$$P_2 = aV_2 + b = (-1200\text{ kPa/m}^3)(0.12\text{ m}^3) + (600\text{ kPa}) = 456\text{ kPa}$$

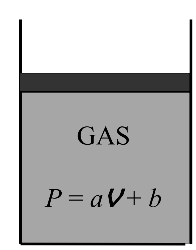
and

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1)$$

$$= \frac{(96+456)\text{kPa}}{2}(0.12-0.42)\text{m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{-82.8\ kJ}$$

(*b*) The boundary work can also be determined by integration to be



$$W_{b,\text{out}} = \int_1^2 P\,dV = \int_1^2 (aV + b)\,dV = a\frac{V_2^2 - V_1^2}{2} + b(V_2 - V_1)$$

$$= (-1200\text{ kPa/m}^3)\frac{(0.12^2 - 0.42^2)\text{m}^6}{2} + (600\text{ kPa})(0.12-0.42)\text{m}^3$$

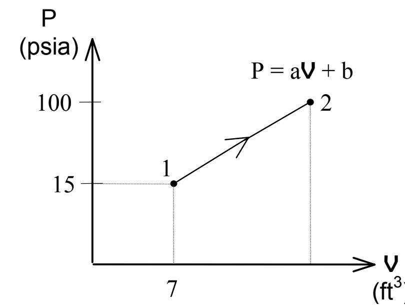
$$= \mathbf{-82.8\ kJ}$$

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

4-15E 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:

$$P_1 = a\mathbf{V}_1 + b$$
$$15 \text{ psia} = (5 \text{ psia/ft}^3)(7 \text{ ft}^3) + b$$
$$b = -20 \text{ psia}$$

At state 2:

$$P_2 = a\mathbf{V}_2 + b$$
$$100 \text{ psia} = (5 \text{ psia/ft}^3)\mathbf{V}_2 + (-20 \text{ psia})$$
$$\mathbf{V}_2 = 24 \text{ ft}^3$$

and,

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2}(\mathbf{V}_2 - \mathbf{V}_1) = \frac{(100+15)\text{psia}}{2}(24-7)\text{ft}^3\left(\frac{1 \text{ Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right)$$
$$= \mathbf{181\ \ Btu}$$

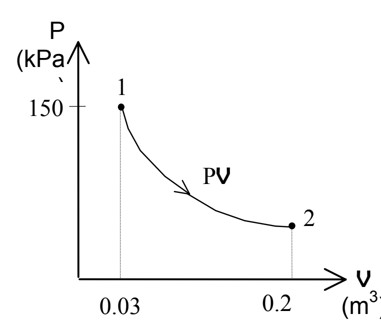
Discussion The positive sign indicates that work is done by the system (work output).

4-16 [*Also solved by EES on enclosed CD*] 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

$$P_2 = P_1\left(\frac{\mathbf{V}_1}{\mathbf{V}_2}\right)^n = (150 \text{ kPa})\left(\frac{0.03 \text{ m}^3}{0.2 \text{ m}^3}\right)^{1.3} = 12.74 \text{ kPa}$$



and,

$$W_{b,\text{out}} = \int_1^2 P\,d\mathbf{V} = \frac{P_2\mathbf{V}_2 - P_1\mathbf{V}_1}{1-n}$$
$$= \frac{(12.74\times 0.2 - 150\times 0.03)\text{ kPa}\cdot\text{m}^3}{1-1.3}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$
$$= \mathbf{6.51\ \ kJ}$$

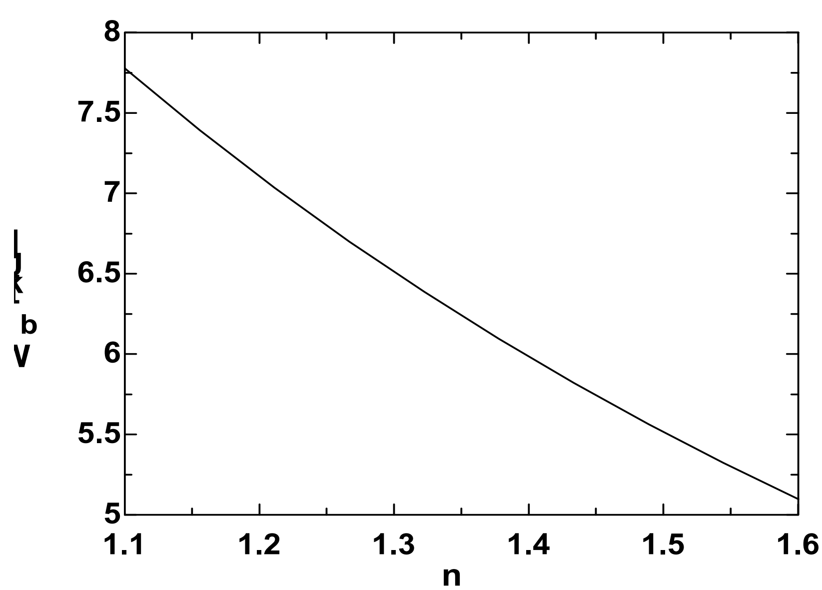
Discussion The positive sign indicates that work is done by the system (work output).

4-17 EES Problem 4-16 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



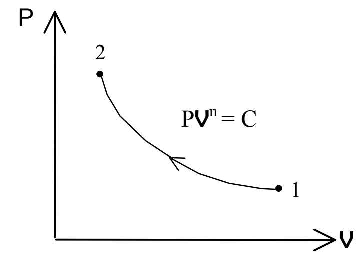
4-18 Nitrogen gas in a cylinder is compressed polytropically until the temperature rises to a specified value. The boundary work done during this process is to be determined.

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).

4-19 [*Also solved by EES on enclosed CD*] 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.

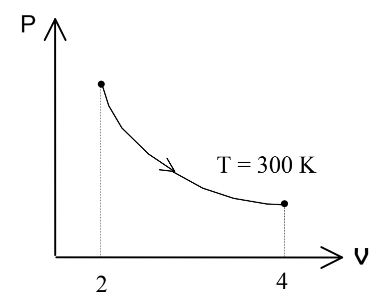
Assumptions The process is quasi-equilibrium.

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

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

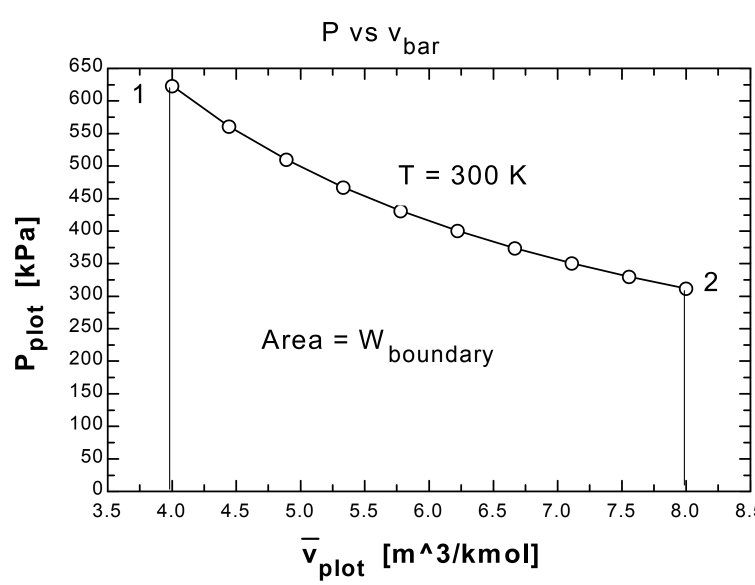
Discussion The positive sign indicates that work is done by the system (work output).

4-20 EES Problem 4-19 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."
```

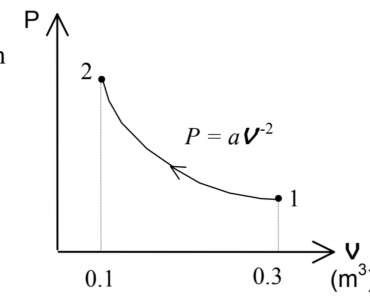
P_{plot}	v_{plot}
622.9	4
560.7	4.444
509.8	4.889
467.3	5.333
431.4	5.778
400.6	6.222
373.9	6.667
350.5	7.111
329.9	7.556
311.6	8



4-21 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



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

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

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

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

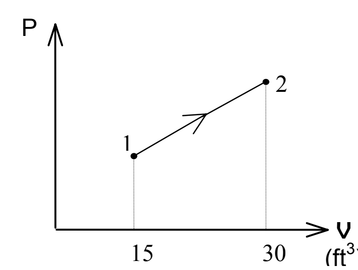
4-22E Hydrogen gas in a cylinder equipped with a spring is heated. The gas expands and compresses the spring until its volume doubles. The final pressure, the boundary work done by the gas, and the work done against the spring are to be determined, and a *P*-$\boldsymbol{V}$ diagram is to be drawn.

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

Analysis (*a*) When the volume doubles, the spring force and the final pressure of H_2 becomes

$$F_s = kx_2 = k\frac{\Delta\boldsymbol{V}}{A} = (15{,}000\text{ lbf/ft})\frac{15\text{ ft}^3}{3\text{ ft}^2} = 75{,}000\text{ lbf}$$

$$P_2 = P_1 + \frac{F_s}{A} = (14.7\text{ psia}) + \frac{75{,}000\text{ lbf}}{3\text{ ft}^2}\left(\frac{1\text{ ft}^2}{144\text{ in}^2}\right) = \mathbf{188.3\ psia}$$



(*b*) The pressure of H_2 changes linearly with volume during this process, and thus the process curve on a *P*-$\boldsymbol{V}$ diagram will be a straight line. Then the boundary work during this process is simply the area under the process curve, which is a trapezoid. Thus,

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2}(\boldsymbol{V}_2 - \boldsymbol{V}_1)$$

$$= \frac{(188.3 + 14.7)\text{psia}}{2}(30 - 15)\text{ft}^3\left(\frac{1\text{ Btu}}{5.40395\text{ psia}\cdot\text{ft}^3}\right) = \mathbf{281.7\ \ Btu}$$

(*c*) If there were no spring, we would have a constant pressure process at P = 14.7 psia. The work done during this process would be

$$W_{b,\text{out,no spring}} = \int_1^2 P\,d\boldsymbol{V} = P(\boldsymbol{V}_2 - \boldsymbol{V}_1)$$

$$= (14.7\text{ psia})(30 - 15)\text{ ft}^3\left(\frac{1\text{ Btu}}{5.40395\text{ psia}\cdot\text{ft}^3}\right) = 40.8\ \text{ Btu}$$

Thus,

$$W_{\text{spring}} = W_b - W_{b,\text{no spring}} = 281.7 - 40.8 = \mathbf{240.9\ Btu}$$

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

4-23 Water in a cylinder equipped with a spring is heated and evaporated. The vapor expands until it compresses the spring 20 cm. The final pressure and temperature, and the boundary work done are to be determined, and the process is to be shown on a P-V diagram.

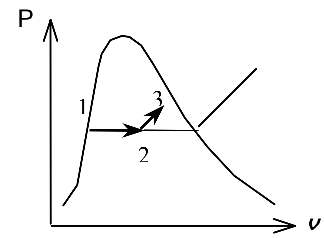
Assumptions The process is quasi-equilibrium.

Analysis (a) The final pressure is determined from

$$P_3 = P_2 + \frac{F_s}{A} = P_2 + \frac{kx}{A} = (250\text{ kPa}) + \frac{(100\text{ kN/m})(0.2\text{ m})}{0.1\text{ m}^2}\left(\frac{1\text{ kPa}}{1\text{ kN/m}^2}\right) = \textbf{450 kPa}$$

The specific and total volumes at the three states are

$$\left.\begin{array}{l} T_1 = 25°\text{C} \\ P_1 = 250\text{ kPa} \end{array}\right\} v_1 \cong v_{f\,@\,25°\text{C}} = 0.001003\text{ m}^3\text{/kg}$$



$$V_1 = m v_1 = (50\text{ kg})(0.001003\text{ m}^3\text{/kg}) = 0.05\text{ m}^3$$

$$V_2 = 0.2\text{ m}^3$$

$$V_3 = V_2 + x_{23}A_p = (0.2\text{ m}^3) + (0.2\text{ m})(0.1\text{ m}^2) = 0.22\text{ m}^3$$

$$v_3 = \frac{V_3}{m} = \frac{0.22\text{ m}^3}{50\text{ kg}} = 0.0044\text{ m}^3\text{/kg}$$

At 450 kPa, $v_f = 0.001088\text{ m}^3\text{/kg}$ and $v_g = 0.41392\text{ m}^3\text{/kg}$. Noting that $v_f < v_3 < v_g$, the final state is a saturated mixture and thus the final temperature is

$$T_3 = T_{\text{sat@450 kPa}} = \textbf{147.9°C}$$

(b) The pressure remains constant during process 1-2 and changes linearly (a straight line) during process 2-3. Then the boundary work during this process is simply the total area under the process curve,

$$W_{b,\text{out}} = \text{Area} = P_1(V_2 - V_1) + \frac{P_2 + P_3}{2}(V_3 - V_2)$$

$$= \left((250\text{ kPa})(0.2 - 0.05)\text{m}^3 + \frac{(250 + 450)\text{ kPa}}{2}(0.22 - 0.2)\text{m}^3\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

$$= \textbf{44.5 kJ}$$

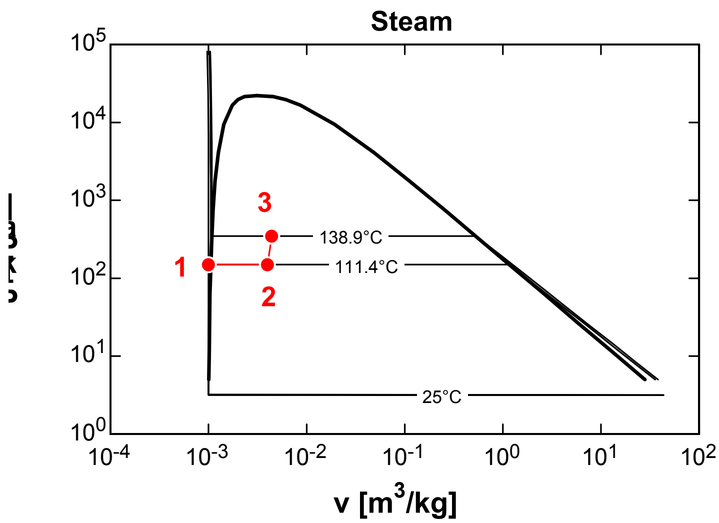
Discussion The positive sign indicates that work is done by the system (work output).

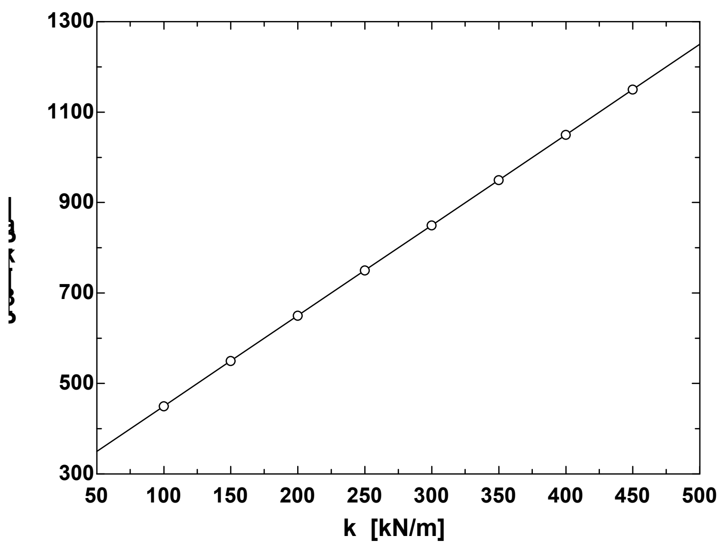
4-24 EES Problem 4-23 is reconsidered. The effect of the spring constant on the final pressure in the cylinder and the boundary work done as the spring constant varies from 50 kN/m to 500 kN/m is to be investigated. The final pressure and the boundary work are to be plotted against the spring constant.

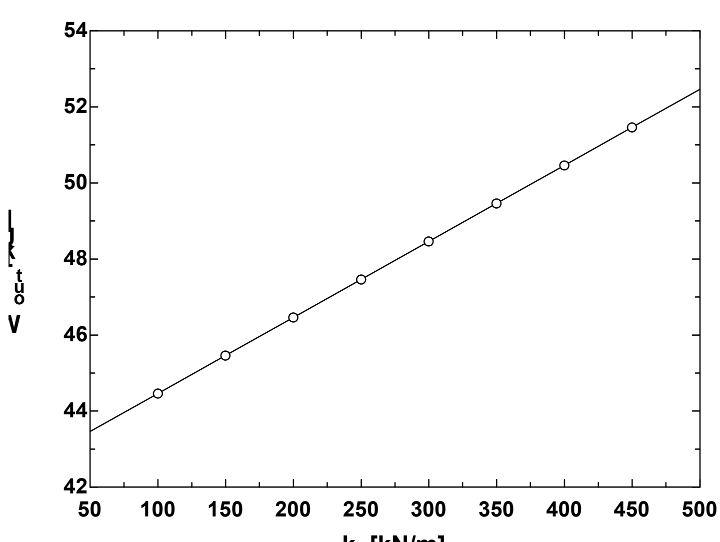
Analysis The problem is solved using EES, and the solution is given below.

```
P[3]=P[2]+(Spring_const)*(V[3] - V[2]) "P[3] is a linear function of V[3]"
"where Spring_const = k/A^2, the actual spring constant divided by the piston face area squared"

"Input Data"
P[1]=150 [kPa]
m=50 [kg]
T[1]=25 [C]
P[2]=P[1]
V[2]=0.2 [m^3]
A=0.1[m^2]
k=100 [kN/m]
DELTAx=20 [cm]
Spring_const=k/A^2 "[kN/m^5]"
V[1]=m*spvol[1]
spvol[1]=volume(Steam_iapws,P=P[1],T=T[1])

V[2]=m*spvol[2]
V[3]=V[2]+A*DELTAx*convert(cm,m)
V[3]=m*spvol[3]

"The temperature at state 2 is:"
T[2]=temperature(Steam_iapws,P=P[2],v=spvol[2])
"The temperature at state 3 is:"
T[3]=temperature(Steam_iapws,P=P[3],v=spvol[3])

Wnet_other = 0
W_out=Wnet_other + W_b12+W_b23
W_b12=P[1]*(V[2]-V[1])
"W_b23 = integral of P[3]*dV[3] for Deltax = 20 cm and is given by:"
 W_b23=P[2]*(V[3]-V[2])+Spring_const/2*(V[3]-V[2])^2
```

k [kN/m]	P_3 [kPa]	W_{out} [kJ]
50	350	43.46
100	450	44.46
150	550	45.46
200	650	46.46
250	750	47.46
300	850	48.46
350	950	49.46
400	1050	50.46
450	1150	51.46
500	1250	52.46


Steam
1
2
3
138.9°C
111.4°C
25°C
v [m3/kg]


k [kN/m]


k [kN/m]

4-25 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.

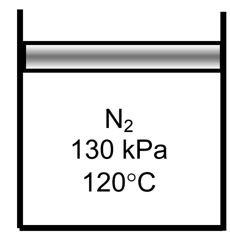
Assumptions The process is quasi-equilibrium.

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

4-26 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



$$V_1 = \frac{mRT}{P_1} = \frac{(0.25\text{ kg})(0.2968\text{ kJ/kg.K})(120+273\text{ K})}{(130\text{ kPa})} = 0.2243\text{ m}^3$$

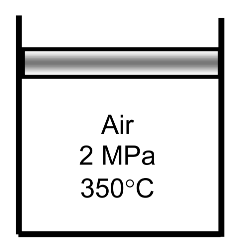
$$V_2 = \frac{mRT}{P_2} = \frac{(0.25\text{ kg})(0.2968\text{ kJ/kg.K})(120+273\text{ K})}{(100\text{ kPa})} = 0.2916\text{ m}^3$$

$$W_b = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = (130\text{ kPa})(0.2243\text{ m}^3)\ln\left(\frac{0.2916\text{ m}^3}{0.2243\text{ m}^3}\right) = \mathbf{7.65\ kJ}$$

4-27 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:



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

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

$$W_{b,1-2} = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = (2000\text{ kPa})(0.01341\text{ m}^3)\ln\left(\frac{0.05364\text{ m}^3}{0.01341\text{ m}^3}\right) = \mathbf{37.18\ kJ}$$

For the polytropic compression process:

$$P_2 V_2^n = P_3 V_3^n \longrightarrow (500\text{ kPa})(0.05364\text{ m}^3)^{1.2} = (2000\text{ kPa})V_3^{1.2} \longrightarrow V_3 = 0.01690\text{ m}^3$$

$$W_{b,2-3} = \frac{P_3 V_3 - P_2 V_2}{1-n} = \frac{(2000\text{ kPa})(0.01690\text{ m}^3) - (500\text{ kPa})(0.05364\text{ m}^3)}{1-1.2} = \mathbf{-34.86\ kJ}$$

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

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

Closed System Energy Analysis

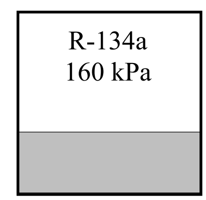
4-28 A rigid tank is initially filled with superheated R-134a. Heat is transferred to the tank until the pressure inside rises to a specified value. The mass of the refrigerant and the amount of heat transfer are to be determined, and the process is to be shown on a P-v diagram.

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

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

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

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



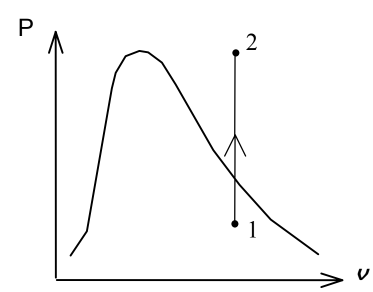
Using data from the refrigerant tables (Tables A-11 through A-13), the properties of R-134a are determined to be

$$\left.\begin{array}{l} P_1 = 160 \text{ kPa} \\ x_1 = 0.4 \end{array}\right\} \begin{array}{ll} v_f = 0.0007437, & v_g = 0.12348 \text{ m}^3/\text{kg} \\ u_f = 31.09, & u_{fg} = 190.27 \text{kJ/kg} \end{array}$$

$$v_1 = v_f + x_1 v_{fg} = 0.0007437 + 0.4(0.12348 - 0.0007437) = 0.04984 \text{ m}^3/\text{kg}$$

$$u_1 = u_f + x_1 u_{fg} = 31.09 + 0.4(190.27) = 107.19 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 700 \text{ kPa} \\ (v_2 = v_1) \end{array}\right\} u_2 = 376.99 \text{ kJ/kg (Superheated vapor)}$$



Then the mass of the refrigerant is determined to be

$$m = \frac{V_1}{v_1} = \frac{0.5 \text{ m}^3}{0.04984 \text{ m}^3/\text{kg}} = \mathbf{10.03 \text{ kg}}$$

(b) Then the heat transfer to the tank becomes

$$\begin{aligned} Q_{in} &= m(u_2 - u_1) \\ &= (10.03 \text{ kg})(376.99 - 107.19) \text{ kJ/kg} \\ &= \mathbf{2707 \text{ kJ}} \end{aligned}$$

4-29E A rigid tank is initially filled with saturated R-134a vapor. Heat is transferred from the refrigerant until the pressure inside drops to a specified value. The final temperature, the mass of the refrigerant that has condensed, and the amount of heat transfer are to be determined. Also, 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** There are no work interactions.

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

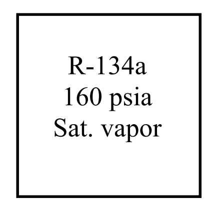
$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

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

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

Using data from the refrigerant tables (Tables A-11E through A-13E), the properties of R-134a are determined to be

$$\left.\begin{array}{l} P_1 = 160 \text{ psia} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} v_1 = v_{g@160 \text{ psia}} = 0.29316 \text{ ft}^3/\text{lbm} \\ u_1 = u_{g@160 \text{ psia}} = 108.50 \text{ Btu/lbm} \end{array}$$



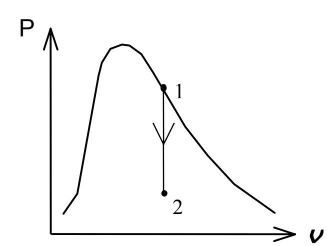
$$\left.\begin{array}{l} P_2 = 50 \text{ psia} \\ (v_2 = v_1) \end{array}\right\} \begin{array}{l} v_f = 0.01252, \quad v_g = 0.94791 \text{ ft}^3/\text{lbm} \\ u_f = 24.832, \quad u_{fg} = 75.209 \text{ Btu/lbm} \end{array}$$

The final state is saturated mixture. Thus,

$$T_2 = T_{sat @ 50 \text{ psia}} = \mathbf{40.23°F}$$

(b) The total mass and the amount of refrigerant that has condensed are

$$m = \frac{V_1}{v_1} = \frac{20 \text{ ft}^3}{0.29316 \text{ ft}^3/\text{lbm}} = 68.22 \text{ lbm}$$



$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.29316 - 0.01252}{0.94791 - 0.01252} = 0.300$$

$$m_f = (1 - x_2)m = (1 - 0.300)(68.22 \text{ lbm}) = \mathbf{47.75\ lbm}$$

Also,

$$u_2 = u_f + x_2 u_{fg} = 24.832 + 0.300(75.209) = 47.40 \text{ Btu/lbm}$$

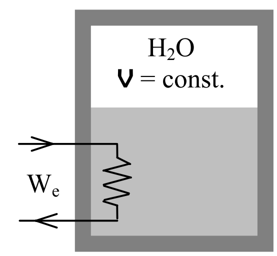
(c) Substituting,

$$\begin{aligned} Q_{out} &= m(u_1 - u_2) \\ &= (68.22 \text{ lbm})(108.50 - 47.40) \text{ Btu/lbm} \\ &= \mathbf{4169\ Btu} \end{aligned}$$

4-30 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



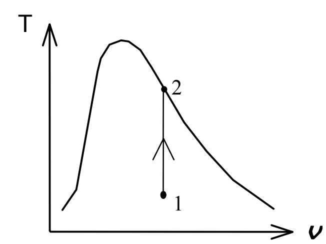
$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

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

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

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

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



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

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

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

Substituting,

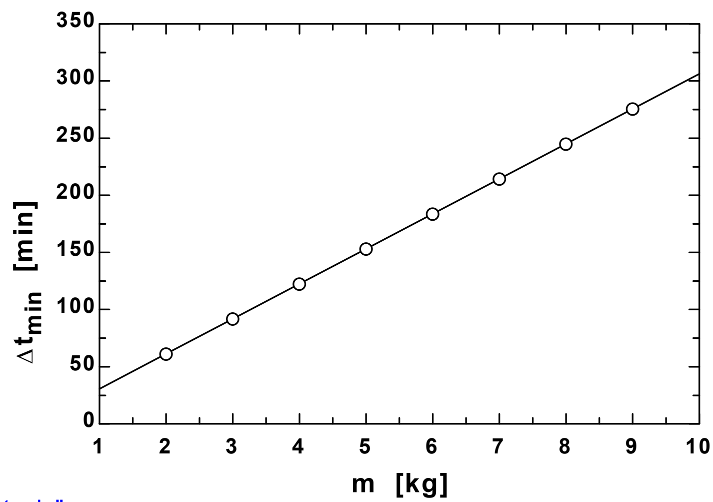
$$(110 \text{ V})(8 \text{ A})\Delta t = (5 \text{ kg})(2556.2 - 939.4)\text{kJ/kg}\left(\frac{1000 \text{ VA}}{1 \text{ kJ/s}}\right)$$

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

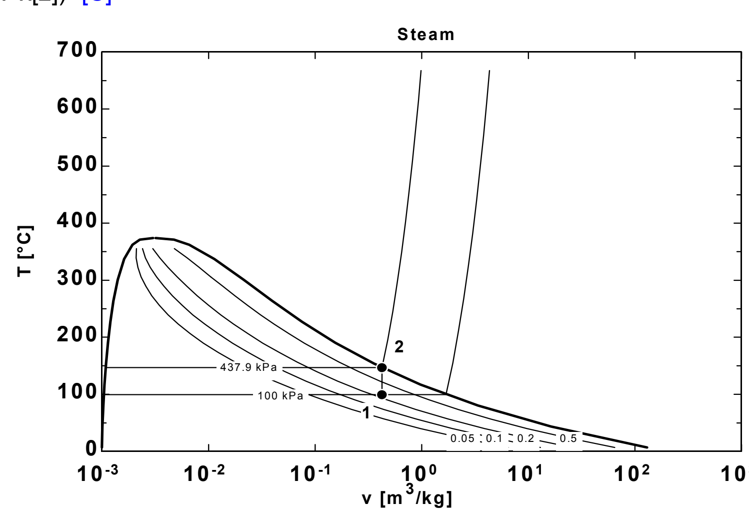
4-31 EES Problem 4-30 is reconsidered. The effect of the initial mass of water on the length of time required to completely vaporize the liquid as the initial mass varies from 1 kg to 10 kg is to be investigated. The vaporization time is to be plotted against the initial mass.

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



4-32 One part of an insulated tank contains compressed liquid while the other side is evacuated. The partition is then removed, and water is allowed to expand into the entire tank. The final temperature and the volume of the tank are to be determined.

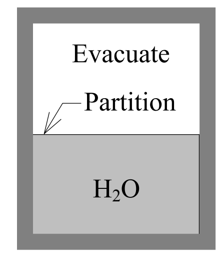
Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** The tank is insulated and thus heat transfer is negligible. **3** There are no work interactions.

Analysis We take the entire 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

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

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

$$u_1 = u_2$$



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

$$\left.\begin{array}{l} P_1 = 600 \text{ kPa} \\ T_1 = 60°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 \cong \boldsymbol{v}_{f@60°\text{C}} = 0.001017 \text{ m}^3/\text{kg} \\ u_1 \cong u_{f@60°\text{C}} = 251.16 \text{ kJ/kg} \end{array}$$

We now assume the final state in the tank is saturated liquid-vapor mixture and determine quality. This assumption will be verified if we get a quality between 0 and 1.

$$\left.\begin{array}{l} P_2 = 10 \text{ kPa} \\ (u_2 = u_1) \end{array}\right\} \begin{array}{l} \boldsymbol{v}_f = 0.001010, \quad \boldsymbol{v}_g = 14.670 \text{ m}^3/\text{kg} \\ u_f = 191.79, \quad u_{fg} = 2245.4 \text{ kJ/kg} \end{array}$$

$$x_2 = \frac{u_2 - u_f}{u_{fg}} = \frac{251.16 - 191.79}{2245.4} = 0.02644$$

Thus,

$$T_2 = = T_{\text{sat @ 10 kPa}} = \mathbf{45.81\ °C}$$

$$\boldsymbol{v}_2 = \boldsymbol{v}_f + x_2 \boldsymbol{v}_{fg} = 0.001010 + [0.02644 \times (14.670 - 0.001010)] = 0.38886 \text{ m}^3/\text{kg}$$

and,

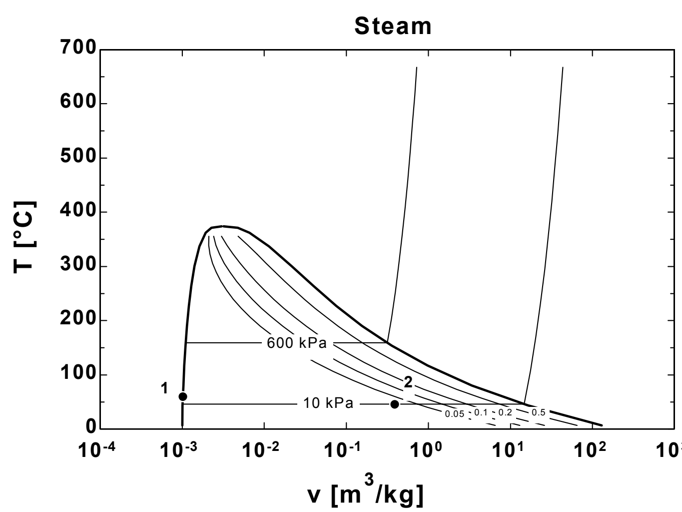
$$\boldsymbol{V} = m\boldsymbol{v}_2 = (2.5 \text{ kg})(0.38886 \text{ m}^3/\text{kg}) = \mathbf{0.972\ m^3}$$

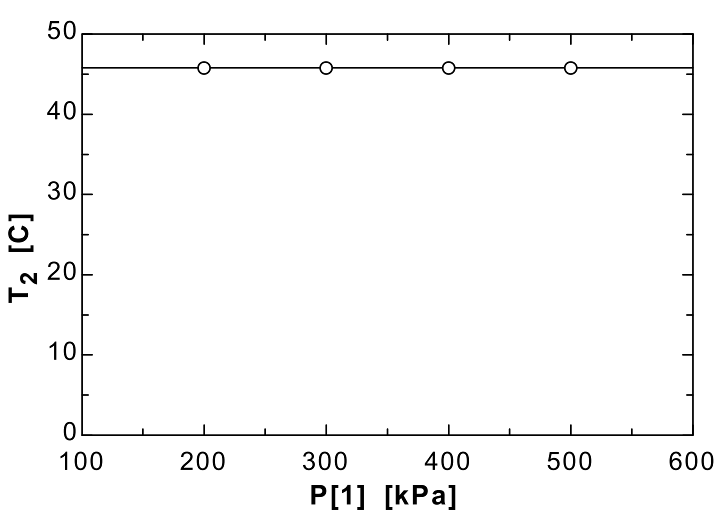
4-33 EES Problem 4-32 is reconsidered. The effect of the initial pressure of water on the final temperature in the tank as the initial pressure varies from 100 kPa to 600 kPa is to be investigated. The final temperature is to be plotted against the initial pressure.

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

```
"Knowns"
m=2.5 [kg]
{P[1]=600 [kPa]}
T[1]=60 [C]
P[2]=10 [kPa]

"Solution"
Fluid$='Steam_IAPWS'
"Conservation of Energy for the closed tank:"
E_in-E_out=DELTAE
E_in=0
E_out=0
DELTAE=m*(u[2]-u[1])
u[1]=INTENERGY(Fluid$,P=P[1], T=T[1])
v[1]=volume(Fluid$,P=P[1], T=T[1])
T[2]=temperature(Fluid$,P=P[2], u=u[2])
T_2=T[2]
v[2]=volume(Fluid$,P=P[2], u=u[2])
V_total=m*v[2]
```

P_1 [kPa]	T_2 [C]
100	45.79
200	45.79
300	45.79
400	45.79
500	45.79
600	45.79





4-34 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.

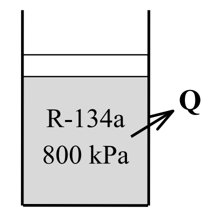
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

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

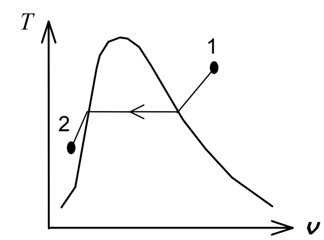
$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

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

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



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)



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

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

Substituting, Q_{out} = - (5 kg)(72.34 - 306.88) kJ/kg = **1173 kJ**

4-35E 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.

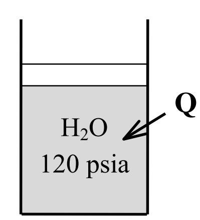
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The thermal energy stored in the cylinder itself is negligible. **3** The compression or expansion process is quasi-equilibrium.

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

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

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

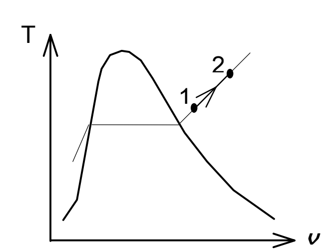
$$Q_{in} = m(h_2 - h_1)$$



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

$$v_1 = \frac{V_1}{m} = \frac{2 \text{ ft}^3}{0.5 \text{ lbm}} = 4 \text{ ft}^3/\text{lbm}$$

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



Substituting,

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

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

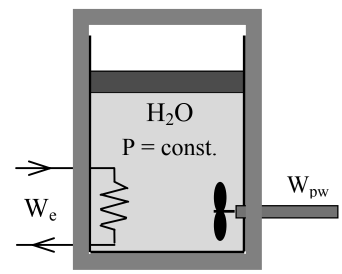
Then,

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

4-36 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



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

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

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

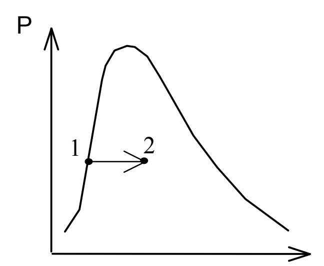
$$(\mathbf{V}I\Delta t) + W_{\text{pw,in}} = m(h_2 - h_1)$$

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,

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

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

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

4-37 A cylinder is initially filled with steam at a specified state. The steam is cooled at constant pressure. The mass of the steam, the final temperature, and the amount of heat transfer are to be determined, and the process is to be shown on a *T-v* diagram.

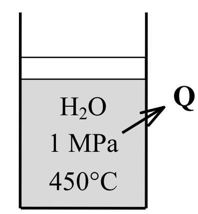
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

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

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

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

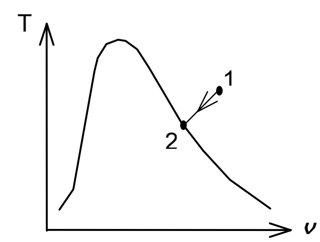
$$-Q_{out} = m(h_2 - h_1)$$



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)

$$\left.\begin{array}{l} P_1 = 1 \text{ MPa} \\ T_2 = 450°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 0.33045 \text{ m}^3/\text{kg} \\ h_1 = 3371.3 \text{ kJ/kg} \end{array}$$

$$m = \frac{V_1}{v_1} = \frac{2.5 \text{ m}^3}{0.33045 \text{ m}^3/\text{kg}} = \mathbf{7.565\ kg}$$



(*b*) The final temperature is determined from

$$\left.\begin{array}{l} P_2 = 1 \text{ MPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} T_2 = T_{sat@1\text{ MPa}} = \mathbf{179.9°C} \\ h_2 = h_{g@1\text{ MPa}} = 2777.1 \text{ kJ/kg} \end{array}$$

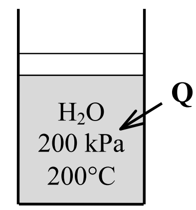
(*c*) Substituting, the energy balance gives

$$Q_{out} = -(7.565 \text{ kg})(2777.1 - 3371.3) \text{ kJ/kg} = \mathbf{4495\ kJ}$$

4-38 [*Also solved by EES on enclosed CD*] 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

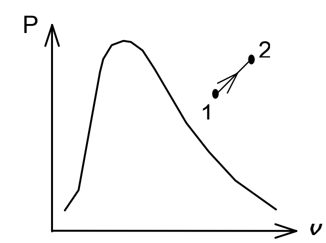


$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

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

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

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,

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

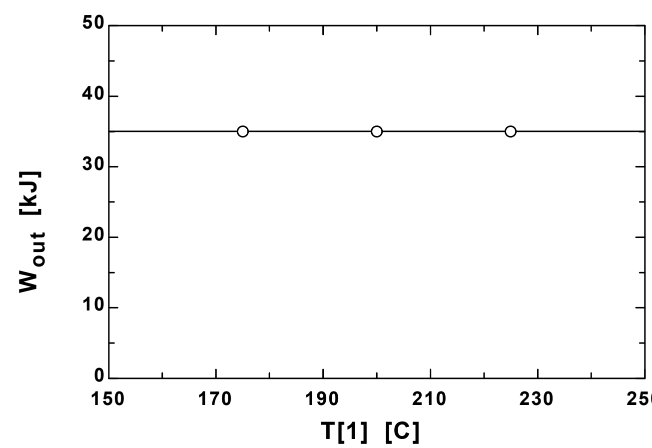
(*c*) From the energy balance we have

Q_{in} = (0.4628 kg)(4325.2 - 2654.6)kJ/kg + 35 kJ = **808 kJ**

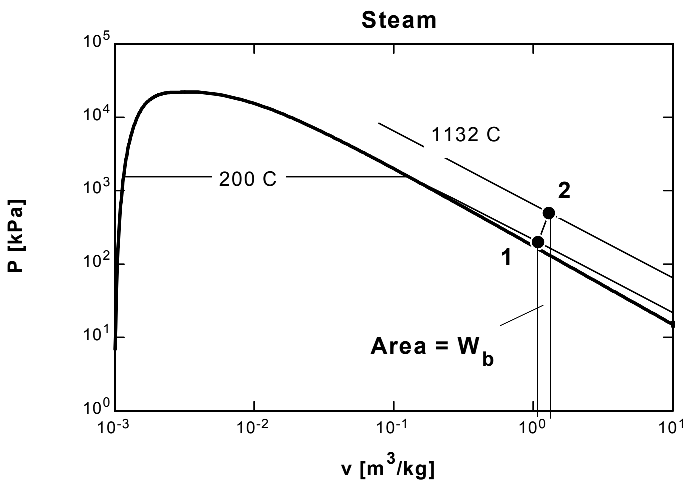
4-39 EES Problem 4-38 is reconsidered. The effect of the initial temperature of steam on the final temperature, the work done, and the total heat transfer as the initial temperature varies from 150°C to 250°C is to be investigated. The final results are to be plotted against the initial temperature.

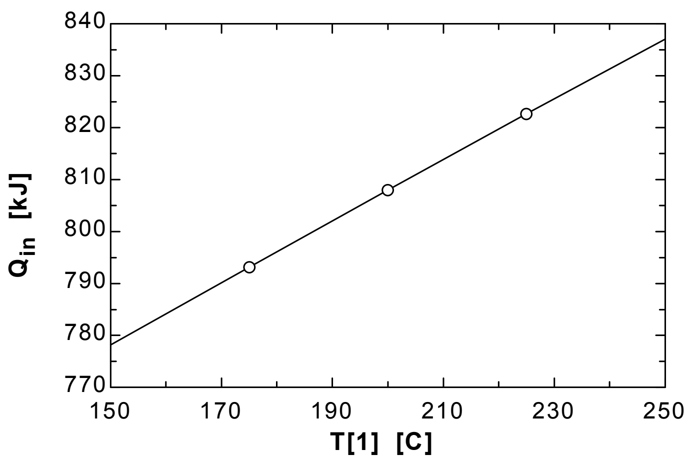
Analysis The problem is solved using EES, and the solution is given below.

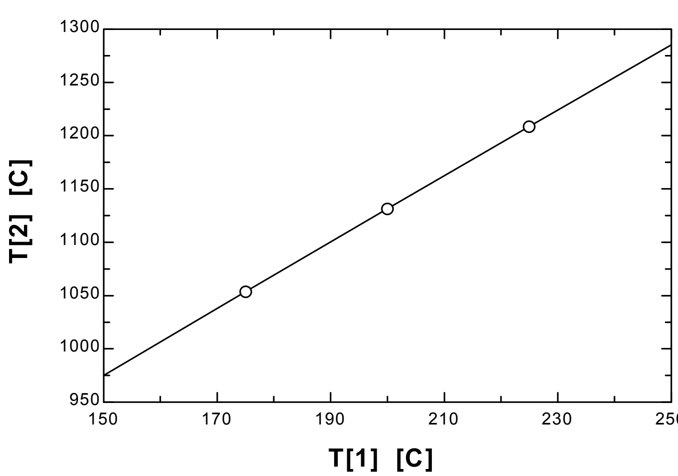
```
"The process is given by:"
"P[2]=P[1]+k*x*A/A, and as the spring moves 'x' amount, the volume changes by V[2]-V[1]."
P[2]=P[1]+(Spring_const)*(V[2] - V[1]) "P[2] is a linear function of V[2]"
"where Spring_const = k/A, the actual spring constant divided by the piston face area"

"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


Steam
P [kPa]
v [m³/kg]
1132 C
200 C
1
2
Area = W_b


Q_in [kJ]
T[1] [C]


T[2] [C]
T[1] [C]

4-40 A cylinder equipped with a set of stops for the piston to rest on is initially filled with saturated water vapor at a specified pressure. Heat is transferred to water until the volume doubles. 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-$\boldsymbol{v}$ diagram.

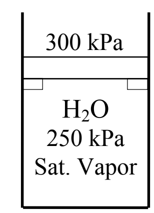
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

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

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

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U = m(u_3 - u_1) \quad \text{(since KE = PE = 0)}$$

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



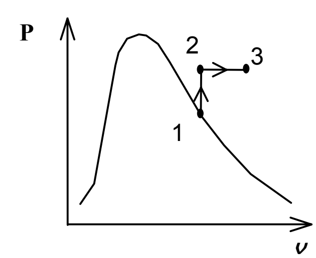
The properties of steam are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 250 \text{ kPa} \\ sat.vapor \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = \boldsymbol{v}_{g@250 \text{ kPa}} = 0.71873 \text{ m}^3/\text{kg} \\ u_1 = u_{g@250 \text{ kPa}} = 2536.8 \text{ kJ/kg} \end{array}$$

$$m = \frac{\boldsymbol{V}_1}{\boldsymbol{v}_1} = \frac{0.8 \text{ m}^3}{0.71873 \text{ m}^3/\text{kg}} = 1.113 \text{ kg}$$

$$\boldsymbol{v}_3 = \frac{\boldsymbol{V}_3}{m} = \frac{1.6 \text{ m}^3}{1.113 \text{ kg}} = 1.4375 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_3 = 300 \text{ kPa} \\ \boldsymbol{v}_3 = 1.4375 \text{ m}^3/\text{kg} \end{array}\right\} \begin{array}{l} T_3 = \mathbf{662^\circ C} \\ u_3 = 3411.4 \text{ kJ/kg} \end{array}$$



(b) The work done during process 1-2 is zero (since $\boldsymbol{V}$= const) and the work done during the constant pressure process 2-3 is

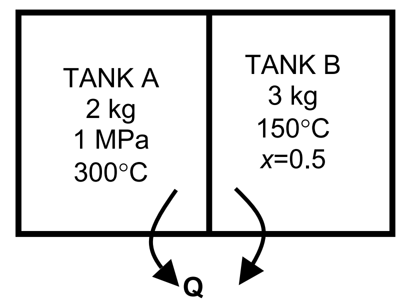
$$W_{b,\text{out}} = \int_2^3 P\,d\boldsymbol{V} = P(\boldsymbol{V}_3 - \boldsymbol{V}_2) = (300 \text{ kPa})(1.6 - 0.8)\text{m}^3 \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = \mathbf{240 \;\; kJ}$$

(c) Heat transfer is determined from the energy balance,

$$Q_{\text{in}} = m(u_3 - u_1) + W_{b,\text{out}}$$
$$= (1.113 \text{ kg})(3411.4 - 2536.8) \text{ kJ/kg} + 240 \text{ kJ} = \mathbf{1213 \;\; kJ}$$

4-41 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)

$$\left.\begin{aligned} P_{1,A} &= 1000 \text{ kPa} \\ T_{1,A} &= 300°\text{C} \end{aligned}\right\} \begin{aligned} \boldsymbol{v}_{1,A} &= 0.25799 \text{ m}^3/\text{kg} \\ u_{1,A} &= 2793.7 \text{ kJ/kg} \end{aligned}$$

$$\left.\begin{aligned} T_{1,B} &= 150°\text{C} \\ x_1 &= 0.50 \end{aligned}\right\} \begin{aligned} \boldsymbol{v}_f &= 0.001091, \quad \boldsymbol{v}_g = 0.39248 \text{ m}^3/\text{kg} \\ u_f &= 631.66, \quad u_{fg} = 1927.4 \text{ kJ/kg} \end{aligned}$$

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

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

The total volume and total mass of the system are

$$\boldsymbol{V} = \boldsymbol{V}_A + \boldsymbol{V}_B = m_A \boldsymbol{v}_{1,A} + m_B \boldsymbol{v}_{1,B} = (2 \text{ kg})(0.25799 \text{ m}^3/\text{kg}) + (3 \text{ kg})(0.19679 \text{ m}^3/\text{kg}) = 1.106 \text{ m}^3$$

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

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

$$\boldsymbol{v}_2 = \frac{\boldsymbol{V}}{m} = \frac{1.106 \text{ m}^3}{5 \text{ kg}} = 0.22127 \text{ m}^3/\text{kg}$$

which fixes the final state and we can determine other properties

$$\left.\begin{aligned} P_2 &= 300 \text{ kPa} \\ \boldsymbol{v}_2 &= 0.22127 \text{ m}^3/\text{kg} \end{aligned}\right\} \begin{aligned} T_2 &= T_{sat @ 300 \text{ kPa}} = \mathbf{133.5°C} \\ x_2 &= \frac{\boldsymbol{v}_2 - \boldsymbol{v}_f}{\boldsymbol{v}_g - \boldsymbol{v}_f} = \frac{0.22127 - 0.001073}{0.60582 - 0.001073} = \mathbf{0.3641} \\ u_2 &= u_f + x_2 u_{fg} = 561.11 + (0.3641 \times 1982.1) = 1282.8 \text{ kJ/kg} \end{aligned}$$

(*b*) Substituting,

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

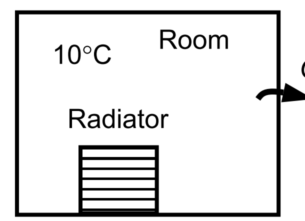
or $\quad Q_{out} = \mathbf{3959 \text{ kJ}}$

4-42 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



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

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

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

The mass of air and oil are

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

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

Substituting,

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

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

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.

Specific Heats, Δu and Δh of Ideal Gases

4-43C It can be used for any kind of process of an ideal gas.

4-44C It can be used for any kind of process of an ideal gas.

4-45C The desired result is obtained by multiplying the first relation by the molar mass M,

$$Mc_p = Mc_v + MR$$

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

4-46C Very close, but no. Because the heat transfer during this process is $Q = mc_p\Delta T$, and c_p varies with temperature.

4-47C It can be either. The difference in temperature in both the K and °C scales is the same.

4-48C 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.

4-49C 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.

4-50C For the constant pressure case. This is because the heat transfer to an ideal gas is $mc_p\Delta T$ at constant pressure, $mc_v\Delta T$ at constant volume, and c_p is always greater than c_v.

4-51 The enthalpy change of nitrogen 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,

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

where a = 28.90, b = -0.1571×10^{-2}, c = 0.8081×10^{-5}, and d = -2.873×10^{-9}. Then,

$$\begin{aligned}
\Delta\bar{h} &= \int_1^2 \bar{c}_p(T)dT = \int_1^2 \left[a + bT + cT^2 + dT^3\right]dT \\
&= a(T_2 - T_1) + \tfrac{1}{2}b(T_2^2 - T_1^2) + \tfrac{1}{3}c(T_2^3 - T_1^3) + \tfrac{1}{4}d(T_2^4 - T_1^4) \\
&= 28.90(1000 - 600) - \tfrac{1}{2}(0.1571\times10^{-2})(1000^2 - 600^2) \\
&\quad + \tfrac{1}{3}(0.8081\times10^{-5})(1000^3 - 600^3) - \tfrac{1}{4}(2.873\times10^{-9})(1000^4 - 600^4) \\
&= 12{,}544 \text{ kJ/kmol}
\end{aligned}$$

$$\Delta h = \frac{\Delta\bar{h}}{M} = \frac{12{,}544 \text{ kJ/kmol}}{28.013 \text{ kg/kmol}} = \mathbf{447.8 \text{ kJ/kg}}$$

(*b*) Using the constant c_p value from Table A-2b at the average temperature of 800 K,

$$c_{p,\text{avg}} = c_{p@800\text{ K}} = 1.121 \text{ kJ/kg}\cdot\text{K}$$

$$\Delta h = c_{p,\text{avg}}(T_2 - T_1) = (1.121 \text{ kJ/kg}\cdot\text{K})(1000 - 600)\text{K} = \mathbf{448.4 \text{ kJ/kg}}$$

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

$$c_{p,\text{avg}} = c_{p@300\text{ K}} = 1.039 \text{ kJ/kg}\cdot\text{K}$$

$$\Delta h = c_{p,\text{avg}}(T_2 - T_1) = (1.039 \text{ kJ/kg}\cdot\text{K})(1000 - 600)\text{K} = \mathbf{415.6 \text{ kJ/kg}}$$

4-52E 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,

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

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

4-53 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

4-54C 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.

4-55E 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 -141°C and 3.77 MPa. **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,

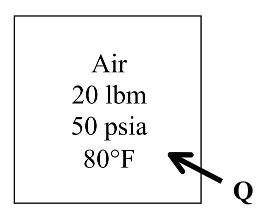
$$\boldsymbol{V} = \frac{mRT_1}{P_1} = \frac{(20 \text{ lbm})(0.3704 \text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(540 \text{ R})}{50 \text{ psia}} = \mathbf{80.0\ \ ft^3}$$

(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

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

The internal energies are (Table A-17E)

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

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

Substituting,

$$Q_{\text{in}} = (20 \text{ lbm})(186.93 - 92.04)\text{Btu/lbm} = \mathbf{1898\ Btu}$$

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,

$$Q_{\text{in}} = (20 \text{ lbm})(\ 0.175 \text{ Btu/lbm.R})(1080 - 540) \text{ R} = \mathbf{1890\ Btu}$$

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

4-56 The hydrogen gas in a rigid tank is cooled until its temperature drops to 300 K. The final pressure in the tank and the amount of heat transfer are to be determined.

Assumptions **1** Hydrogen is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -240°C and 1.30 MPa. **2** The tank is stationary, and thus the kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$.

Properties The gas constant of hydrogen is R = 4.124 kPa.m^3/kg.K (Table A-1). The constant volume specific heat of hydrogen at the average temperature of 450 K is , $c_{v,\text{avg}}$ = 10.377 kJ/kg.K (Table A-2).

Analysis (*a*) The final pressure of hydrogen can be determined from the ideal gas relation,

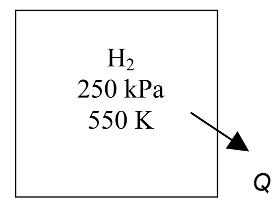
$$\frac{P_1 \mathbf{V}}{T_1} = \frac{P_2 \mathbf{V}}{T_2} \longrightarrow P_2 = \frac{T_2}{T_1} P_1 = \frac{350 \text{ K}}{550 \text{ K}} (250 \text{ kPa}) = \mathbf{159.1\ kPa}$$

(*b*) We take the hydrogen in 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

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

$$-Q_{\text{out}} = \Delta U$$

$$Q_{\text{out}} = -\Delta U = -m(u_2 - u_1) \cong mC_v(T_1 - T_2)$$



where

$$m = \frac{P_1 \mathbf{V}}{RT_1} = \frac{(250 \text{ kPa})(3.0 \text{ m}^3)}{(4.124 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(550 \text{ K})} = 0.3307 \text{ kg}$$

Substituting into the energy balance,

Q_{out} = (0.33307 kg)(10.377 kJ/kg·K)(550 - 350)K = **686.2 kJ**

4-57 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.

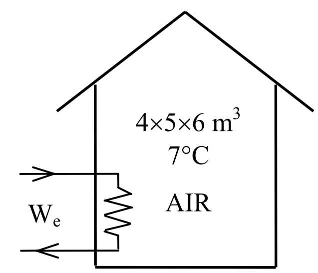
Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature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

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

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



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.

4-58 A room is heated by a radiator, and the warm air is distributed by a fan. Heat is lost from the room. The time it takes for the air temperature to rise to 20°C is to be determined.

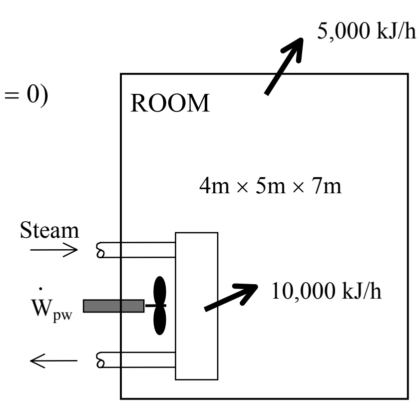
Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature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

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

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

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



or,

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

The mass of air is

$$V = 4 \times 5 \times 7 = 140 \text{ m}^3$$

$$m = \frac{P_1 V}{RT_1} = \frac{(100 \text{ kPa})(140 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(283 \text{ K})} = 172.4 \text{ kg}$$

Using the c_v value at room temperature,

$$\left[(10{,}000 - 5{,}000)/3600 \ \text{ kJ/s} + 0.1 \text{ kJ/s}\right]\Delta t = (172.4 \text{ kg})(0.718 \ \text{ kJ/kg}\cdot^\circ\text{C})(20 - 10)^\circ\text{C}$$

It yields

$$\Delta t = \mathbf{831 \text{ s}}$$

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.

4-59 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.

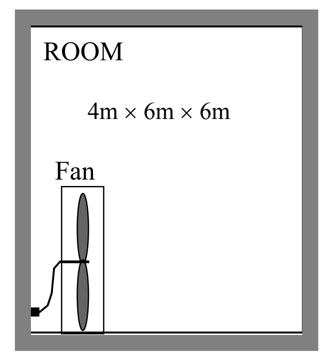
Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1). Also, c_v = 0.718 kJ/kg.K for air at room temperature (Table A-2).

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,

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

$$T_2 = \mathbf{58.2°C}$$

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.

4-60E A paddle wheel in an oxygen tank is rotated until the pressure inside rises to 20 psia while some heat is lost to the surroundings. The paddle wheel work done is 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 -181°F and 736 psia. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** The energy stored in the paddle wheel is negligible. **4** This is a rigid tank and thus its volume remains constant.

Properties The gas constant and molar mass of oxygen are R = 0.3353 psia.ft^3/lbm.R and M = 32 lbm/lbmol (Table A-1E). The specific heat of oxygen at the average temperature of T_{avg} = (735+540)/2= 638 R is $c_{v,avg}$ = 0.160 Btu/lbm.R (Table A-2E).

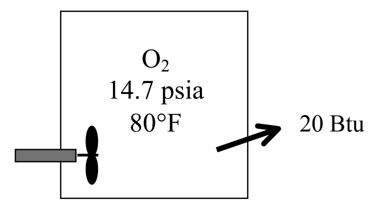
Analysis We take the oxygen in the tank as our system. This is a *closed system* since no mass enters or leaves. The energy balance for this system can be expressed as

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

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

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

$$\cong Q_{out} + mc_v(T_2 - T_1)$$



The final temperature and the mass of oxygen are

$$\frac{P_1 V}{T_1} = \frac{P_2 V}{T_2} \longrightarrow T_2 = \frac{P_2}{P_1} T_1 = \frac{20 \text{ psia}}{14.7 \text{ psia}} (540 \text{ R}) = 735 \text{ R}$$

$$m = \frac{P_1 V}{RT_1} = \frac{(14.7 \text{ psia})(10 \text{ ft}^3)}{(0.3353 \text{ psia} \cdot \text{ft}^3/\text{lbmol} \cdot \text{R})(540 \text{ R})} = 0.812 \text{ lbm}$$

Substituting,

$$W_{pw,in} = (20 \text{ Btu}) + (0.812 \text{ lbm})(0.160 \text{ Btu/lbm.R})(735 - 540) \text{ R} = \mathbf{45.3 \text{ Btu}}$$

4-61 One part of an insulated rigid tank contains an ideal gas while the other side is evacuated. The final temperature and pressure in the tank are to be determined when the partition is removed.

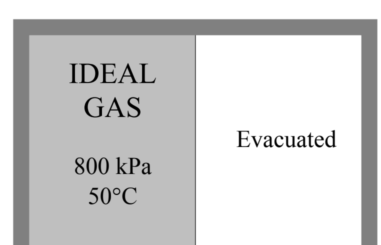
Assumptions **1** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **2** The tank is insulated and thus heat transfer is negligible.

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

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

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

$$u_2 = u_1$$



Therefore,

$$T_2 = T_1 = \mathbf{50°C}$$

Since $u = u(T)$ for an ideal gas. Then,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \longrightarrow P_2 = \frac{V_1}{V_2} P_1 = \frac{1}{2}(800 \text{ kPa}) = \mathbf{400 \text{ kPa}}$$

4-62 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.

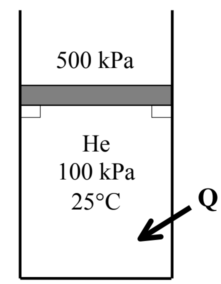
Properties The specific heat of helium at room temperature is c_v = 3.1156 kJ/kg.K (Table A-2).

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

$$Q_{\text{in}} = (0.5 \text{ kg})(3.1156 \text{ kJ/kg·K})(1490 - 298)\text{K} = \mathbf{1857 \text{ kJ}}$$

4-63 An insulated cylinder is initially filled with air at a specified state. A paddle-wheel in the cylinder stirs the air at constant pressure. The final temperature of air is to be determined.

Assumptions **1** Air is an ideal gas with variable specific heats. **2** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **3** There are no work interactions involved other than the boundary work. **4** The cylinder is well-insulated and thus heat transfer is negligible. **5** The thermal energy stored in the cylinder itself and the paddle-wheel is negligible. **6** The compression or expansion process is quasi-equilibrium.

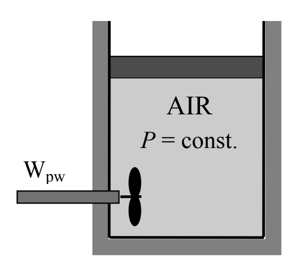
Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1). Also, c_p = 1.005 kJ/kg.K for air at room temperature (Table A-2). The enthalpy of air at the initial temperature is

$$h_1 = h_{@298 \text{ K}} = 298.18 \text{ kJ/kg} \qquad \text{(Table A-17)}$$

Analysis We take the air in 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

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

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



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

The mass of air is

$$m = \frac{P_1 V}{RT_1} = \frac{(400 \text{ kPa})(0.1 \text{ m}^3)}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298 \text{ K})} = 0.468 \text{ kg}$$

Substituting into the energy balance,

$$15 \text{ kJ} = (0.468 \text{ kg})(h_2 - 298.18 \text{ kJ/kg}) \rightarrow h_2 = 330.23 \text{ kJ/kg}$$

From Table A-17, T_2 = **329.9 K**

Alternative solution Using specific heats at room temperature, c_p = 1.005 kJ/kg.°C, the final temperature is determined to be

$$W_{\text{pw,in}} = m(h_2 - h_1) \cong mc_p(T_2 - T_1) \rightarrow 15 \text{ kJ} = (0.468 \text{ kg})(1.005 \text{ kJ/kg.°C})(T_2 - 25)\text{°C}$$

which gives T_2 = **56.9°C**

4-64E A cylinder is initially filled with nitrogen gas at a specified state. The gas is cooled by transferring heat from it. The amount of heat transfer is to be determined.

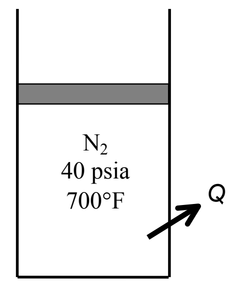
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium. **5** Nitrogen is an ideal gas with constant specific heats.

Properties The gas constant of nitrogen is 0.3830 psia.ft^3/lbm.R. The specific heat of nitrogen at the average temperature of T_{avg} = (700+200)/2 = 450°F is $c_{p,avg}$ = 0.2525 Btu/lbm.°F (Table A-2Eb).

Analysis We take the nitrogen gas in 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

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

$$-Q_{out} - W_{b,out} = \Delta U = m(u_2 - u_1) \longrightarrow -Q_{out} = m(h_2 - h_1) = mc_p(T_2 - T_1)$$



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

$$m = \frac{P_1 \boldsymbol{V}}{RT_1} = \frac{(40 \text{ psia})(25 \text{ ft}^3)}{(0.3830 \text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(1160 \text{ R})} = 2.251 \text{ lbm}$$

Substituting, Q_{out} = (2.251 lbm)(0.2525 Btu/lbm.°F)(700 - 200)°F = **284.2 Btu**

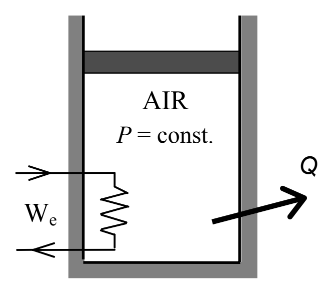
4-65 A cylinder is initially filled with air at a specified state. Air is heated electrically at constant pressure, and some heat is lost in the process. The amount of electrical energy supplied is to be determined. √

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-17)

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

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



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,

$W_{e,in}$ = (15 kg)(350.49 - 298.18)kJ/kg + (60 kJ) = 845 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, $c_{p,avg}$ = 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, $$W_{\text{e,in}} = (845 \text{ kJ})\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right) = \mathbf{0.235\ kWh}$$

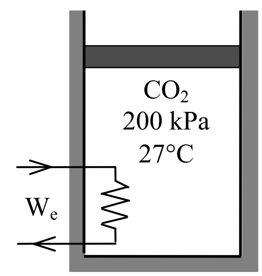
Discussion Note that for small temperature differences, both approaches give the same result.

4-66 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

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

The mass of CO_2 is

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

Substituting,

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

Then,

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

4-67 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.

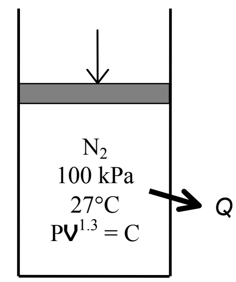
Properties The gas constant of N_2 are R = 0.2968 kPa.m^3/kg.K (Table A-1). The c_v value of N_2 at the average temperature (369+300)/2 = 335 K is 0.744 kJ/kg.K (Table A-2b).

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

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

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

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

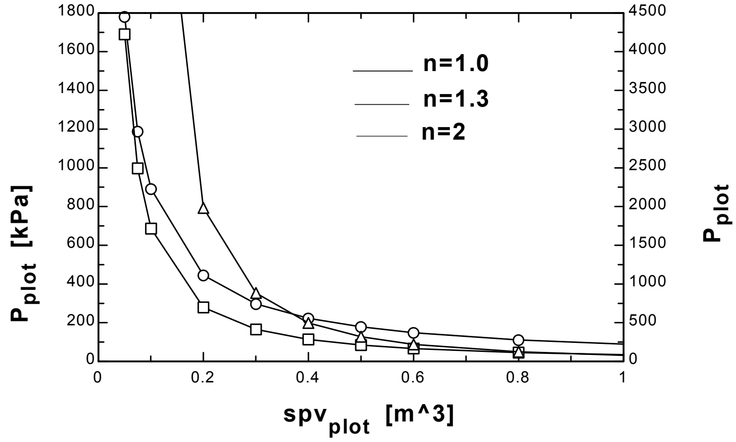
4-68 EES Problem 4-67 is reconsidered. The process is to be plotted on a *P-V* diagram, and the effect of the polytropic exponent n on the boundary work and heat transfer as the polytropic exponent varies from 1.1 to 1.6 is to be investigated. The boundary work and the heat transfer are to be plotted versus the polytropic exponent.

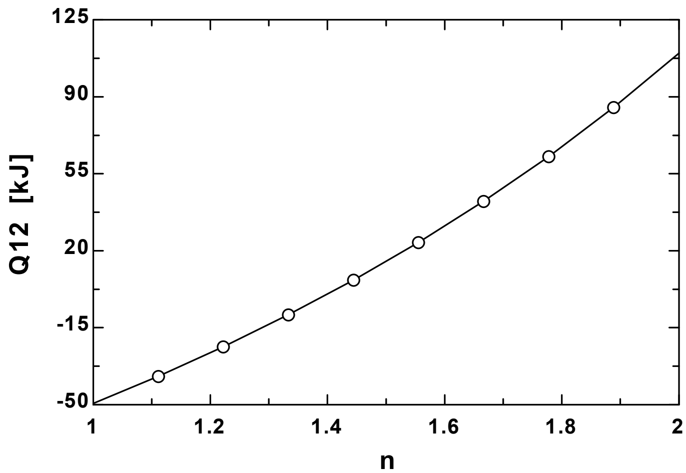
Analysis The problem is solved using EES, and the solution is given below.

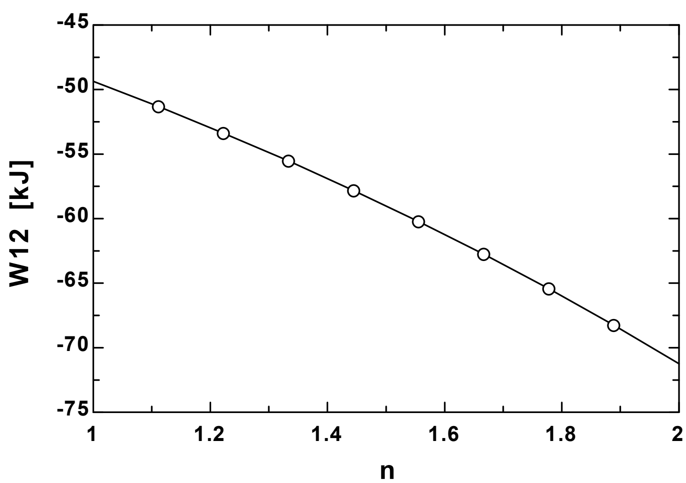
```
Procedure     Work(P[2],V[2],P[1],V[1],n:W12)
If n=1 then
W12=P[1]*V[1]*ln(V[2]/V[1])
Else
W12=(P[2]*V[2]-P[1]*V[1])/(1-n)
endif
End

"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



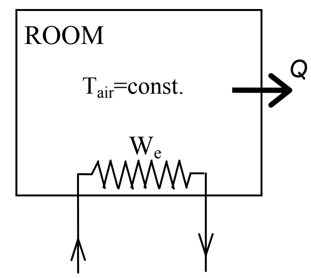




4-69 It is observed that the air temperature in a room heated by electric baseboard heaters remains constant even though the heater operates continuously when the heat losses from the room amount to 6500 kJ/h. The power rating of the heater is to be determined.

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



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

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

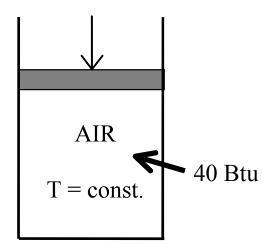
since $\Delta U = mc_v\Delta T = 0$ for isothermal processes of ideal gases. Thus,

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

4-70E A cylinder initially contains air at a specified state. Heat is transferred to the air, and air expands isothermally. The boundary work done is to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The air is an ideal gas with constant specific heats. **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 crosses the system boundary. The energy balance for this closed system can be expressed as



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

$$Q_{\text{in}} - W_{\text{b,out}} = \Delta U = m(u_2 - u_1) = mc_v(T_2 - T_1) = 0$$

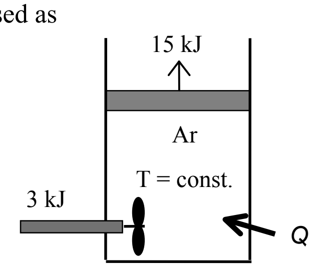
since $u = u(T)$ for ideal gases, and thus $u_2 = u_1$ when $T_1 = T_2$. Therefore,

$$W_{\text{b,out}} = Q_{\text{in}} = \mathbf{40\ Btu}$$

4-71 A cylinder initially contains argon gas at a specified state. The gas is stirred while being heated and expanding isothermally. The amount of heat transfer is to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The air is an ideal gas with constant specific heats. **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 crosses the system boundary. The energy balance for this closed system can be expressed as



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

$$Q_{\text{in}} + W_{\text{pw,in}} - W_{\text{b,out}} = \Delta U = m(u_2 - u_1) = mc_v(T_2 - T_1) = 0$$

since $u = u(T)$ for ideal gases, and thus $u_2 = u_1$ when $T_1 = T_2$. Therefore,

$$Q_{\text{in}} = W_{\text{b,out}} - W_{\text{pw,in}} = 15 - 3 = \mathbf{12\ kJ}$$

4-72 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.

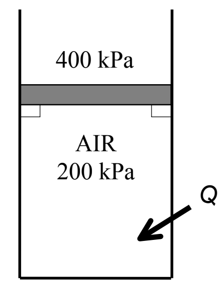
Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1).

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

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

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

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

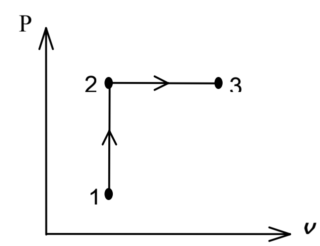


The initial and the final volumes and the final temperature of air are

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

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

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



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

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

The initial and final internal energies of air are (Table A-17)

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

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

Then from the energy balance,

Q_{in} = (3 kg)(933.33 - 214.07)kJ/kg + 516 kJ = **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, $c_{v,\text{avg}}$ = 0.800 kJ/kg.K. Substituting,

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

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

4-73 **[***Also solved by EES on enclosed CD***]** 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** There are no work interactions involved. **3** The thermal energy stored in the cylinder itself is negligible.

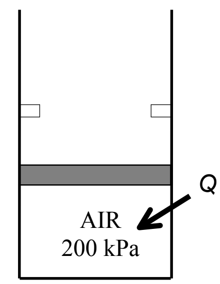
Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K (Table A-1).

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

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

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

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

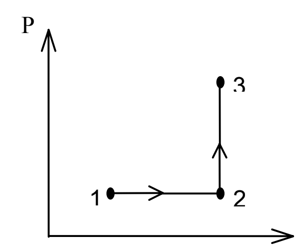


The initial and the final volumes and the final temperature of air are determined from

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

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

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



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

$$W_b = \int_1^2 P\,dV = P_2(V_3 - V_2) = (200\text{ kPa})(2.58-1.29)\text{ m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = \mathbf{258\text{ kJ}}$$

The initial and final internal energies of air are (Table A-17)

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

$$u_2 = u_{@\,1200\text{ K}} = 933.33\text{ kJ/kg}$$

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

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

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