Chapter 4

ENERGY TRANSFER BY HEAT, WORK, AND MASS

Heat Transfer and Work

4-1C Energy can cross the boundaries of a closed system in two forms: heat and work.

4-2C The form of energy that crosses the boundary of a closed system because of a temperature difference is heat; all other forms are work.

4-3C An adiabatic process is a process during which there is no heat transfer. A system that does not exchange any heat with its surroundings is an adiabatic system.

4-4C It is a work interaction.

4-5C It is a work interaction since the electrons are crossing the system boundary, thus doing electrical work.

4-6C It is a heat interaction since it is due to the temperature difference between the sun and the room.

4-7C This is neither a heat nor a work interaction since no energy is crossing the system boundary. This is simply the conversion of one form of internal energy (chemical energy) to another form (sensible energy).

4-8C Point functions depend on the state only whereas the path functions depend on the path followed during a process. Properties of substances are point functions, heat and work are path functions.

4-9C The caloric theory is based on the assumption that heat is a fluid-like substance called the "caloric" which is a massless, colorless, odorless substance. It was abandoned in the middle of the nineteenth century after it was shown that there is no such thing as the caloric.

Boundary Work

4-10C It represents the boundary work for quasi-equilibrium processes.

4-11C Yes.

4-12C The area under the process curve, and thus the boundary work done, is greater in the constant pressure case.

4-13C $1\ \text{kPa}\cdot\text{m}^3 = 1\ \text{k(N/m}^2)\cdot\text{m}^3 = 1\ \text{kN}\cdot\text{m} = 1\ \text{kJ}$

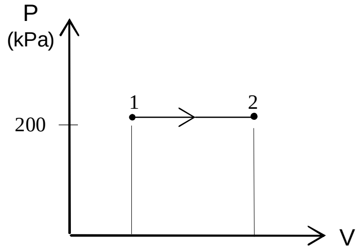
4-14 Saturated water vapor in a cylinder is heated at constant pressure until its temperature rises to a specified value. The boundary work done during this process is to be determined.

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)

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ \text{Sat.vapor} \end{array}\right\} v_1 = v_{g\,@\,200\text{kPa}} = 0.8857 \text{ m}^3\text{/kg}$$

$$\left.\begin{array}{l} P_2 = 200 \text{ kPa} \\ T_2 = 300^\circ\text{C} \end{array}\right\} v_2 = 1.3162 \text{ m}^3\text{/kg}$$



Analysis The boundary work is determined from its definition to be

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

$$= (5\text{kg})(200\text{kPa})(1.3162 - 0.8857)\text{m}^3\text{/kg}\left(\frac{1\text{kJ}}{1\text{kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{430.5\ kJ}$$

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

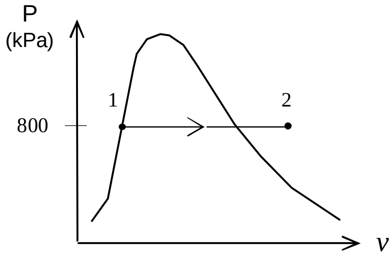
4-15 Refrigerant-134a in a cylinder is heated at constant pressure until its temperature rises to a specified value. The boundary work done during this process is to be determined.

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)

$$\left.\begin{array}{l} P_1 = 800 \text{ kPa} \\ \text{Sat.liquid} \end{array}\right\} v_1 = v_{f\,@\,800\text{kPa}} = 0.0008454 \text{m}^3\text{/kg}$$

$$\left.\begin{array}{l} P_2 = 800 \text{kPa} \\ T_2 = 50^\circ\text{C} \end{array}\right\} v_2 = 0.02846 \text{m}^3\text{/kg}$$



Analysis The boundary work is determined from its definition to be

$$m = \frac{V_1}{v_1} = \frac{0.2 \text{ m}^3}{0.0008454 \text{ m}^3/\text{kg}} = 236.6 \text{ kg}$$

and

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

$$= (236.6\text{kg})(800\text{kPa})(0.02846 - 0.0008454)\text{m}^3\text{/kg}\left(\frac{1\text{kJ}}{1\text{kPa}\cdot\text{m}^3}\right)$$

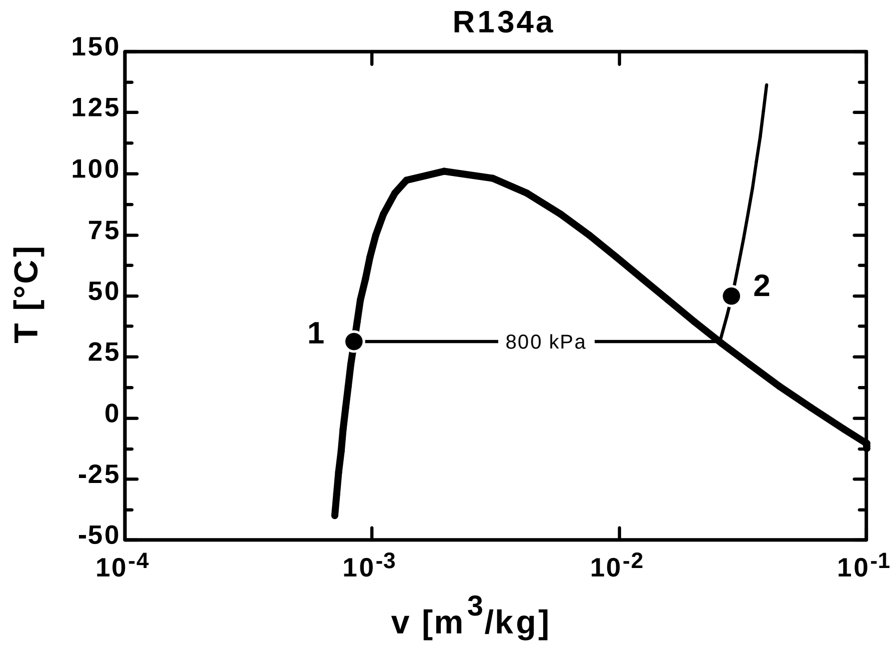
$$= \mathbf{5227 kJ}$$

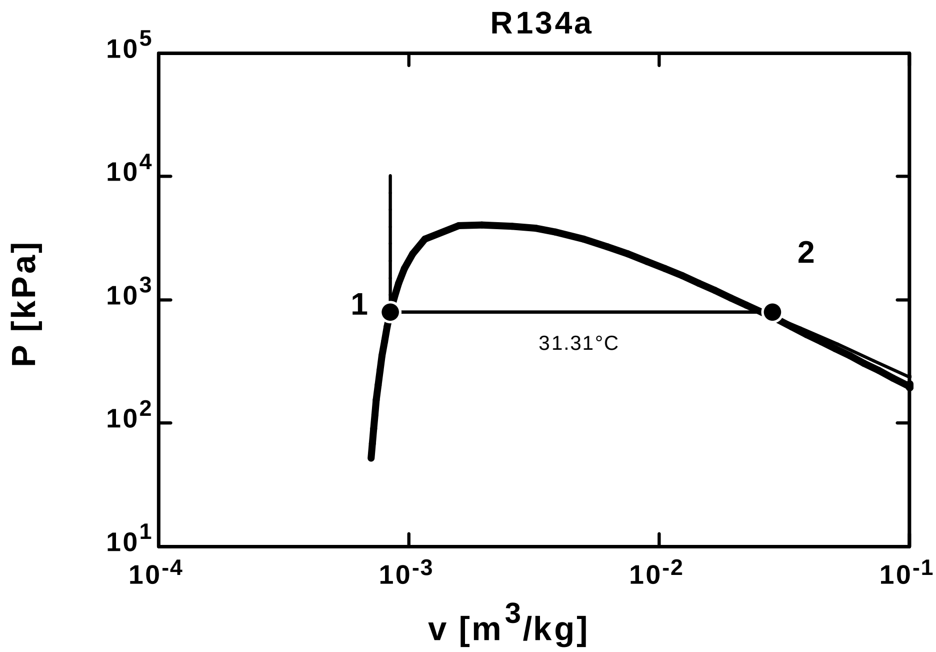
Discussion The positive sign indicates that work is done by the system (work output).

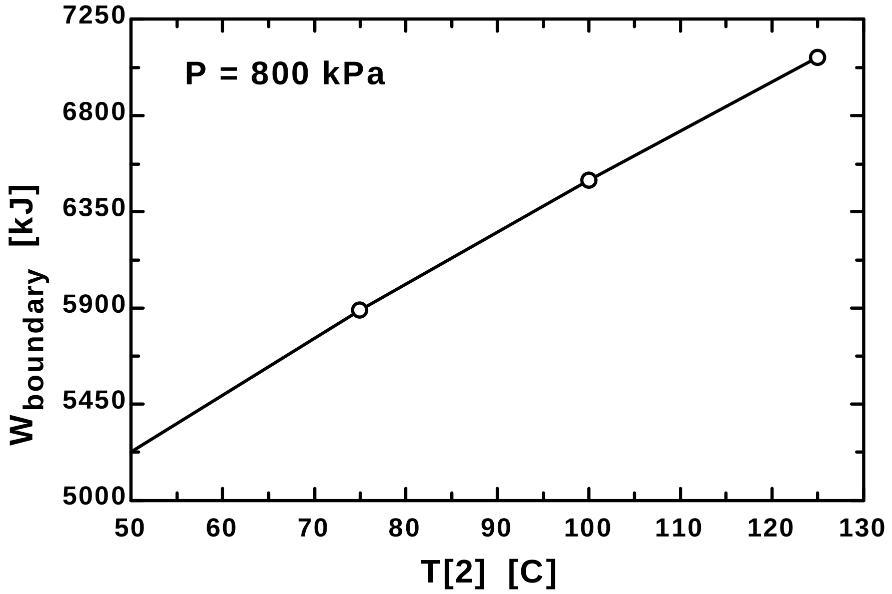
4-16 Problem 4-15 is reconsidered. The effect of pressure on the work done. as the pressure varies from 400 kPa to 1200 kPa is to be investigated. The work done is to be plotted versus the pressure.

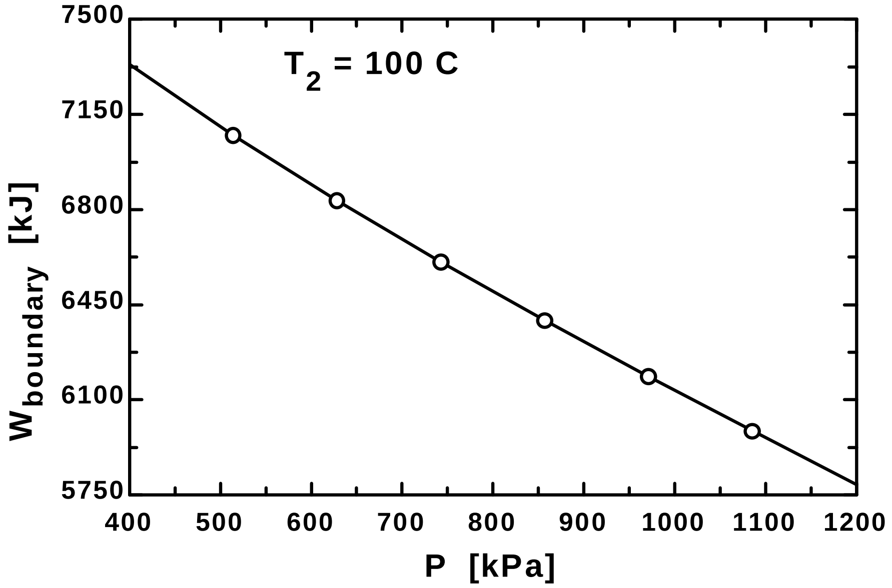
```
"Knowns"
Vol_1L=200"[L]"
x_1=0         "saturated liquid state"
P=800"[kPa]"
T_2=50"[C]"

"Solution"
Vol_1=Vol_1L*convert(L,m^3)"[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)"[kJ]"

"The mass is:"

Vol_1=m*v_1"[m^3]"
v_1=volume(R134a,P=P,x=x_1)"[m^3/kg]"
Vol_2=m*v_2"[m^3]"
v_2=volume(R134a,P=P,T=T_2)"[m^3/kg]"

"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	7334
514.3	7073
628.6	6833
742.9	6607
857.1	6392
971.4	6186
1086	5986
1200	5790


R134a
150
125
100
75
50
25
0
-25
-50
T [°C]
1
2
800 kPa
10-4
10-3
10-2
10-1
v [m3/kg]


R134a
105
104
103
102
101
P [kPa]
1
2
31.31°C
10-4
10-3
10-2
10-1
v [m3/kg]


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


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

4-17E 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.

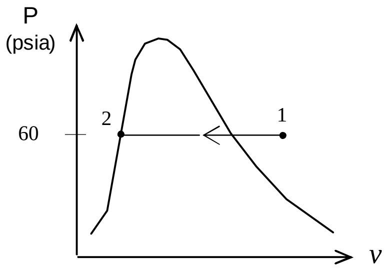
Properties Noting that the pressure remains constant during this process, the specific volumes at the initial and the final states are (Table A-4E through A-6E)

$$\left.\begin{array}{l} P_1 = 60 \text{ psia} \\ T_1 = 500^\circ\text{F} \end{array}\right\} v_1 = 9.399 \text{ft}^3/\text{lbm}$$

$$\left.\begin{array}{l} P_2 = 60 \text{ psia} \\ x_2 = 0.3 \end{array}\right\} v_2 = v_f + x_2 v_{fg}$$

$$= 0.017378 + 0.3(7.177 - 0.017378)$$

$$= 2.165 \text{ft}^3/\text{lbm}$$



Analysis The boundary work is determined from its definition to be

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

$$= (12 \text{ lbm})(60 \text{psia})(2.165 - 9.399)\text{ft}^3/\text{lbm}\left(\frac{1 \text{Btu}}{5.4039 \text{psia} \cdot \text{ft}^3}\right)$$

$$= \mathbf{-963.8 \text{Btu}}$$

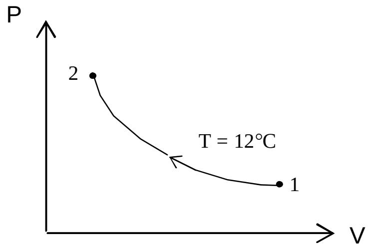
Discussion The negative sign indicates that work is done on the system (work input).

4-18 Air in a cylinder is compressed at constant temperature until its pressure rises to a specified value. The boundary work done during this process is to be determined.

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

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

Analysis The boundary work is determined from its definition to be



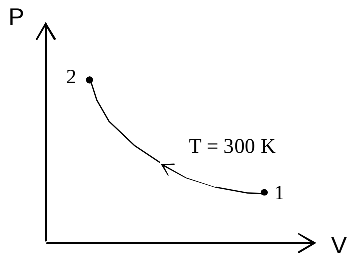
$$\begin{aligned} W_{b,\text{out}} &= \int_1^2 P\,dV = P_1 V_1 \ln\frac{V_2}{V_1} = mRT\ln\frac{P_1}{P_2} \\ &= (2.4\text{ kg})(0.287\text{ kJ/kg}\cdot\text{K})(285\text{ K})\ln\frac{150\text{ kPa}}{600\text{ kPa}} \\ &= \mathbf{-272\ \ kJ} \end{aligned}$$

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

4-19 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



$$\begin{aligned} W_{b,\text{out}} &= \int_1^2 P\,dV = P_1 V_1 \ln\frac{V_2}{V_1} = P_1 V_1 \ln\frac{P_1}{P_2} \\ &= (150\text{kPa})(0.2\text{m}^3)\left(\ln\frac{150\text{kPa}}{800\text{kPa}}\right)\left(\frac{1\text{kJ}}{1\text{kPa}\cdot\text{m}^3}\right) \\ &= \mathbf{-50.2kJ} \end{aligned}$$

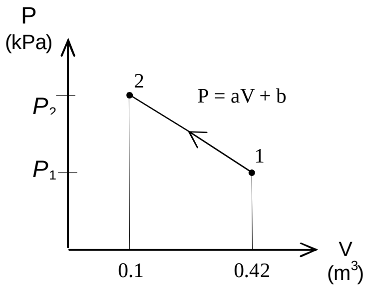
Discussion The negative sign indicates that work is done on the system (work input).

4-20 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,

$$P_1 = aV_1 + b = (-1200 \text{ kPa / m}^3)(0.42 \text{ m}^3) + (600 \text{ kPa}) = 96 \text{ kPa}$$
$$P_2 = aV_2 + b = (-1200 \text{ kPa / m}^3)(0.12 \text{ m}^3) + (600 \text{ kPa}) = 456 \text{ kPa}$$

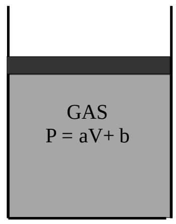


and

$$\begin{aligned} W_{b,\text{out}} &= \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1) \\ &= \frac{(96 + 456)\text{kPa}}{2}(0.12 - 0.42)\text{m}^3\left(\frac{1\text{kJ}}{1\text{kPa}\cdot\text{m}^3}\right) \\ &= \mathbf{-82.8kJ} \end{aligned}$$

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

$$\begin{aligned} W_{b,\text{out}} &= \int_1^2 PdV = \int_1^2 (aV + b)dV = a\frac{V_2^2 - V_1^2}{2} + b(V_2 - V_1) \\ &= (-1200 \text{ kPa/m}^3)\frac{(0.12^2 - 0.42^2)\text{m}^6}{2} + (600 \text{ kPa})(0.12 - 0.42)\text{m}^3 \\ &= \mathbf{-82.8\ kJ} \end{aligned}$$

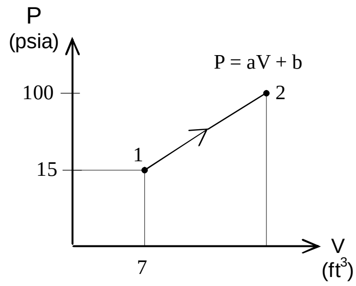


Discussion The negative sign indicates that work is done on the system (work input).

4-21E 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:

$$P_1 = aV_1 + b$$

$$15 \text{ psia} = (5 \text{ psia/ft}^3)(7 \text{ ft}^3) + b$$

$$b = -20 \text{ psia}$$

At state 2:

$$P_2 = aV_2 + b$$

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

$$V_2 = 24 \text{ ft}^3$$

and,

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

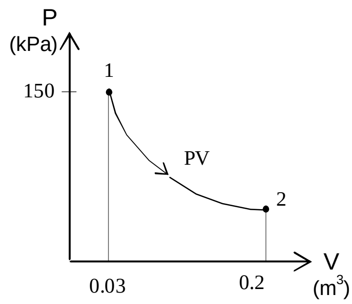
$$= \mathbf{181\ \ Btu}$$

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

4-22 [*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



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

and,

$$W_{b,out} = \int_1^2 PdV = \frac{P_2V_2 - P_1V_1}{1-n}$$

$$= \frac{(12.74\times 0.2 - 150\times 0.03)\text{ kPa}\cdot\text{m}^3}{1-1.3}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$

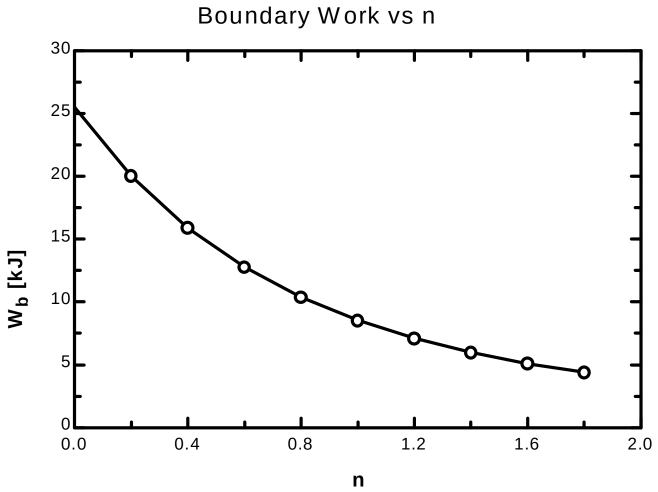
$$= \mathbf{6.51\ \ kJ}$$

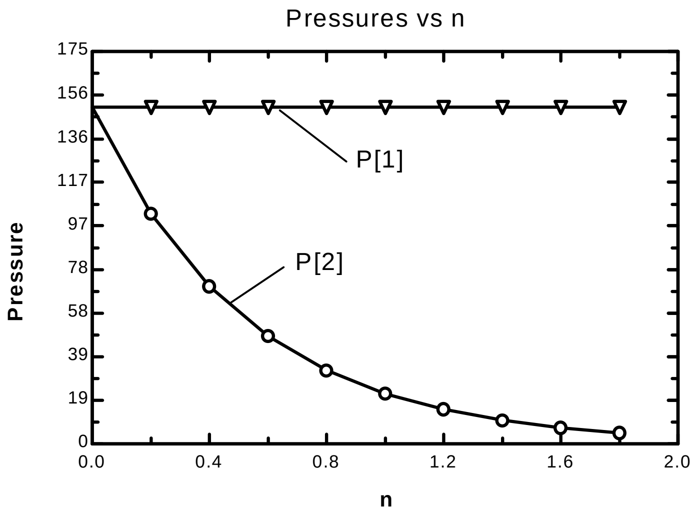
Discussion The positive sign indicates that work is done by the system (work output).

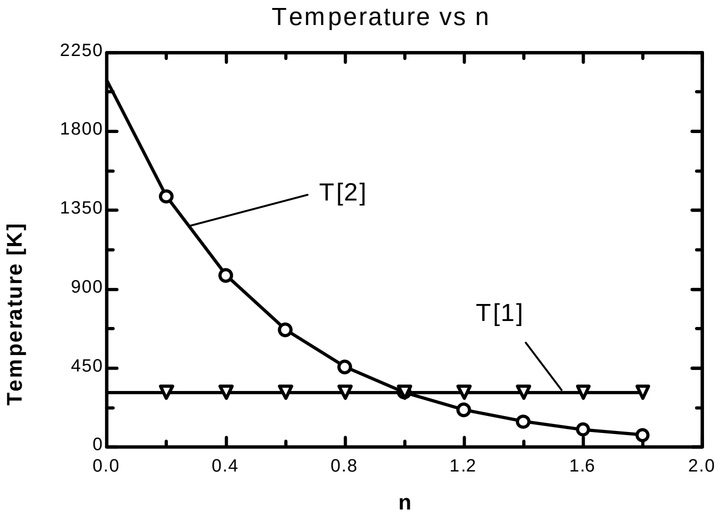
4-23 Problem 4-22 is reconsidered. The process described in the problem is to be plotted on a P-V diagram, and the effect of the polytropic exponent n on the boundary work as the polytropic exponent varies from 1.1 to 1.6 is to be plotted.

```
Function BoundWork(P[1],V[1],P[2],V[2],n)
"This function returns the Boundary Work for the polytropic process.  This function is
required since the expression for boundary work depends on whether n=1 or n<>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]"[kg]" "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$,P=P[1],v=V[1]/m[1])"[K]"
T[2]=temperature(gas$,P=P[2],v=V[2]/m[2])"[K]"
```

n	P_1 [kPa]	P_2 [kPa]	T_1 [K]	T_2 [K]	V_1 [m^3]
0	150	150	313.6	2090	0.03
0.2	150	102.6	313.6	1430	0.03
0.4	150	70.23	313.6	978.8	0.03
0.6	150	48.06	313.6	669.7	0.03
0.8	150	32.88	313.6	458.3	0.03
1	150	22.5	313.6	313.6	0.03
1.2	150	15.4	313.6	214.6	0.03
1.4	150	10.53	313.6	146.8	0.03
1.6	150	7.208	313.6	100.5	0.03
1.8	150	4.932	313.6	68.74	0.03


Boundary Work vs n
W_b [kJ]
n
0
5
10
15
20
25
30
0.0
0.4
0.8
1.2
1.6
2.0

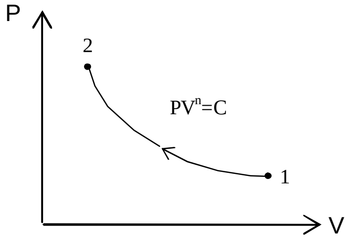

Pressures vs n
Pressure
n
P[1]
P[2]
0
19
39
58
78
97
117
136
156
175
0.0
0.4
0.8
1.2
1.6
2.0


Temperature vs n
Temperature [K]
n
T[2]
T[1]
0
450
900
1350
1800
2250
0.0
0.4
0.8
1.2
1.6
2.0

4-24 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.

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



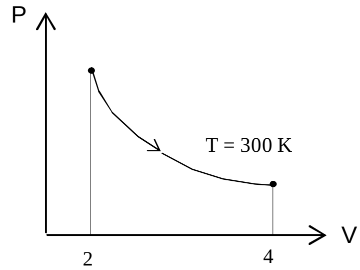
$$W_{b,\text{out}} = \int_1^2 P\,dV = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{mR(T_2 - T_1)}{1-n}$$
$$= \frac{(2\text{kg})(0.2968\text{kJ/kg}\cdot\text{K})(360-300)\text{K}}{1-1.4}$$
$$= \mathbf{-89.0\ kJ}$$

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

4-25 [*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

$$W_{b,\text{out}} = \int_1^2 P\,dV = \int_1^2 \left(\frac{NR_uT}{V} - \frac{10N^2}{V^2}\right)dV = NR_uT\ln\frac{V_2}{V_1} + 10N^2\left(\frac{1}{V_2} - \frac{1}{V_1}\right)$$
$$= (0.5\text{ kmol})(8.314\text{ kJ/kmol}\cdot\text{K})(300\text{ K})\ln\frac{4\text{ m}^3}{2\text{ m}^3}$$
$$+ (10\text{ kPa}\cdot\text{m}^6/\text{kmol}^2)(0.5\text{kmol})^2\left(\frac{1}{4\text{ m}^3} - \frac{1}{2\text{ m}^3}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$
$$= \mathbf{863\ \ kJ}$$

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

4-26 Problem 4-25 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.

"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 equation 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)"[kJ]"

"We can show that W_bhand= integral of Pdv_bar is
(one should solve for P=F(v_bar) and do the integral 'by hand' for practice)."

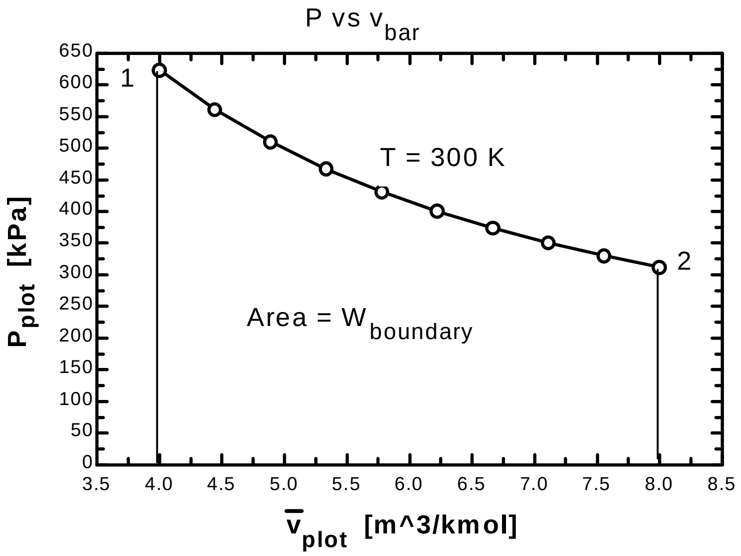
W_b_hand = N*(R_u*T*ln(v2_bar/v1_bar) +10*(1/v2_bar-1/v1_bar))"[kJ]"

"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."

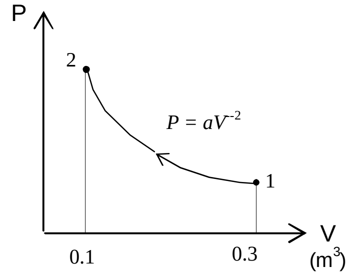
P_{plot}	v_{plot}
622.9	4
560.7	4.444
509.8	4.889
467.3	5.333
431.4	5.778
400.6	6.222
373.9	6.667
350.5	7.111
329.9	7.556
311.6	8



4-27 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 $P = aV^{-2}$. 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



$$W_{b,\text{out}} = \int_1^2 P dV = \int_1^2 \left(\frac{a}{V^2}\right) dV = -a\left(\frac{1}{V_2} - \frac{1}{V_1}\right)$$

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

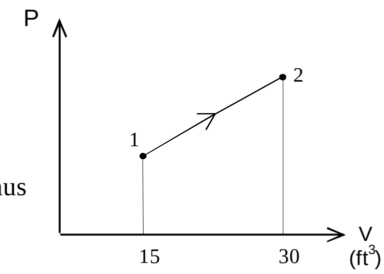
$$= \mathbf{-53.3\ kJ}$$

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

4-28E 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-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



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

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

(*b*) The pressure of H_2 changes linearly with volume during this process, and thus the process curve on a *P-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,

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

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

(*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

$$W_{b,\text{out,no spring}} = \int_1^2 P dV = P(V_2 - V_1)$$

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

Thus,

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

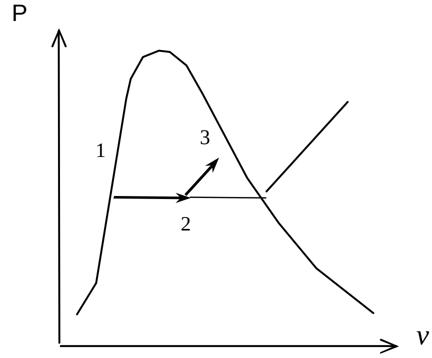
Discussion The positive sign for boundary work indicates that work is done by the system (work output).

4-29 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

$$P_3 = P_2 + \frac{F_s}{A} = P_2 + \frac{kx}{A} = (150\text{kPa}) + \frac{(100\text{kN/m})(0.2\text{m})}{0.1\text{m}^2}\left(\frac{1\text{kPa}}{1\text{kN/m}^2}\right) = \mathbf{350\ kPa}$$



The specific and total volumes at the three states are

$$\left.\begin{aligned} T_1 &= 25\,^\circ\text{C} \\ P_1 &= 150\text{kPa} \end{aligned}\right\} v_1 \cong v_{f\,@\,25^\circ\text{C}} = 0.001003\text{m}^3/\text{kg}$$

$$V_1 = mv_1 = (50\text{kg})(0.001003\text{m}^3/\text{kg}) = 0.05\text{m}^3$$

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

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

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

At 350 kPa, v_f = 0.0010 m^3/kg and v_g = 0.5243 m^3/kg. Noting that $v_f < v_3 < v_g$, the final state is a saturated mixture and thus the final temperature is

$$T_3 = T_{\text{sat@350 kPa}} = \mathbf{138.88\ ^\circ C}$$

(*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,

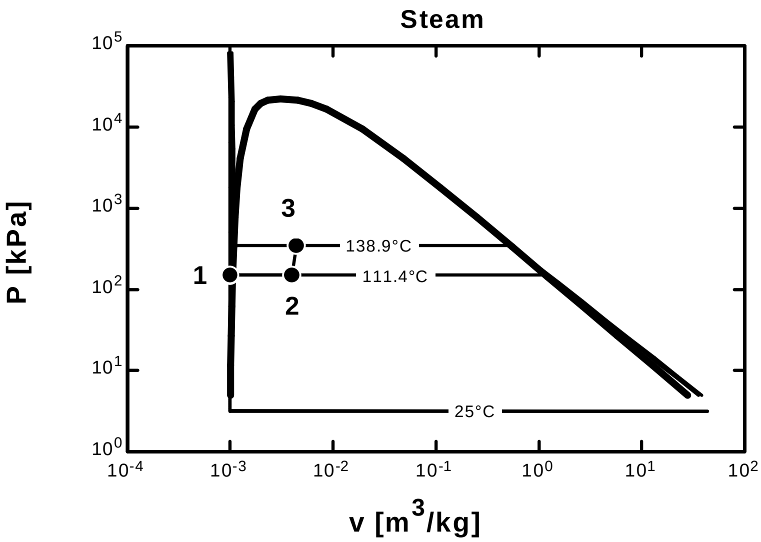
$$\begin{aligned} W_{b,\text{out}} &= \text{Area} = P_1(V_2 - V_1) + \frac{P_2 + P_3}{2}(V_3 - V_2) \\ &= \left((150\ \text{kPa})(0.2 - 0.05)\text{m}^3 + \frac{(150 + 350)\text{kPa}}{2}(0.22 - 0.2)\text{m}^3\right)\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= \mathbf{27.5\ \ kJ} \end{aligned}$$

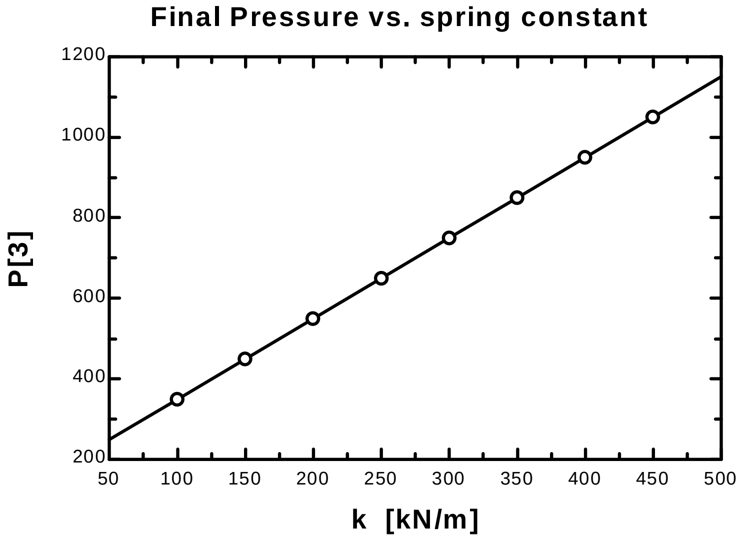
Discussion The positive sign indicates that work is done by the system (work output).

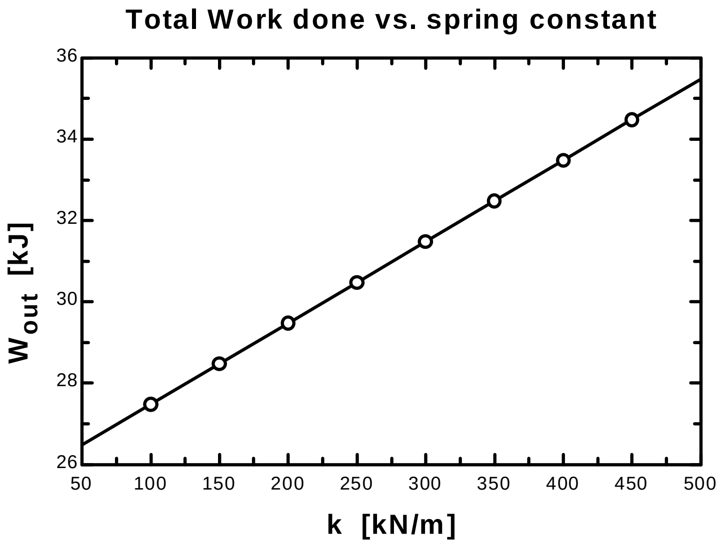
4-30 Problem 4-29 is reconsidered. The effect of the spring constant on the final pressure in the cylinder and the boundary work done as the spring constant varies from 50 kN/m to 500 kN/m is to be investigated. The final pressure and the boundary work are to be plotted against the spring constant.

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

Wnet_other = 0"[kJ]"
W_out=Wnet_other + W_b12+W_b23"[kJ]"
W_b12=P[1]*(V[2]-V[1])"[kJ]"
"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 "[kJ]"
```

k [kN/m]	P_3 [kPa]	W_{out} [kJ]
50	250	26.48
100	350	27.48
150	450	28.48
200	550	29.48
250	650	30.48
300	750	31.48
350	850	32.48
400	950	33.48
450	1050	34.48
500	1150	35.48


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


Final Pressure vs. spring constant
P[3]
k [kN/m]


Total Work done vs. spring constant
Wout [kJ]
k [kN/m]

4-31 Refrigerant-134a in a cylinder equipped with a set of stops is heated and evaporated. The vapor expands until the piston hits the stops. The final 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.

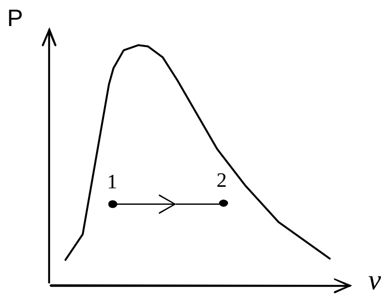
Analysis (a) This a constant pressure process. Initially the system contains a saturated mixture, and thus the pressure is

$$P_2 = P_1 = P_{sat@-8^\circ\mathrm{C}} = 217.04 \text{ kPa}$$

The specific volume of the refrigerant at the final state is

$$v_2 = \frac{V_2}{m} = \frac{0.4 \text{ m}^3}{10 \text{ kg}} = 0.04 \text{ m}^3/\text{kg}$$

At 217.04 kPa (or -8 °C), v_f = 0.0007569 m^3/kg and v_g = 0.0919 m^3/kg. Noting that $v_f < v_2 < v_g$, the final state is a saturated mixture and thus the final temperature is



$$T_2 = T_{\mathrm{sat@217.04kPa}} = \mathbf{-8^\circ C}$$

(*b*) The total initial volume is

$$V_1 = m_f v_f + m_g v_g = 8 \times 0.0007569 + 2 \times 0.0919 = 0.19 \text{ m}^3$$

Thus,

$$\begin{aligned} W_{b,\mathrm{out}} &= \int_1^2 P dV = P(V_2 - V_1) \\ &= (217.04 \text{ kPa})(0.4 - 0.19)\text{m}^3 \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \\ &= \mathbf{45.6 \ \ kJ} \end{aligned}$$

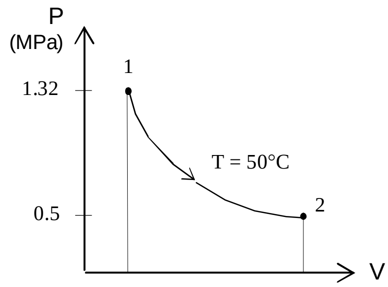
Discussion The positive sign indicates that work is done by the system (work output).

4-32 Saturated refrigerant-134a vapor in a cylinder is allowed to expand isothermally by gradually decreasing the pressure inside to 500 kPa. The boundary work done during this process is to be determined by using property data from the refrigerant tables, and by treating the refrigerant vapor as an ideal gas.

Assumptions The process is quasi-equilibrium.

Analysis From the refrigerant tables, the specific volume of the refrigerant at various pressures at 50°C are determined to be

P, MPa	***v*, m^3 / kg**
1.320	0.01505
1.200	0.01712
1.0	0.02171
0.9	0.02472
0.8	0.02846
0.7	0.03324
0.6	0.03958
0.5	0.04842



Plotting these on a P-V diagram and finding the area under the process curve, the boundary work during this isothermal process is determined to be

$$W_b = \mathbf{262.9\ kJ}$$

(*b*) Treating the refrigerant as an ideal gas, the boundary work for this isothermal process can be determined from

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

$$= (10\text{ kg})(0.08149\text{ kJ/kg}\cdot\text{K})(323\text{ K})\ln\frac{1320\text{ kPa}}{500\text{ kPa}}$$

$$= \mathbf{255.5\ kJ}$$

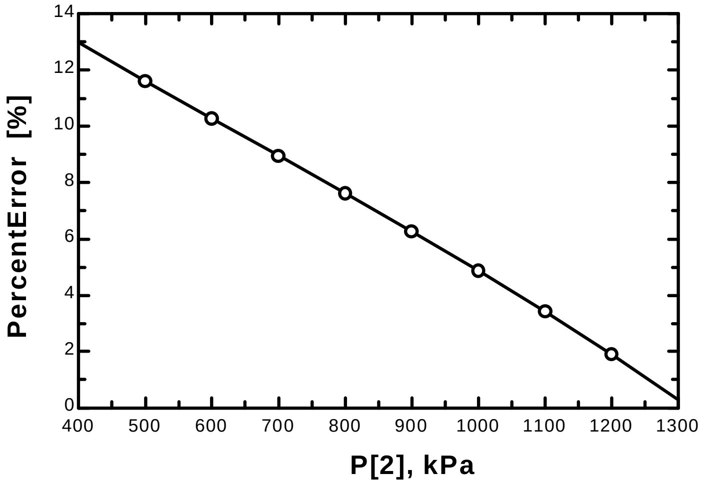
which is sufficiently close to the experimental value.

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

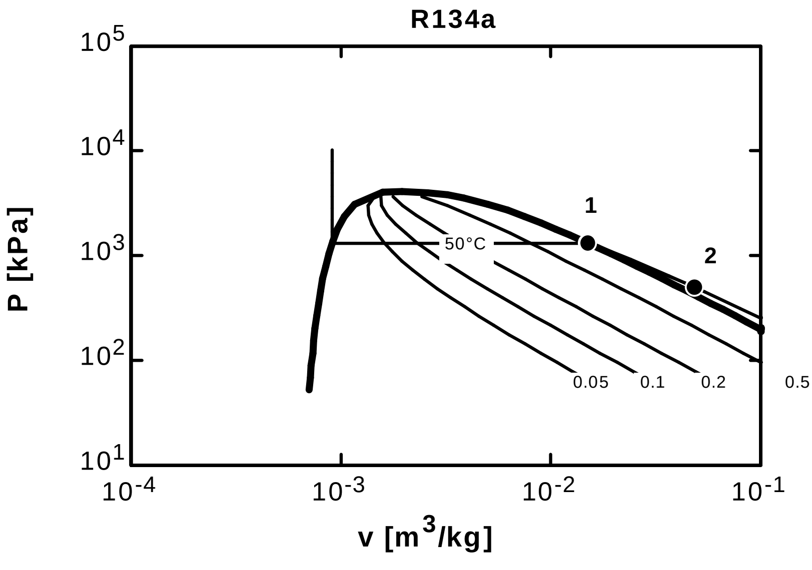
4-33 Problem 4-32 is reconsidered. Using the integration feature, the work done is to be calculated and compared to the result obtained by the ideal gas assumption. Also, the process is to be plotted on a P-v diagram.

```
"Let's plot the percent error as a function of P[2]"
"Knowns"
m=10"[kg]"
T[1]=50"[C]"
x[1]=1.0  "saturated vapor"
P[2]=500"[kPa]"  "Remove the {} when not using the solve table feature of EES."

"Solution"

"The process is isothermal:"
T[2]=T[1]"[C]"

Vol[1]=m*v[1]"[m^3]"
v[1]=volume(R134a,T=T[1],x=x[1])"[m^3/kg]"

Vol[2]=m*v[2]"[m^3]"
v[2]=volume(R134a,P=P[2],T=T[2])"[m^3/kg]"

"The boundary work is the integral of PdV over the isothermal process."

"The ideal gas result is:"

W_idealgas=P[1]*Vol[1]*ln(Vol[2]/Vol[1])"[kJ]"
P[1]=pressure(R134a,T=T[1],x=x[1])"[kPa]"

"The work using the experimental values is found by numerically integrating PdV
over the process.  P_int and V_int are integration functions"
P_int=pressure(R134a,T=T[1],v=v_int)"[kPa]"
m*v_int=Vol_int
W_exp=integral(P_int,Vol_int,Vol[1],Vol[2],0.005)"[kJ]"
PercentError=(W_exp-W_idealgas)/W_exp*100
```

PercentError [%]	P_2 [kPa]	W_{exp} [kJ]	$W_{idealgas}$ [kJ
0.2994	1300	3.857	3.845
1.914	1200	26.42	25.92
3.43	1100	50.55	48.82
4.875	1000	76.65	72.91
6.266	900	105.2	98.62
7.62	800	136.9	126.5
8.95	700	172.6	157.2
10.27	600	213.6	191.7
11.61	500	262	231.6
12.97	400	321	279.3



Percent error in the boundary work when treating R134a as an ideal gas during an isothermal expansion process.



4-34 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**.

Other Forms of Work

4-35C The work done is the same, but the power is different.

4-36C The work done is the same, but the power is different.

4-37 A car is accelerated from rest to 100 km/h. The work needed to achieve this is to be determined.

Analysis The work needed to accelerate a body the change in kinetic energy of the body,

$$W_a = \frac{1}{2}m\left(\mathbf{V}_2^2 - \mathbf{V}_1^2\right) = \frac{1}{2}(800\text{kg})\left(\left(\frac{100{,}000\text{m}}{3600\text{s}}\right)^2 - 0\right)\left(\frac{1\text{kJ}}{1000\text{kg}\cdot\text{m}^2/\text{s}^2}\right) = \mathbf{308.6kJ}$$

4-38 A car is accelerated from 20 to 70 km/h on an uphill road. The work needed to achieve this is to be determined.

Analysis The total work required is the sum of the changes in potential and kinetic energies,

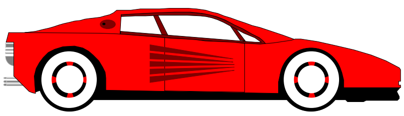
$$W_a = \frac{1}{2}m\left(\mathbf{V}_2^2 - \mathbf{V}_1^2\right) = \frac{1}{2}(2000\text{kg})\left(\left(\frac{70{,}000\text{m}}{3600\text{s}}\right)^2 - \left(\frac{20{,}000\text{m}}{3600\text{s}}\right)^2\right)\left(\frac{1\text{kJ}}{1000\text{kg}\cdot\text{m}^2/\text{s}^2}\right) = 347.2\text{kJ}$$

and,

$$W_g = mg(z_2 - z_1) = (2000\text{kg})(9.807\text{m/s}^2)(40\text{m})\left(\frac{1\text{kJ}}{1000\text{kg}\cdot\text{m}^2/\text{s}^2}\right) = 784.6\text{kJ}$$

Thus,

$$W_{\text{total}} = W_a + W_g = 347.2 + 784.6 = \mathbf{1131.8kJ}$$



4-39E A engine of a car develops 450 hp at 3000 rpm. The torque transmitted through the shaft is to be determined.

Analysis The torque is determined from

$$T=\frac{\dot{W}_{sh}}{2\pi\dot{n}}=\frac{450\text{ hp}}{2\pi(3000/60)/\text{s}}\left(\frac{550\text{ lbf}\cdot\text{ft/s}}{1\text{ hp}}\right)=\mathbf{787.8\ lbf\cdot ft}$$

4-40 A linear spring is elongated by 20 cm from its rest position. The work done is to be determined.

Analysis The spring work can be determined from

$$W_{spring}=\frac{1}{2}k\left(x_2^2-x_1^2\right)=\frac{1}{2}(70\text{ kN/m})(0.2^2-0)\text{m}^2=1.4\text{ kN}\cdot\text{m}=\mathbf{1.4\ \ kJ}$$

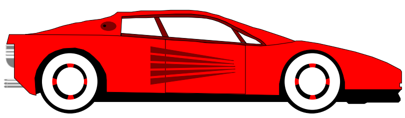
4-41 The engine of a car develops 75 kW of power. The acceleration time of this car from rest to 85 km/h on a level road is to be determined.

Analysis The work needed to accelerate a body is the change in its kinetic energy,

$$W_a=\frac{1}{2}m\left(\mathbf{V}_2^2-\mathbf{V}_1^2\right)=\frac{1}{2}(1500\text{ kg})\left(\left(\frac{85{,}000\text{ m}}{3600\text{ s}}\right)^2-0\right)\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)=418.1\text{ kJ}$$

Thus the time required is

$$\Delta t=\frac{W_a}{\dot{W}_a}=\frac{418.1\text{ kJ}}{75\text{ kJ/s}}=\mathbf{5.57\ \ s}$$



This answer is not realistic because part of the power will be used against the air drag, friction, and rolling resistance.

4-42 A ski lift is operating steadily at 10 km/h. The power required to operate and also to accelerate this ski lift from rest to the operating speed are to be determined.

Assumptions **1** Air drag and friction are negligible. **2** The average mass of each loaded chair is 250 kg. **3** The mass of chairs is small relative to the mass of people, and thus the contribution of returning empty chairs to the motion is disregarded (this provides a safety factor).

Analysis The lift is 1000 m long and the chairs are spaced 20 m apart. Thus at any given time there are 1000/20 = 50 chairs being lifted. Considering that the mass of each chair is 250 kg, the load of the lift at any given time is

Load = (50 chairs)(250 kg/chair) = 12,500 kg

Neglecting the work done on the system by the returning empty chairs, the work needed to raise this mass by 200 m is

$$W_g = mg(z_2 - z_1) = (12{,}500\text{ kg})(9.81\text{ m/s}^2)(200\text{ m})\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right) = 24{,}525\text{ kJ}$$

At 10 km/h, it will take

$$\Delta t = \frac{\text{distance}}{\text{velocity}} = \frac{1\text{ km}}{10\text{ km/h}} = 0.1\text{ h} = 360\text{ s}$$

to do this work. Thus the power needed is

$$\dot{W}_g = \frac{W_g}{\Delta t} = \frac{24{,}525\text{ kJ}}{360\text{ s}} = \mathbf{68.1\text{ kW}}$$

The velocity of the lift during steady operation, and the acceleration during start up are

$$\mathbf{V} = (10\text{ km/h})\left(\frac{1\text{ m/s}}{3.6\text{ km/h}}\right) = 2.778\text{ m/s}$$

$$a = \frac{\Delta\mathbf{V}}{\Delta t} = \frac{2.778\text{ m/s - 0}}{5\text{ s}} = 0.556\text{ m/s}^2$$

During acceleration, the power needed is

$$\dot{W}_a = \frac{1}{2}m\left(\mathbf{V}_2^2 - \mathbf{V}_1^2\right)/\Delta t = \frac{1}{2}(12{,}500\text{ kg})\left((2.778\text{ m/s})^2 - 0\right)\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)/(5\text{ s}) = 9.6\text{ kW}$$

Assuming the power applied is constant, the acceleration will also be constant and the vertical distance traveled during acceleration will be

$$h = \frac{1}{2}at^2\sin\alpha = \frac{1}{2}at^2\frac{200\text{ m}}{1000\text{ m}} = \frac{1}{2}(0.556\text{ m/s}^2)(5\text{ s})^2(0.2) = 1.39\text{ m}$$

and

$$\dot{W}_g = mg(z_2 - z_1)/\Delta t = (12{,}500\text{ kg})(9.81\text{ m/s}^2)(1.39\text{ m})\left(\frac{1\text{ kJ/kg}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(5\text{ s}) = 34.1\text{ kW}$$

Thus,

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = 9.6 + 34.1 = \mathbf{43.7\text{ kW}}$$

4-43 A car is to climb a hill in 10 s. The power needed is to be determined for three different cases.

Assumptions Air drag, friction, and rolling resistance are negligible.

Analysis The total power required for each case is the sum of the rates of changes in potential and kinetic energies. That is,

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g$$

(*a*) $\dot{W}_a = 0$ since the velocity is constant. Also, the vertical rise is h = (100 m)(sin 30°) = 50 m. Thus,

$$\dot{W}_g = mg(z_2 - z_1)/\Delta t = (2000\text{ kg})(9.81\text{ m/s}^2)(50\text{ m})\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(10\text{ s}) = 98.1\text{ kW}$$

and

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = 0 + 98.1 = \mathbf{98.1\ kW}$$

(*b*) The power needed to accelerate is

$$\dot{W}_a = \frac{1}{2}m(\mathbf{V}_2^2 - \mathbf{V}_1^2)/\Delta t = \frac{1}{2}(2000\text{kg})\left((30\text{m/s})^2 - 0\right)\left(\frac{1\text{kJ}}{1000\text{kg}\cdot\text{m}^2/\text{s}^2}\right)/(10\text{s}) = 90\text{kW}$$

and

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = 90 + 98.1 = \mathbf{188.1\ kW}$$

(*c*) The power needed to decelerate is

$$\dot{W}_a = \frac{1}{2}m(\mathbf{V}_2^2 - \mathbf{V}_1^2)/\Delta t = \frac{1}{2}(2000\text{kg})\left((5\text{m/s})^2 - (35\text{m/s})^2\right)\left(\frac{1\text{kJ}}{1000\text{kg}\cdot\text{m}^2/\text{s}^2}\right)/(10\text{s}) = -120\text{kW}$$

and

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = -120 + 98.1 = \mathbf{-21.9\ kW} \quad \text{(breaking power)}$$

4-44 A damaged car is being towed by a truck. The extra power needed is to be determined for three different cases.

Assumptions Air drag, friction, and rolling resistance are negligible.

Analysis The total power required for each case is the sum of the rates of changes in potential and kinetic energies. That is,

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g$$

(*a*) Zero.

(*b*) $\dot{W}_a = 0$. Thus,

$$\dot{W}_{\text{total}} = \dot{W}_g = mg(z_2 - z_1)/\Delta t = mg\frac{\Delta z}{\Delta t} = mg\mathbf{V}_z = mg\mathbf{V}\sin 30^{\circ}$$

$$= (1200\text{kg})(9.8\text{m/s}^2)\left(\frac{50{,}000\text{m}}{3600\text{s}}\right)\left(\frac{1\text{kJ/kg}}{1000\text{m}^2/\text{s}^2}\right)(0.5) = \mathbf{81.7kW}$$

(*c*) $\dot{W}_g = 0$. Thus,

$$\dot{W}_{\text{total}} = \dot{W}_a = \frac{1}{2}m\left(\mathbf{V}_2^2 - \mathbf{V}_1^2\right)/\Delta t$$

$$= \frac{1}{2}(1200\text{kg})\left(\left(\frac{90{,}000\text{m}}{3600\text{s}}\right)^2 - 0\right)\left(\frac{1\text{kJ/kg}}{1000\text{m}^2/\text{s}^2}\right)/(12\text{s}) = \mathbf{31.25kW}$$

Conservation of Mass

4-45C Mass flow rate is the amount of mass flowing through a cross-section per unit time whereas the volume flow rate is the amount of volume flowing through a cross-section per unit time.

4-46C The amount of mass or energy entering a control volume does not have to be equal to the amount of mass or energy leaving during an unsteady-flow process.

4-47C Flow through a control volume is steady when it involves no changes with time at any specified position.

4-48C No, a flow with the same volume flow rate at the inlet and the exit is not necessarily steady (unless the density is constant). To be steady, the mass flow rate through the device must remain constant.

4-49E A garden hose is used to fill a water bucket. The volume and mass flow rates of water, the filling time, and the discharge velocity are to be determined.

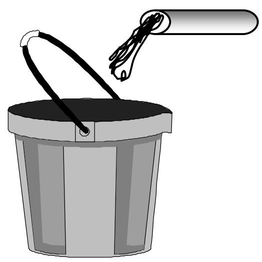
Assumptions **1** Water is an incompressible substance. **2** Flow through the hose is steady. **3** There is no waste of water by splashing.

Properties We take the density of water to be 62.4 lbm/ft^3.

Analysis (*a*) The volume and mass flow rates of water are

$$\dot{V} = A\mathbf{V} = (\pi D^2/4)\mathbf{V} = [\pi(1/12\text{ ft})^2/4](8\text{ ft/s}) = \mathbf{0.04363\,ft^3/s}$$

$$\dot{m} = \rho\dot{V} = (62.4\text{ lbm/ft}^3)(0.04363\text{ ft}^3\text{/s}) = \mathbf{2.72\,lbm/s}$$



(*b*) The time it takes to fill a 20-gallon bucket is

$$\Delta t = \frac{V}{\dot{V}} = \frac{20\text{ gal}}{0.04363\text{ ft}^3\text{/s}}\left(\frac{1\text{ ft}^3}{7.4804\text{ gal}}\right) = \mathbf{61.3\,s}$$

(*c*) The average discharge velocity of water at the nozzle exit is

$$\mathbf{V}_e = \frac{\dot{V}}{A_e} = \frac{\dot{V}}{\pi D_e^2/4} = \frac{0.04363\text{ ft}^3\text{/s}}{[\pi(0.5/12\text{ ft})^2/4]} = \mathbf{32\,ft/s}$$

Discussion Note that for a given flow rate, the average velocity is inversely proportional to the square of the velocity. Therefore, when the diameter is reduced by half, the velocity quadruples.

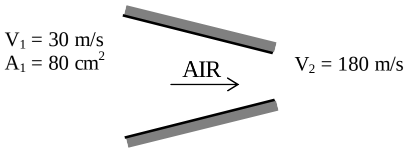
4-50 Air is accelerated in a nozzle. The mass flow rate and the exit area of the nozzle are to be determined.

Assumptions Flow through the nozzle is steady.

Properties The density of air is given to be 2.21 kg/m^3 at the inlet, and 0.762 kg/m^3 at the exit.

Analysis (a) The mass flow rate of air is determined from the inlet conditions to be

$$\dot{m} = \rho_1 A_1 V_1 = (2.21\,\text{kg/m}^3)(0.008\,\text{m}^2)(30\,\text{m/s}) = \mathbf{0.530\,kg/s}$$



(*b*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.
Then the exit area of the nozzle is determined to be

$$\dot{m} = \rho_2 A_2 \mathbf{V}_2 \longrightarrow A_2 = \frac{\dot{m}}{\rho_2 \mathbf{V}_2} = \frac{0.530\text{ kg/s}}{(0.762\text{ kg/m}^3)(180\text{ m/s})} = 0.00387\text{ m}^2 = \mathbf{38.7\,cm^2}$$

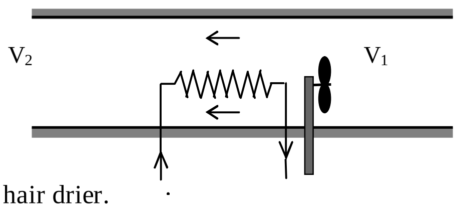
4-51 Air is expanded and is accelerated as it is heated by a hair dryer of constant diameter. The percent increase in the velocity of air as it flows through the drier is to be determined.

Assumptions Flow through the nozzle is steady.

Properties The density of air is given to be 1.20 kg/m^3 at the inlet, and 1.05 kg/m^3 at the exit.

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

$$\dot{m}_1 = \dot{m}_2$$
$$\rho_1 A \mathbf{V}_1 = \rho_2 A \mathbf{V}_2$$
$$\frac{\mathbf{V}_2}{\mathbf{V}_1} = \frac{\rho_1}{\rho_2} = \frac{1.20\,\text{kg/m}^3}{1.05\,\text{kg/m}^3} = 1.14 \quad \text{(or, and increase of } \mathbf{14\%}\text{)}$$



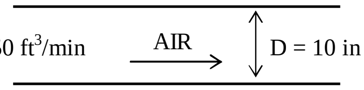
Therefore, the air velocity increases 14% as it flows through the hair drier.

4-52E The ducts of an air-conditioning system pass through an open area. The inlet velocity and the mass flow rate of air are to be determined.

Assumptions Flow through the air conditioning duct is steady.

Properties The density of air is given to be 0.078 lbm/ft^3 at the inlet.

Analysis The inlet velocity of air and the mass flow rate through the duct are



$$\mathbf{V}_1 = \frac{\dot{V}_1}{A_1} = \frac{\dot{V}_1}{\pi D^2/4} = \frac{450\ \text{ft}^3/\text{min}}{\pi(10/12\ \text{ft})^2/4} = \mathbf{825\ ft/min = 13.8\ ft/s}$$

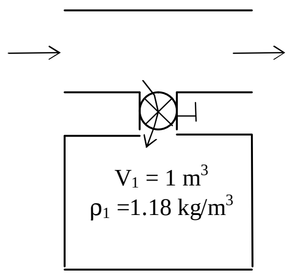
$$\dot{m} = \rho_1 \dot{V}_1 = (0.078\ \text{lbm/ft}^3)(450\ \text{ft}^3/\text{min}) = 35.1\ \text{lbm/min} = \mathbf{0.585\ lbm/s}$$

4-53 A rigid tank initially contains air at atmospheric conditions. The tank is connected to a supply line, and air is allowed to enter the tank until the density rises to a specified level. The mass of air that entered the tank is to be determined.

Properties The density of air is given to be 1.18 kg/m^3 at the beginning, and 7.20 kg/m^3 at the end.

Analysis We take the tank as the system, which is a control volume since mass crosses the boundary. The mass balance for this system can be expressed as

Mass balance: $m_{in} - m_{out} = \Delta m_{\text{system}} \rightarrow m_i = m_2 - m_1 = \rho_2 V - \rho_1 \text{V}$



Substituting,

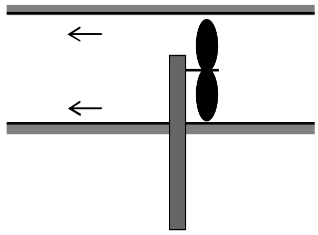
$$m_i = (\rho_2 - \rho_1)\text{V} = [(7.20 - 1.18)\ \text{kg/m}^3](1\ \text{m}^3) = 6.02\ \text{kg}$$

Therefore, 6.02 kg of mass entered the tank.

4-54 The ventilating fan of the bathroom of a building runs continuously. The mass of air "vented out" per day is to be determined.

Assumptions Flow through the fan is steady.

Properties The density of air in the building is given to be 1.20 kg/m^3.



Analysis The mass flow rate of air vented out is

$$\dot{m}_{\text{air}} = \rho \dot{V}_{\text{air}} = (1.20\ \text{kg/m}^3)(0.030\ \text{m}^3/\text{s}) = 0.036\ \text{kg/s}$$

Then the mass of air vented out in 24 h becomes

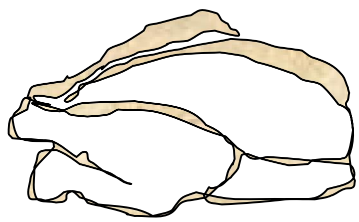
$$m = \dot{m}_{\text{air}} \Delta t = (0.036\ \text{kg/s})(24 \times 3600\ \text{s}) = \mathbf{3110\ kg}$$

Discussion Note that more than 3 tons of air is vented out by a bathroom fan in one day.

4-55E Chickens are to be cooled by chilled water in an immersion chiller. The mass flow rate of chicken through the chiller is to be determined.

Assumptions Chickens are dropped into the chiller steadily.

Properties The average mass of a chicken is 4.5 lbm.



Analysis Chickens are dropped into the chiller at a rate of 500 per hour. Therefore, chickens can be considered to flow steadily through the chiller at a mass flow rate of

$$\dot{m}_{\text{chicken}} = (500\ \text{chicken/h})(4.5\ \text{lbm/chicken}) = 2250\ \text{kg/h} = \mathbf{0.625\ lbm/s}$$

Note that chicken can be treated conveniently as a "flowing fluid" in calculations.

4-56 A desktop computer is to be cooled by a fan at a high elevation where the air density is low. The mass flow rate of air through the fan and the diameter of the casing for a given velocity are to be determined.

Assumptions Flow through the fan is steady.

Properties The density of air at a high elevation is given to be 0.7 kg/m^3.

Analysis The mass flow rate of air is

$$\dot{m}_{\text{air}} = \rho \dot{V}_{\text{air}} = (0.7\ \text{kg/m}^3)(0.34\ \text{m}^3/\text{min}) = 0.238\ \text{kg/min} = \mathbf{0.0040\ kg/s}$$

If the mean velocity is 110 m/min, the diameter of the casing is

$$\dot{V} = A\mathbf{V} = \frac{\pi D^2}{4}\mathbf{V} \quad \rightarrow \quad D = \sqrt{\frac{4\dot{V}}{\pi \mathbf{V}}} = \sqrt{\frac{4(0.34\ \text{m}^3/\text{min})}{\pi(110\ \text{m/min})}} = \mathbf{0.063\,m}$$

Therefore, the diameter of the casing must be at least 6.3 cm to ensure that the mean velocity does not exceed 110 m/min.

Discussion This problem shows that engineering systems are sized to satisfy certain constraints imposed by certain considerations.

Flow Work and Energy Transfer by Mass

4-57C Energy can be transferred to or from a control volume as heat, various forms of work, and by mass.

4-58C Flow energy or flow work is the energy needed to push a fluid into or out of a control volume. Fluids at rest do not possess any flow energy.

4-59C Flowing fluids possess flow energy in addition to the forms of energy a fluid at rest possesses. The total energy of a fluid at rest consists of internal, kinetic, and potential energies. The total energy of a flowing fluid consists of internal, kinetic, potential, and flow energies.

4-60E Steam is leaving a pressure cooker at a specified pressure. The velocity, flow rate, the total and flow energies, and the rate of energy transfer by mass are to be determined.

Assumptions **1** The flow is steady, and the initial start-up period is disregarded. **2** The kinetic and potential energies are negligible, and thus they are not considered. **3** Saturation conditions exist within the cooker at all times so that steam leaves the cooker as a saturated vapor at 30 psia.

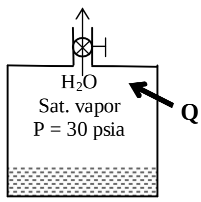
Properties The properties of saturated liquid water and water vapor at 30 psia are v_f = 0.017004 ft^3/lbm, v_g = 13.748 ft^3/lbm, u_g = 1088.0 Btu/lbm, and h_g = 1164.3 Btu/lbm (Table A-5E).

Analysis (*a*) Saturation conditions exist in a pressure cooker at all times after the steady operating conditions are established. Therefore, the liquid has the properties of saturated liquid and the exiting steam has the properties of saturated vapor at the operating pressure. The amount of liquid that has evaporated, the mass flow rate of the exiting steam, and the exit velocity are

$$m = \frac{\Delta V_{\text{liquid}}}{v_f} = \frac{0.4\text{ gal}}{0.017004\text{ ft}^3/\text{lbm}}\left(\frac{0.13368\text{ ft}^3}{1\text{ gal}}\right) = 3.145\text{ lbm}$$

$$\dot{m} = \frac{m}{\Delta t} = \frac{3.145\text{ lbm}}{45\text{ min}} = 0.0699\text{ lbm/min} = \mathbf{1.165\times10^{-3}\ lbm/s}$$

$$\mathbf{V} = \frac{\dot{m}}{\rho_g A_c} = \frac{\dot{m}v_g}{A_c} = \frac{(1.165\times10^{-3}\text{ lbm/s})(13.748\text{ ft}^3/\text{lbm})}{0.15\text{ in}^2}\left(\frac{144\text{ in}^2}{1\text{ ft}^2}\right) = \mathbf{15.4\ ft/s}$$



(*b*) Noting that $h = u + Pv$ and that the kinetic and potential energies are disregarded, the flow and total energies of the exiting steam are

$$e_{\text{flow}} = Pv = h - u = 1164.3 - 1088.0 = \mathbf{76.3\ Btu/lbm}$$

$$\theta = h + ke + pe \cong h = \mathbf{1164.3\ Btu/lbm}$$

Note that the kinetic energy in this case is ke = $\mathbf{V}^2/2$ = (15.4 ft/s)^2 = 237 ft^2/s^2 = 0.0095 Btu/lbm, which is very small compared to enthalpy.

(*c*) The rate at which energy is leaving the cooker by mass is simply the product of the mass flow rate and the total energy of the exiting steam per unit mass,

$$\dot{E}_{\text{mass}} = \dot{m}\theta = (1.165\times10^{-3}\text{ lbm/s})(1164.3\text{ Btu/lbm}) = \mathbf{1.356\ Btu/s}$$

Discussion The numerical value of the energy leaving the cooker with steam alone does not mean much since this value depends on the reference point selected for enthalpy (it could even be negative). The significant quantity is the difference between the enthalpies of the exiting vapor and the liquid inside (which is h_{fg}) since it relates directly to the amount of energy supplied to the cooker.

4-61 Refrigerant-134a enters a compressor as a saturated vapor at a specified pressure, and leaves as superheated vapor at a specified rate. The rates of energy transfer by mass into and out of the compressor are to be determined.

Assumptions **1** The flow of the refrigerant through the compressor is steady. **2** The kinetic and potential energies are negligible, and thus they are not considered.

Properties The enthalpy of refrigerant-134a at the inlet and the exit are (Tables A-12 and A-13)

$$h_1 = h_{g@0.14\text{ MPa}} = 236.04\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 0.8\text{ MPa} \\ T_2 = 50°\text{C} \end{array}\right\} h_2 = 284.39\text{ kJ/kg}$$

Analysis Noting that the total energy of a flowing fluid is equal to its enthalpy when the kinetic and potential energies are negligible, and that the rate of energy transfer by mass is equal to the product of the mass flow rate and the total energy of the fluid per unit mass, the rates of energy transfer by mass into and out of the compressor are

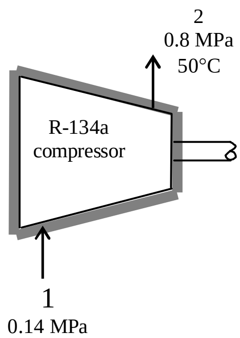
$$\dot{E}_{\text{mass, in}} = \dot{m}\theta_{in} = \dot{m}h_1 = (0.04\text{ kg/s})(236.04\text{ kJ/kg}) = 9.442\text{ kJ/s} = \mathbf{9.44\ kW}$$

$$\dot{E}_{\text{mass, out}} = \dot{m}\theta_{out} = \dot{m}h_2 = (0.04\text{ kg/s})(284.39\text{ kJ/kg}) = 11.38\text{ kJ/s} = \mathbf{11.38\ kW}$$

Discussion The numerical values of the energy entering or leaving a device by mass alone does not mean much since this value depends on the reference point selected for enthalpy (it could even be negative). The significant quantity here is the difference between the outgoing and incoming energy flow rates, which is

$$\Delta\dot{E}_{\text{mass}} = \dot{E}_{\text{mass, out}} - \dot{E}_{\text{mass, in}} = 11.38 - 9.44 = 1.94\text{ kW}$$

This quantity represents the rate of energy transfer to the refrigerant in the compressor.



4-62 Warm air in a house is forced to leave by the infiltrating cold outside air at a specified rate. The net energy loss due to mass transfer is to be determined.

Assumptions **1** The flow of the air into and out of the house through the cracks is steady. **2** The kinetic and potential energies are negligible. **3** Air is an ideal gas with constant specific heats at room temperature.

Properties The gas constant of air is R = 0.287 kPa·m^3/kg·K (Table A-1). The constant pressure specific heat of air at room temperature is C_p = 1.005 kJ/kg·°C (Table A-2).

Analysis The density of air at the indoor conditions and its mass flow rate are

$$\rho = \frac{P}{RT} = \frac{101.325\,\text{kPa}}{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(24+273)\text{K}} = 1.189\,\text{kg/m}^3$$

$$\dot{m} = \rho\dot{V} = (1.189\,\text{kg/m}^3)(150\,\text{m}^3/\text{h}) = 178.35\,\text{kg/h} = 0.0495\,\text{kg/s}$$

Noting that the total energy of a flowing fluid is equal to its enthalpy when the kinetic and potential energies are negligible, and that the rate of energy transfer by mass is equal to the product of the mass flow rate and the total energy of the fluid per unit mass, the rates of energy transfer by mass into and out of the house by air re

$$\dot{E}_{\text{mass, in}} = \dot{m}\theta_{in} = \dot{m}h_1$$

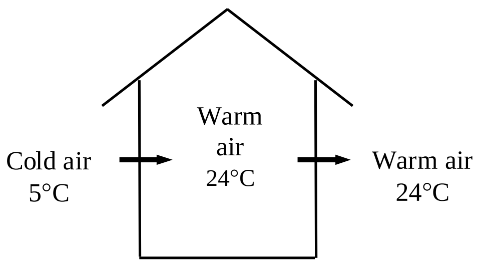
$$\dot{E}_{\text{mass, out}} = \dot{m}\theta_{out} = \dot{m}h_2$$

The net energy loss by air infiltration is equal to the difference between the outgoing and incoming energy flow rates, which is

$$\begin{aligned}\Delta\dot{E}_{\text{mass}} &= \dot{E}_{\text{mass, out}} - \dot{E}_{\text{mass, in}} = \dot{m}(h_2 - h_1) = \dot{m}C_p(T_2 - T_1)\\ &= (0.0495\,\text{kg/s})(1.005\,\text{kJ/kg}\cdot{}^\circ\text{C})(24-5)^\circ\text{C} = 0.945\,\text{kJ/s}\\ &= \mathbf{0.945\,kW}\end{aligned}$$

This quantity represents the rate of energy transfer to the refrigerant in the compressor.

Discussion The rate of energy loss by infiltration will be less in reality since some air will leave the house before it is fully heated to 24°C.



Review Problems

4-63 The weight of the cabin of an elevator is balanced by a counterweight. The power needed when the fully loaded cabin is rising , and when the empty cabin is descending at a constant speed are to be determined.

Assumptions **1** The weight of the cables is negligible. **2** The guide rails and pulleys are frictionless. **3** Air drag is negligible.

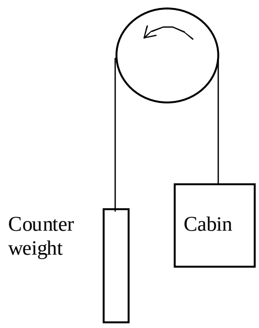
Analysis (*a*) When the cabin is fully loaded, half of the weight is balanced by the counterweight. The power required to raise the cabin at a constant speed of 2 m/s is

$$\dot{W} = \frac{mgz}{\Delta t} = mg\mathbf{V} = (400\text{kg})(9.8\text{m/s}^2)(2\text{m/s})\left(\frac{1\text{N}}{1\text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\text{kW}}{1000\text{N}\cdot\text{m/s}}\right) = \mathbf{7.84kW}$$

If no counterweight is used, the mass would double to 800 kg and the power would be 2×7.84 = **15.68 kW**.

(*b*) When the empty cabin is descending (and the counterweight is ascending) there is mass imbalance of 400-150 = 250 kg. The power required to raise this mass at a constant speed of 2 m/s is

$$\dot{W} = \frac{mgz}{\Delta t} = mg\mathbf{V} = (250\text{ kg})(9.81\text{ m/s}^2)(2\text{ m/s})\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1\text{ kW}}{1000\text{ N}\cdot\text{m/s}}\right) = \mathbf{4.9\text{ kW}}$$



If a friction force of 1200 N develops between the cabin and the guide rails, we will need

$$\dot{W}_{\text{friction}} = \frac{F_{\text{friction}}z}{\Delta t} = F_{\text{friction}}\mathbf{V} = (1200\text{ N})(2\text{ m/s})\left(\frac{1\text{ kW}}{1000\text{ N}\cdot\text{m/s}}\right) = 2.4\text{ kW}$$

of additional power to combat friction which always acts in the opposite direction to motion. Therefore, the total power needed in this case is

$$\dot{W}_{\text{total}} = \dot{W} + \dot{W}_{\text{friction}} = 4.9 + 2.4 = \mathbf{7.3kW}$$

4-64 A cylinder equipped with an external spring is initially filled with air at a specified state. Heat is transferred to the air, and both the temperature and pressure rise. The total boundary work done by the air, and the amount of work done against the spring are to be determined, and the process is to be shown on a *P-v* diagram.

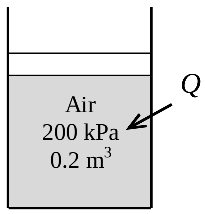
Assumptions **1** The process is quasi-equilibrium. **2** The spring is a linear spring.

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

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

$$= \frac{(200 + 800)\text{kPa}}{2}(0.5 - 0.2)\text{m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

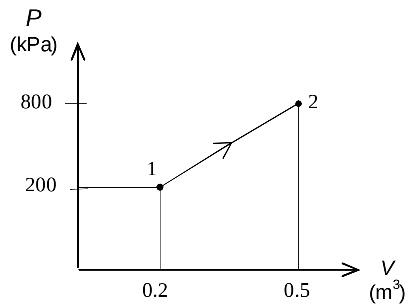
$$= \mathbf{150\ kJ}$$



(*b*) If there were no spring, we would have a constant pressure process at P = 200 kPa. The work done during this process is

$$W_{\text{b,out,nospring}} = \int_1^2 PdV = P(V_2 - V_1)$$

$$= (200\text{ kPa})(0.5 - 0.2)\text{m}^3/\text{kg}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 60\text{ kJ}$$



Thus,

$$W_{\text{spring}} = W_b - W_{\text{b,nospring}} = 150 - 60 = \mathbf{90\ kJ}$$

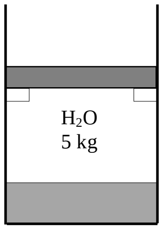
4-65 A cylinder equipped with a set of stops for the piston is initially filled with saturated liquid-vapor mixture of water a specified pressure. Heat is transferred to the water until the volume increases by 20%. The initial and final temperature, the mass of the liquid when the piston starts moving, and the work done during the process are to be determined, and the process is to be shown on a *P-v* diagram.

Assumptions The process is quasi-equilibrium.

Analysis (*a*) Initially the system is a saturated mixture at 100 kPa pressure, and thus the initial temperature is

$$T_1 = T_{sat@100\text{ kPa}} = \mathbf{99.63^\circ C}$$

The total initial volume is



$$V_1 = m_f v_f + m_g v_g = 2\times 0.001043 + 3\times 1.6940 = 5.084\text{ m}^3$$

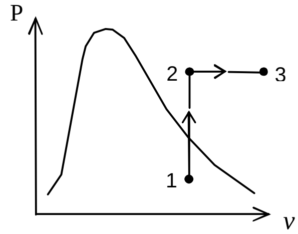
Then the total and specific volumes at the final state are

$$V_3 = 1.2V_1 = 1.2\times 5.084 = 6.101\text{ m}^3$$

$$v_3 = \frac{V_3}{m} = \frac{6.101\text{ m}^3}{5\text{ kg}} = 1.220\text{ m}^3/\text{kg}$$

Thus,

$$\left.\begin{array}{l} P_3 = 200\text{ kPa} \\ v_3 = 1.220\text{ m}^3/\text{kg} \end{array}\right\} T_3 = \mathbf{259.0^\circ C}$$



(*b*) When the piston first starts moving, P_2 = 200 kPa and $V_2 = V_1$ = 5.084 m^3. The specific volume at this state is

$$v_2 = \frac{V_2}{m} = \frac{5.084\text{ m}^3}{5\text{ kg}} = 1.017\text{ m}^3/\text{kg}$$

which is greater than v_g = 0.8857 m^3/kg at 200 kPa. Thus **no liquid** is left in the cylinder when the piston starts moving.

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

$$W_b = \int_2^3 P dV = P_2(V_3 - V_2) = (200\text{ kPa})(6.101 - 5.084)\text{m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = \mathbf{203\ kJ}$$

4-66E A spherical balloon is initially filled with air at a specified state. The pressure inside is proportional to the square of the diameter. Heat is transferred to the air until the volume doubles. The work done is to be determined.

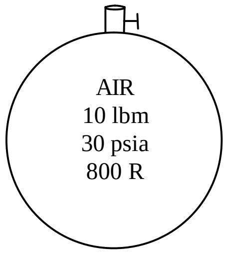
Assumptions **1** Air is an ideal gas. **2** The process is quasi-equilibrium.

Properties The gas constant of air is R = 0.06855 Btu/lbm.R (Table A-1E).

Analysis The dependence of pressure on volume can be expressed as

$$V = \frac{1}{6}\pi D^3 \longrightarrow D = \left(\frac{6V}{\pi}\right)^{1/3}$$

$$P \propto D^2 \longrightarrow P = kD^2 = k\left(\frac{6V}{\pi}\right)^{2/3}$$



or, $$k\left(\frac{6}{\pi}\right)^{2/3} = P_1 V_1^{-2/3} = P_2 V_2^{-2/3}$$

Also, $$\frac{P_2}{P_1} = \left(\frac{V_2}{V_1}\right)^{2/3} = 2^{2/3} = 1.587$$

and $$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \longrightarrow T_2 = \frac{P_2V_2}{P_1V_1}T_1 = 1.587 \times 2 \times (800\text{R}) = 2539\text{R}$$

Thus,

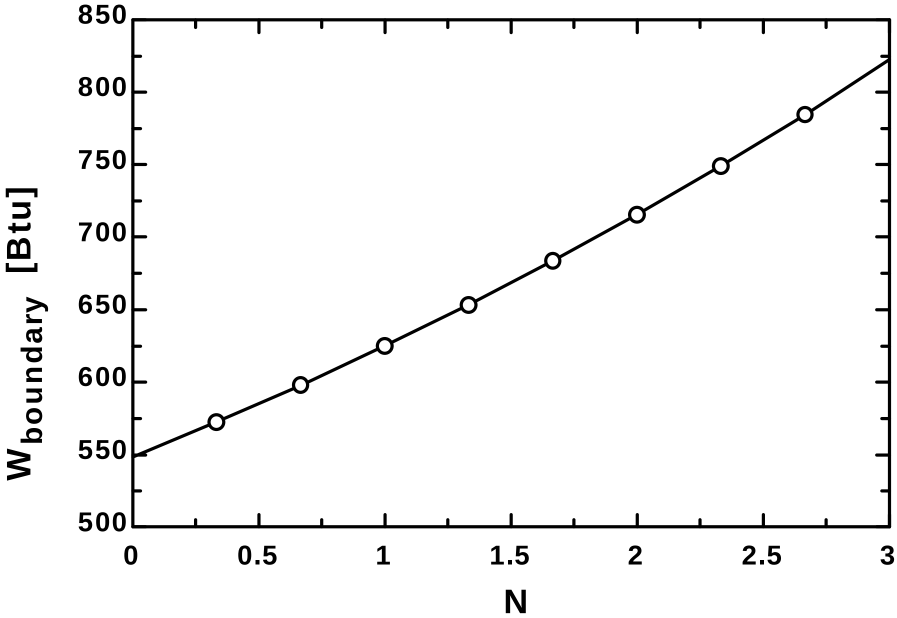
$$W_b = \int_1^2 P dV = \int_1^2 k\left(\frac{6V}{\pi}\right)^{2/3} dV = \frac{3k}{5}\left(\frac{6}{\pi}\right)^{2/3}\left(V_2^{5/3} - V_1^{5/3}\right) = \frac{3}{5}(P_2V_2 - P_1V_1)$$

$$= \frac{3}{5}mR(T_2 - T_1) = \frac{3}{5}(10\text{ lbm})(0.06855\text{ Btu/lbm}\cdot\text{R})(2539 - 800)\text{R} = \mathbf{715\ Btu}$$

4-67E Problem 4-66E is reconsidered. Using the integration feature, the work done is to be determined and compared to the 'hand calculated' result.

```
N=2
m=10"[lbm]"
P_1=30"[psia]"
T_1=800"[R]"
V_2=2*V_1
R=1545"[ft-lbf/lbmol-R]"/molarmass(air)"[ft-lbf/lbm-R]"
P_1*Convert(psia,lbf/ft^2)*V_1=m*R*T_1
V_1=4*pi*(D_1/2)^3/3"[ft^3]"
C=P_1/D_1^N
(D_1/D_2)^3=V_1/V_2
P_2=C*D_2^N"[psia]"
P_2*Convert(psia,lbf/ft^2)*V_2=m*R*T_2

P=C*D^N*Convert(psia,lbf/ft^2)"[ft^2]"
V=4*pi*(D/2)^3/3"[ft^3]"

W_boundary_EES=integral(P,V,V_1,V_2)*convert(ft-lbf,Btu)"[Btu]"
W_boundary_HAND=pi*C/(2*(N+3))*(D_2^(N+3)-D_1^(N+3))*convert(ft-
lbf,Btu)*convert(ft^2,in^2)"[Btu]"
```

N	$W_{boundary}$ [Btu]
0	548.3
0.3333	572.5
0.6667	598.1
1	625
1.333	653.5
1.667	683.7
2	715.5
2.333	749.2
2.667	784.8
3	822.5

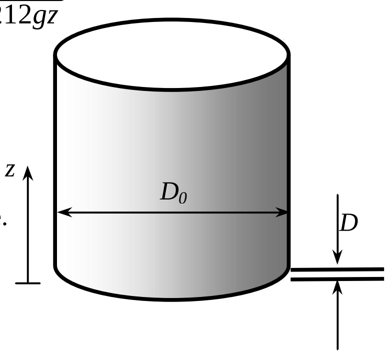


4-68 A water tank open to the atmosphere is initially filled with water. The tank discharges to the atmosphere through a long pipe connected to a valve. The initial discharge velocity from the tank and the time required to empty the tank are to be determined. √

Assumptions **1** The flow is uniform and incompressible. **2** The draining pipe is horizontal. **3** The tank is considered to be empty when the water level drops to the center of the valve.

Analysis (*a*) Substituting the known quantities, the discharge velocity can be expressed as

$$\mathbf{V} = \sqrt{\frac{2gz}{1.5 + fL/D}} = \sqrt{\frac{2gz}{1.5 + 0.015(100\,\text{m})/(0.10\,\text{m})}} = \sqrt{0.1212gz}$$



Then the initial discharge velocity becomes

$$\mathbf{V}_1 = \sqrt{0.1212gz_1} = \sqrt{0.1212(9.81\,\text{m/s}^2)(2\,\text{m})} = \mathbf{1.54\ m/s}$$

where z is the water height relative to the center of the orifice at that time.

(*b*) The flow rate of water from the tank can be obtained by multiplying the discharge velocity by the pipe cross-sectional area,

$$\dot{V} = A_{\text{pipe}}\mathbf{V}_2 = \frac{\pi D^2}{4}\sqrt{0.1212gz}$$

Then the amount of water that flows through the pipe during a differential time interval dt is

$$dV = \dot{V}dt = \frac{\pi D^2}{4}\sqrt{0.1212gz}\,dt \qquad (1)$$

which, from conservation of mass, must be equal to the decrease in the volume of water in the tank,

$$dV = A_{\tan k}(-dz) = -\frac{\pi D_0^2}{4}dz \qquad (2)$$

where dz is the change in the water level in the tank during dt. (Note that dz is a negative quantity since the positive direction of z is upwards. Therefore, we used $-dz$ to get a positive quantity for the amount of water discharged). Setting Eqs. (1) and (2) equal to each other and rearranging,

$$\frac{\pi D^2}{4}\sqrt{0.1212gz}\,dt = -\frac{\pi D_0^2}{4}dz \;\rightarrow\; dt = -\frac{D_0^2}{D^2}\frac{dz}{\sqrt{0.1212gz}} = -\frac{D_0^2}{D^2\sqrt{0.1212g}}z^{-\frac{1}{2}}dz$$

The last relation can be integrated easily since the variables are separated. Letting t_f be the discharge time and integrating it from $t = 0$ when $z = z_1$ to $t = t_f$ when $z = 0$ (completely drained tank) gives

$$\int_{t=0}^{t_f} dt = -\frac{D_0^2}{D^2\sqrt{0.1212g}}\int_{z=z_1}^{0} z^{-1/2}dz \;\rightarrow\; t_f = -\frac{D_0^2}{D^2\sqrt{0.1212g}}\left|\frac{z^{\frac{1}{2}}}{\frac{1}{2}}\right|_{z_1}^{0} = \frac{2D_0^2}{D^2\sqrt{0.1212g}}z_1^{\frac{1}{2}}$$

Simplifying and substituting the values given, the draining time is determined to be

$$t_f = \frac{2D_0^2}{D^2}\sqrt{\frac{z_1}{0.1212g}} = \frac{2(10\,\text{m})^2}{(0.1\,\text{m})^2}\sqrt{\frac{2\,\text{m}}{0.1212(9.81\,\text{m/s}^2)}} = 25{,}940\,\text{s} = \mathbf{7.21\,h}$$

Discussion The draining time can be shortened considerably by installing a pump in the pipe.

4-69 Milk is transported from Texas to California in a cylindrical tank. The amount of milk in the tank is to be determined.

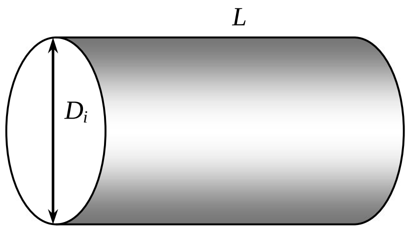
Assumptions Milk is mostly water, and thus the properties of water can be used for milk.

Properties The density of milk is the same as that of water, $\rho = 1000\ \text{kg/m}^3$.

Analysis Noting that the thickness of insulation is 0.05 m on all sides, the volume and mass of the milk in a full tank is determined to be

$$V_{\text{milk}} = (\pi D_i^2/4)L_i = [\pi(1.9\ \text{m})^2/4](6.9\ \text{m}) = 19.56\ \text{m}^3$$

$$m_{\text{milk}} = \rho V_{\text{milk}} = (1000\ \text{kg/m}^3)(19.56\ \text{m}^3) = \mathbf{19{,}560\ \ kg}$$



The volume of the milk in gallons is

$$V_{\text{milk}} = (19.56\ \text{m}^3)\left(\frac{264.17\ \text{gal}}{1\ \text{m}^3}\right) = \mathbf{5167\ gal}$$

4-70 The rate of accumulation of water in a pool and the rate of discharge are given. The rate supply of water to the pool is to be determined.

Assumptions **1** Water is supplied and discharged steadily. **2** The rate of evaporation of water is negligible. **3** No water is supplied or removed through other means.

Analysis The conservation of mass principle applied to the pool requires that the rate of increase in the amount of water in the pool be equal to the difference between the rate of supply of water and the rate of discharge. That is,

$$\frac{dm_{\text{pool}}}{dt} = \dot{m}_i - \dot{m}_e \quad \rightarrow \quad \dot{m}_i = \frac{dm_{\text{pool}}}{dt} + \dot{m}_e \quad \rightarrow \quad \dot{V}_i = \frac{dV_{\text{pool}}}{dt} + \dot{V}_e$$

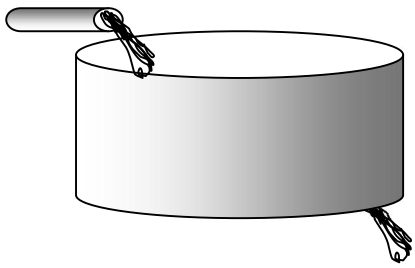
since the density of water is constant and thus the conservation of mass is equivalent to conservation of volume. The rate of discharge of water is

$$\dot{V}_e = A_e \mathbf{V}_e = (\pi D^2/4)\mathbf{V}_e = [\pi(0.05\,\text{m})^2/4](5\,\text{m/s}) = 0.00982\,\text{m}^3/\text{s}$$

The rate of accumulation of water in the pool is equal to the cross-section of the pool times the rate at which the water level rises,

$$\frac{dV_{\text{pool}}}{dt} = A_{\text{cross-section}} \mathbf{V}_{\text{level}} = (3\,\text{m} \times 4\,\text{m})(0.015\,\text{m/min}) = 0.18\,\text{m}^3/\text{min} = 0.00300\,\text{m}^3/\text{s}$$

Substituting, the rate at which water is supplied to the pool is determined to be

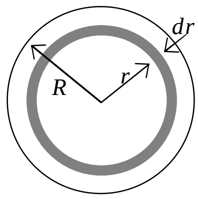


$$\dot{V}_i = \frac{dV_{\text{pool}}}{dt} + \dot{V}_e = 0.003 + 0.00982 = \mathbf{0.01282\ m^3/s}$$

Therefore, water is supplied at a rate of 0.01282 m^3/s = 12.82 L/s.

4-71 A fluid is flowing in a circular pipe. A relation is to be obtained for the average fluid velocity in therms of $V(r)$, R, and r.

Analysis Choosing a circular ring of area dA = 2πrdr as our differential area, the mass flow rate through a cross-sectional area can be expressed as



$$\dot{m} = \int_A \rho \mathbf{V}(r) dA = \int_0^R \rho \mathbf{V}(r) 2\pi r\, dr$$

Setting this equal to and solving for V_{av},

$$\mathbf{V}_{av} = \frac{2}{R^2}\int_0^R \mathbf{V}(r) r\, dr$$

4-72 Air is accelerated in a nozzle. The density of air at the nozzle exit is to be determined.

Assumptions Flow through the nozzle is steady.

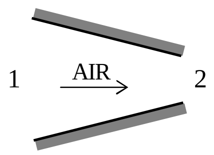
Properties The density of air is given to be 4.18 kg/m^3 at the inlet.

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

$$\dot{m}_1 = \dot{m}_2$$

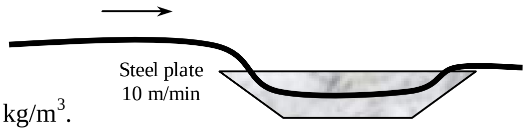
$$\rho_1 A_1 \mathbf{V}_1 = \rho_2 A_2 \mathbf{V}_2$$

$$\rho_2 = \frac{A_1}{A_2}\frac{\mathbf{V}_1}{\mathbf{V}_2}\rho_1 = 2\frac{120\ \text{m/s}}{380\ \text{m/s}}(4.18\ \text{kg/m}^3) = \mathbf{2.64\ kg/m^3}$$



Discussion Note that the density of air decreases considerably despite a decrease in the cross-sectional area of the nozzle.

4-73 A long roll of large 1-Mn manganese steel plate is to be quenched in an oil bath at a specified rate. The mass flow rate of the plate is to be determined.



Assumptions The plate moves through the bath steadily.

Properties The density of steel plate is given to be ρ = 7854 kg/m³.

Analysis The mass flow rate of the sheet metal through the oil bath is

$$\dot{m} = \rho \dot{V} = \rho w t V = (7854\,\text{kg/m}^3)(1\,\text{m})(0.005\,\text{m})(10\,\text{m/min}) = 393\,\text{kg/min} = \mathbf{6.55\,kg/s}$$

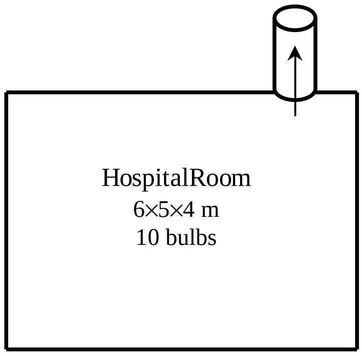
Therefore, steel plate can be treated conveniently as a "flowing fluid" in calculations.

4-74 The air in a hospital room is to be replaced every 20 minutes. The minimum diameter of the duct is to be determined if the air velocity is not to exceed a certain value.

Assumptions **1** The volume occupied by the furniture etc in the room is negligible. **2** The incoming conditioned air does not mix with the air in the room.

Analysis The volume of the room is

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



To empty this air in 20 min, the volume flow rate must be

$$\dot{V} = \frac{V}{\Delta t} = \frac{120\,\text{m}^3}{20 \times 60\,\text{s}} = 0.10\,\text{m}^3/\text{s}$$

If the mean velocity is 5 m/s, the diameter of the duct is

$$\dot{V} = A\mathbf{V} = \frac{\pi D^2}{4}\mathbf{V} \quad \rightarrow \quad D = \sqrt{\frac{4\dot{V}}{\pi \mathbf{V}}} = \sqrt{\frac{4(0.10\,\text{m}^3/\text{s})}{\pi(5\,\text{m/s})}} = \mathbf{0.16\,m}$$

Therefore, the diameter of the duct must be at least 0.16 m to ensure that the air in the room is exchanged completely within 20 min while the mean velocity does not exceed 5 m/s.

Discussion This problem shows that engineering systems are sized to satisfy certain constraints imposed by certain considerations.

4-75E A study quantifies the cost and benefits of enhancing IAQ by increasing the building ventilation. The net monetary benefit of installing an enhanced IAQ system to the employer per year is to be determined.

Assumptions The analysis in the report is applicable to this work place.

Analysis The report states that enhancing IAQ increases the productivity of a person by $90 per year, and decreases the cost of the respiratory illnesses by $39 a year while increasing the annual energy consumption by $6 and the equipment cost by about $4 a year. The net monetary benefit of installing an enhanced IAQ system to the employer per year is determined by adding the benefits and subtracting the costs to be

$$\text{Net benefit} = \text{Total benefits} - \text{total cost} = (90+39) - (6+4) = \$119/\text{year} \quad \text{(per person)}$$

The total benefit is determined by multiplying the benefit per person by the number of employees,

$$\text{Total net benefit} = \text{No. of employees} \times \text{Net benefit per person} = 120 \times \$119/\text{year} = \mathbf{\$14,280/year}$$

Discussion Note that the unseen savings in productivity and reduced illnesses can be very significant when they are properly quantified.

4-76 … 4-78 Design and Essay Problems
