3-1. HEAT TRANSFER

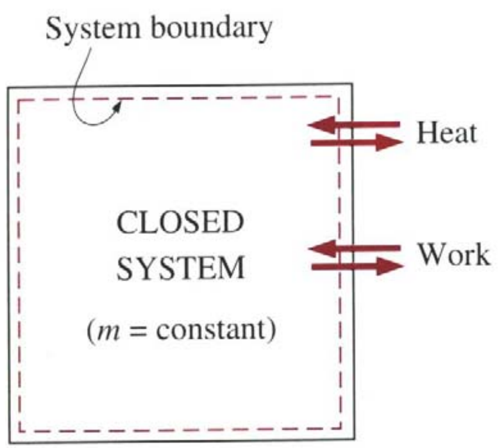

FIGURE 3–1
Energy can cross the boundaries of a closed system in the form of heat and work.

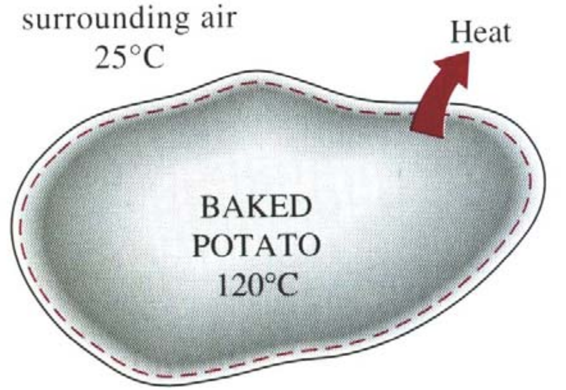

FIGURE 3–2
Heat is transferred from hot bodies to colder ones by virtue of a temperature difference.

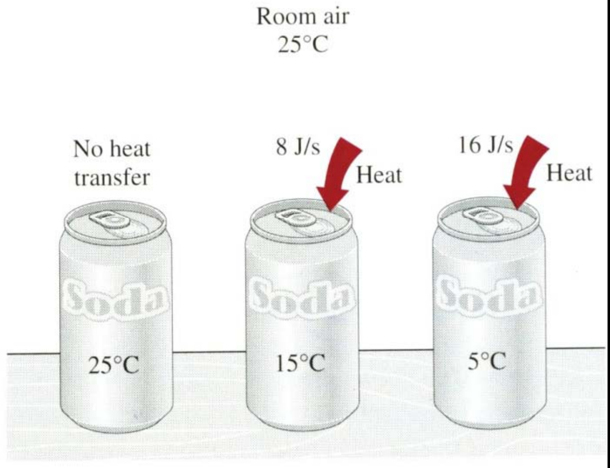

FIGURE 3–3
Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

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3-1. HEAT TRANSFER

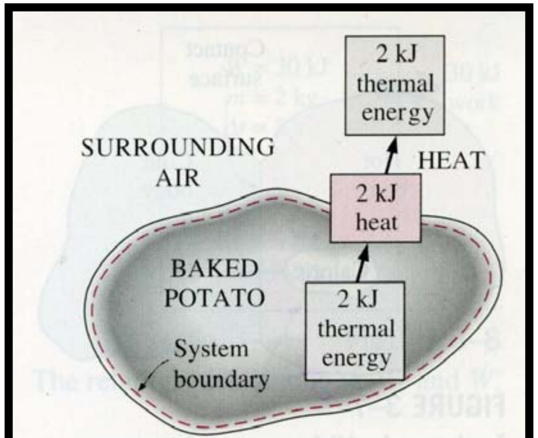

FIGURE 3–4
Energy is recognized as heat transfer only as it crosses the system boundary.

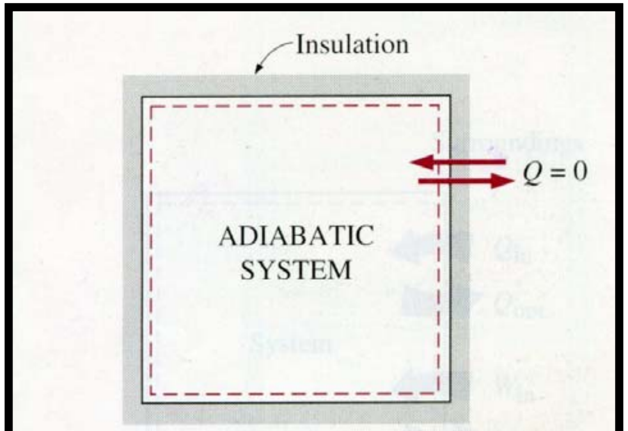

FIGURE 3–5
During an adiabatic process, a system exchanges no heat with its surroundings.

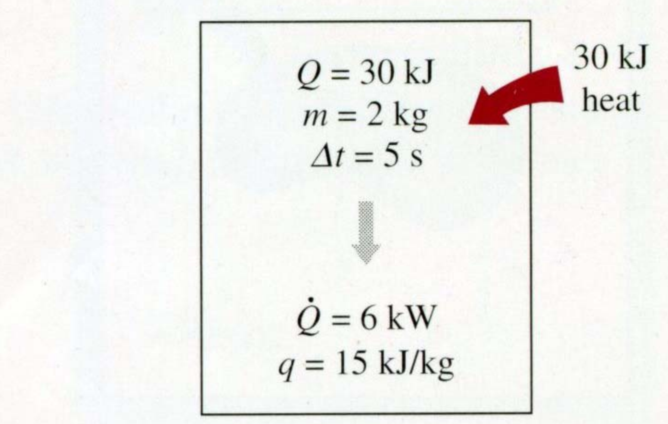

FIGURE 3–6
The relationships among q, Q, and $\dot{Q}$.

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3-1. HEAT TRANSFER

Heat Transfer per unit mass

$$q = \frac{Q}{m} \qquad \text{(kJ/kg)}$$

Heat Transfer rate is denoted *Q*

$$Q = \int_{t1}^{t2} \dot{Q}dt \qquad \text{(kJ)}$$

Heat Transfer rate is denoted *Q*

$$Q = \dot{Q}\,\Delta t \qquad \text{(kJ)}$$

$$\Delta t = t_2 - t_1$$

Historical Background on Heat

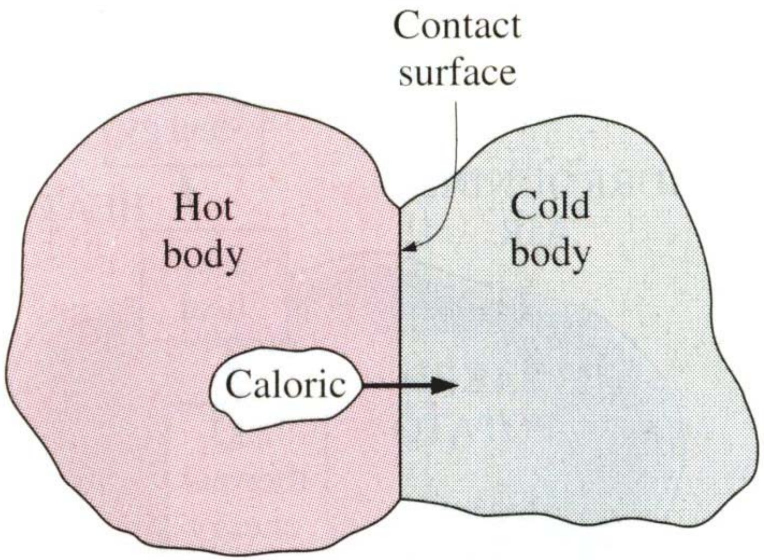


FIGURE 3–7
In the early 19th century, heat was thought to be an invisible fluid called the *caloric* that flowed from warmer bodies to the cooler ones.

Energy transfer by Work

Work done per unit mass of system, *w*

$$w = \frac{W}{m} \qquad \text{(kJ/kg)}$$

Work done per unit time is called *power*

$$\dot{W} \qquad \text{kJ/s, or kW}$$

Path function have inexact differential designated by the symbol δ

Exact differential designated by the symbol d

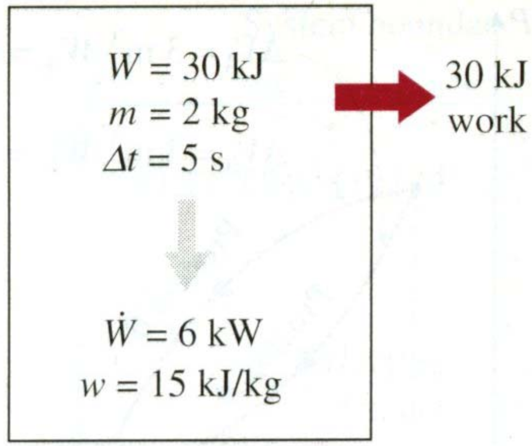


FIGURE 3–8
The relationships among w, W, and $\dot{W}$.

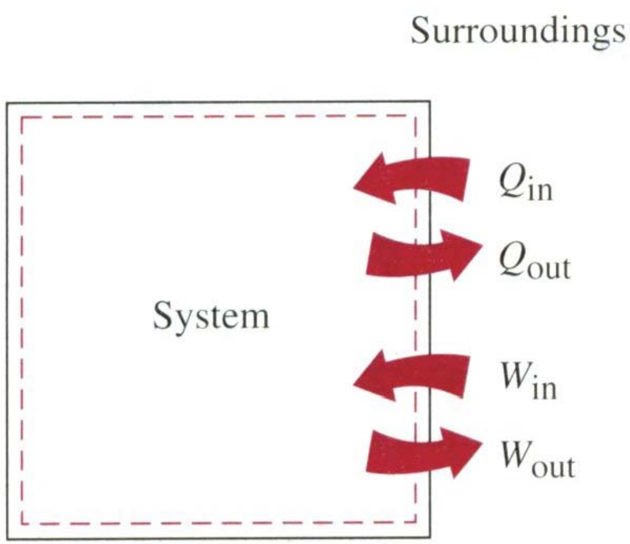


FIGURE 3–9
Specifying the directions of heat and work.

The volume change during a process between states 1 and 2 is

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

Total work done during process 1-2

$$\int_1^2 \delta W = W_{12} \qquad (not \quad \Delta W)$$

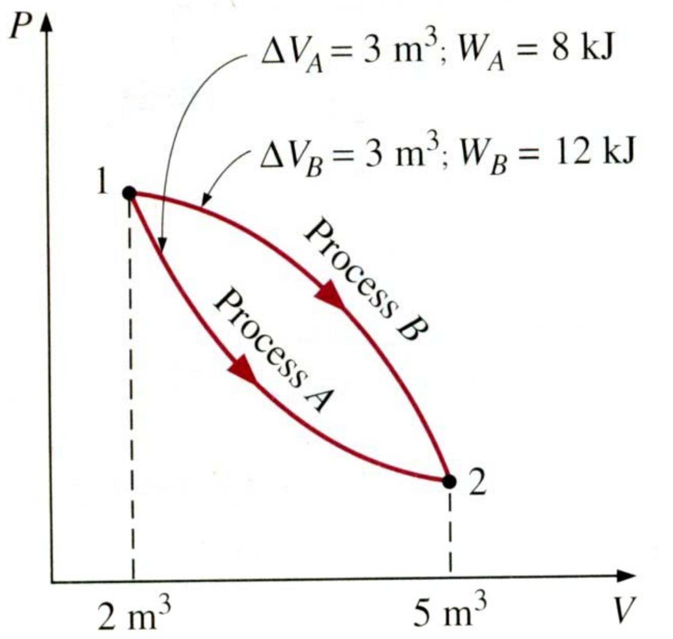


FIGURE 3–10
Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

Electrical Work

$$W_e = VN$$

N คือปริมาณไฟฟ้าที่ผ่านจุดหนึ่ง ๆ โดยมีกระแส 1 แอมป์ แรงเคลื่อน 1 โวลต์ใน 1 นาที

$$\dot{W}_e = VI \qquad \text{(W)}$$

$\dot{W}_e$ *is the electrical power*

โดยทั่วไปแรงเคลื่อน และกระแสไฟฟ้าแปรผันตามเวลา

$$W_e = \int_1^2 VI\ dt \qquad (kJ)$$

Vและ I คงที่

$$W_e = VI\ \Delta t \qquad (kJ)$$

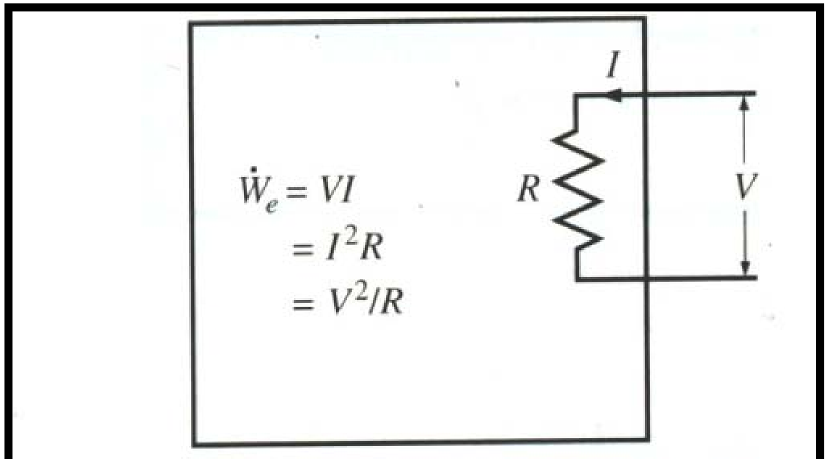


FIGURE 3–15
Electrical power in terms of resistance R, current I, and potential difference V.

MECHANICAL FROMS OF WORK

$$W = Fs \qquad (kJ)$$

F is not constant

$$W = \int_1^2 F\,ds \qquad (kJ)$$

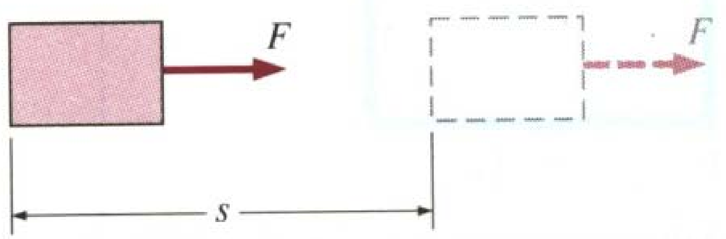


FIGURE 3–16
The work done is proportional to the force applied (F) and the distance traveled (s).

Moving Boundary Work

งานที่ได้จากการเคลื่อนที่ของขอบเขต

F is not constant

$$\delta W_b = Fds = PAds = PdV$$

$$W_b = \int_1^2 PdV \qquad \text{(kJ)}$$

The total area A under the process curve 1-2 is obtained by adding these differential area

$$Aera = A = \int_1^2 dA = \int_1^2 PdV \qquad \text{(kJ)}$$

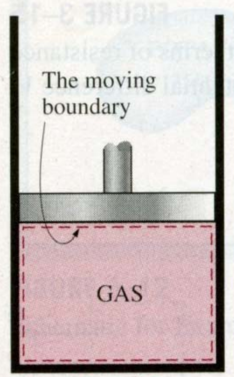


FIGURE 3–18
The work associated with a moving boundary is called *boundary work*.

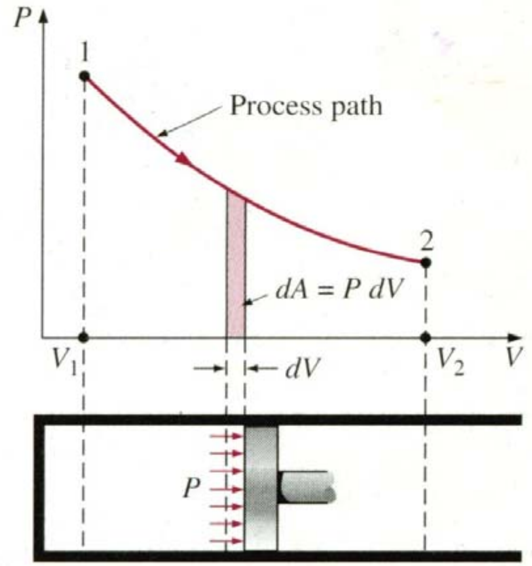


FIGURE 3–20
The area under the process curve on a *P-V* diagram represents the boundary work.

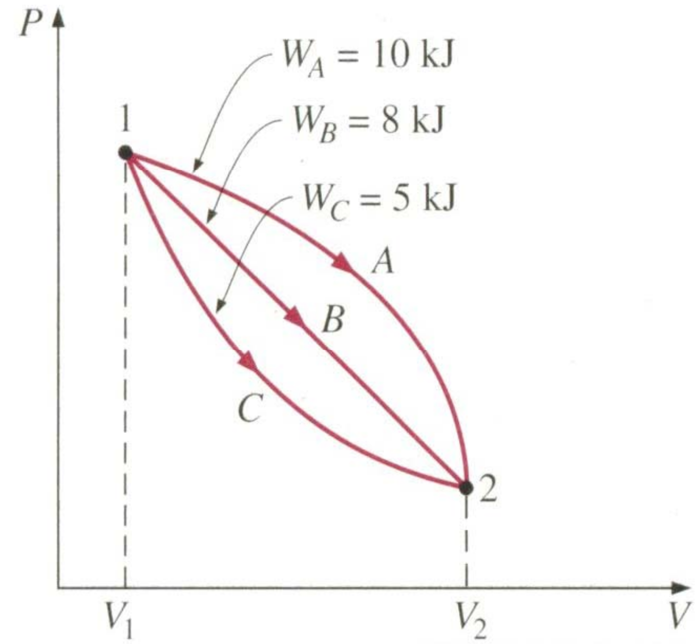


FIGURE 3–21

The boundary work done during a process depends on the path followed as well as the end states.

Moving Boundary Work

$$W_b = \int_1^2 P_i dV \qquad \text{(kJ)}$$

P_i=Pressure is inner face of the piston
W_b = represent the amount of energy transferred from the system during an expansion process

$$W_b = W_{friction} + W_{atm} + W_{crank}$$

$$= \int_1^2 (F_{friction} + P_{atm} A + F_{crank}) dx$$

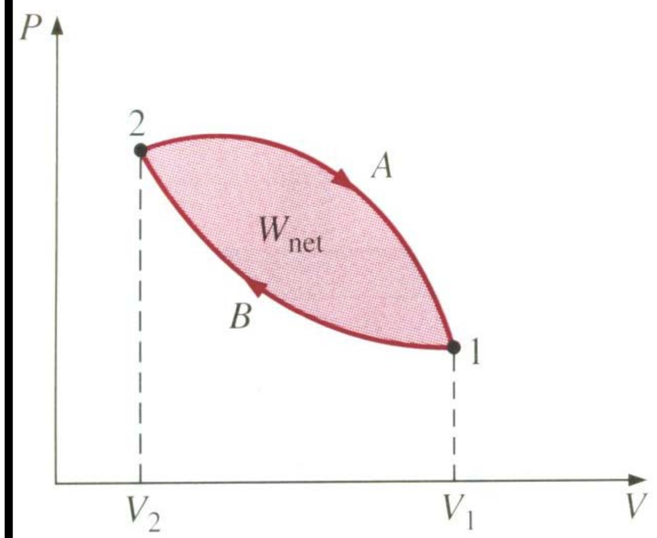


FIGURE 3–22
The net work done during a cycle is the difference between the work done by the system and the work done on the system.

EXAMPLE 3-5 A rigid tank contains air at 500 kPa and 150 °C . As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65 °C and 400 kPa, respectively. Determine the boundary work done during this process.

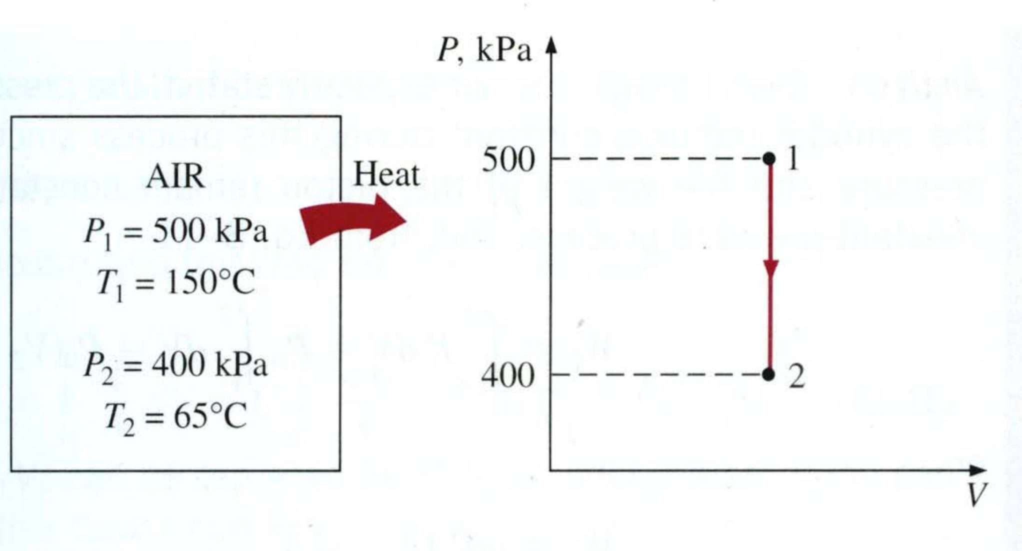


FIGURE 3–23
Schematic and *P*-*V* diagram for Example 3–5.

Analysis: The boundary work can be determined from eq. 3-11 to be

$$W_b = \int_1^2 P dV = 0 \qquad (\text{kJ}),\ (dv = 0)$$

EXAMPLE 3-6 A frictionless piston-cylinder device contains 4.5 kg of water vapor at 0.4 MPa and 200 °C. Heat is now transferred to the steam unit the temperature reaches 250 °C. If the piston is not attached to the shaft and its mass is constant, determine to work done by the steam during this process.

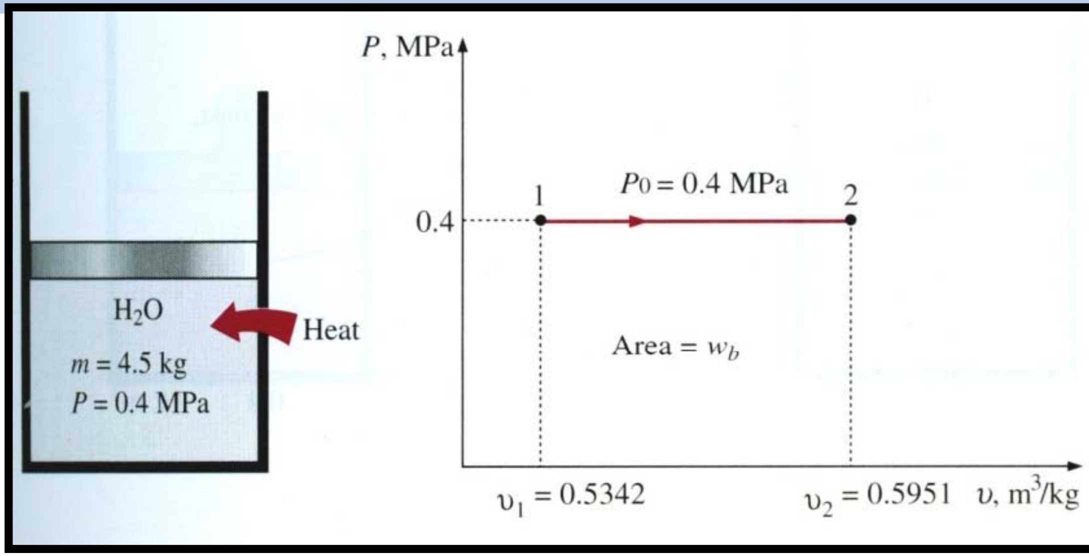


FIGURE 3–24
Schematic and P-v diagram for Example 3–6.

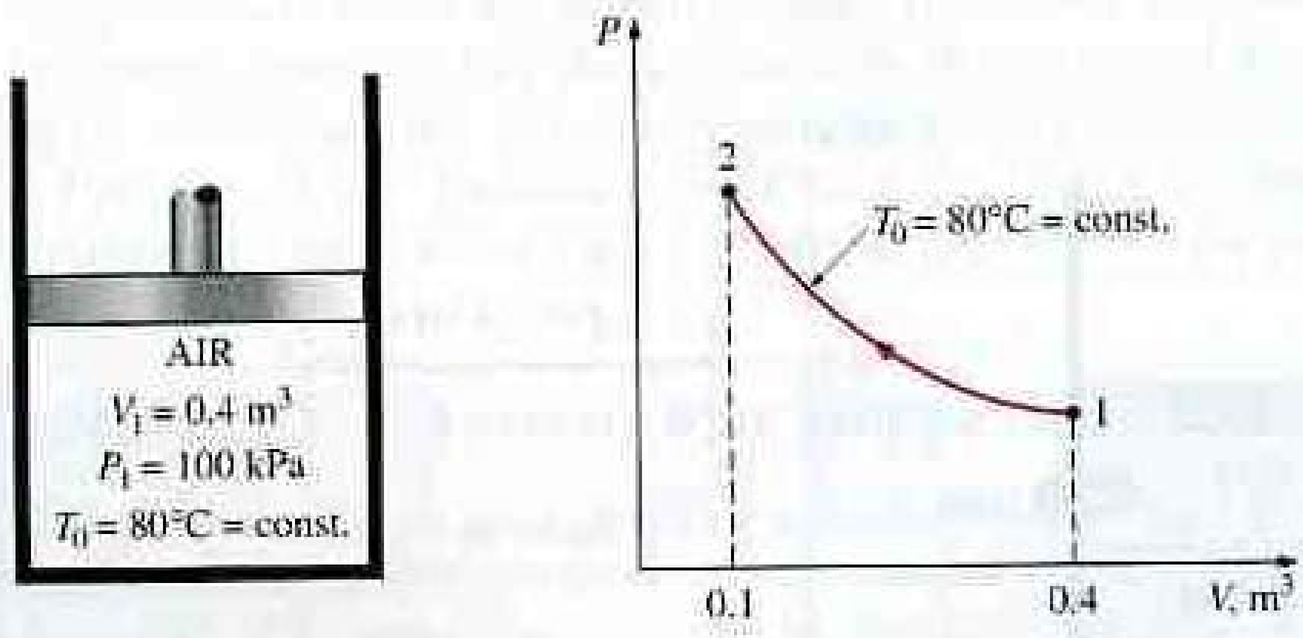
$$W_b = \int_1^2 P_i dV = P_o \int_1^2 dV = P_0(V_2 - V_1) \quad or\ W_b = mP_o(V_2 - V_1)$$

$$W_b = (4.5kg)(400\,kPa)[(0.5951 - 0.5342)m^3/kg] = 109.62\,kJ$$

EXAMPLE 3-6: Isothermal Compression of an ideal gas

A piston-cylinder device initially contains 0.4 m^3 of air at 100 kPa and 80 °C. The air is now compressed to 0.1 m^3 in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

FIGURE 3–25
Schematic and P-V diagram for Example 3–7.



EAMPLE 3-7

Analysis For an ideal gas at constant temperature T_0,

$$PV = mRT_0 = C \quad \text{or} \quad P = \frac{C}{V}$$

where C is a constant. Substituting this into Eq. 3–11, we have

$$W_b = \int_1^2 P\,dV = \int_1^2 \frac{C}{V}\,dV = C\int_1^2 \frac{dV}{V} = C \ln \frac{V_2}{V_1} = P_1V_1 \ln \frac{V_2}{V_1} \qquad \textbf{(3–16)}$$

In the above equation, P_1V_1 can be replaced by P_2V_2 or mRT_0. Also, V_2/V_1 can be replaced by P_1/P_2 for this case since $P_1V_1 = P_2V_2$.

Substituting the numerical values into the above equation yields

$$W_b = (100\ \text{kPa})(0.4\ \text{m}^3)\left(\ln \frac{0.1}{0.4}\right)\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{-55.45\ kJ}$$

Polytropic Process

$$PV^n = C$$

sure for a polytropic process can be expressed as

$$P = CV^{-n} \qquad (3\text{–}17)$$

Substituting this relation into Eq. 3–11, we obtain

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\,\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n} \qquad (3\text{–}18)$$

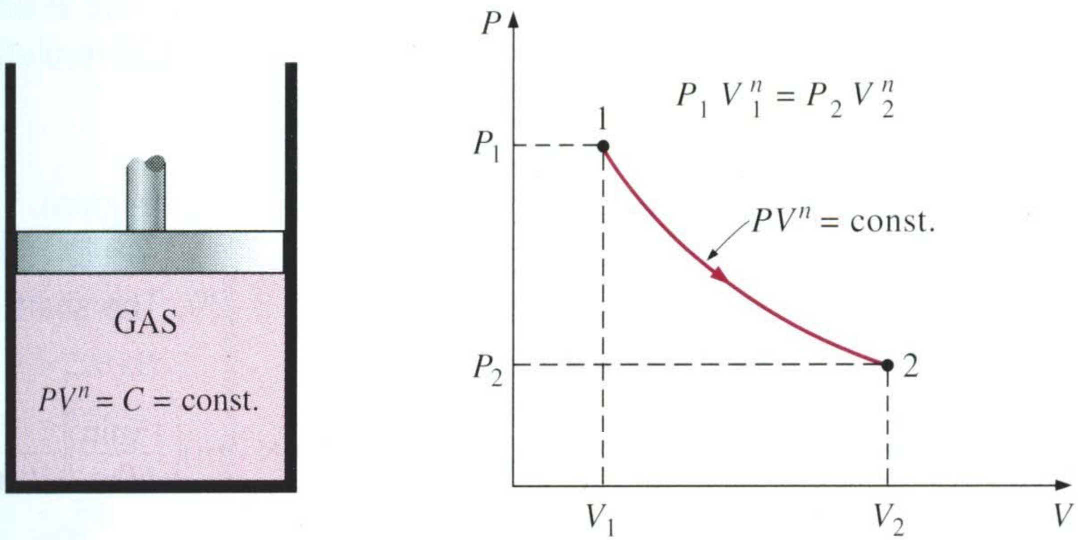


FIGURE 3–26
Schematic and P-V diagram for a polytropic process.

since $C = P_1V_1^n = P_2V_2^n$. For an ideal gas ($PV = mRT$), this equation can a
be written as

$$W_b = \frac{mR(T_2 - T_1)}{1 - n} \qquad n \neq 1 \qquad \text{(kJ)} \qquad \text{(3-}$$

For the special case of $n = 1$ the boundary work becomes

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = PV \ln\left(\frac{V_2}{V_1}\right)$$

For an ideal gas this result is equivalent to the isothermal process discusse
the previous example.

2 Shaft Work

Energy transmission with a rotating shaft is very common in engineering pr tice (Fig. 3–27). Often the torque **T** applied to the shaft is constant, wh means that the force F applied is also constant. For a specified const torque, the work done during n revolutions is determined as follows: A fo F acting through a moment arm r generates a torque **T** of

$$\mathbf{T} = Fr \longrightarrow F = \frac{\mathbf{T}}{r}$$

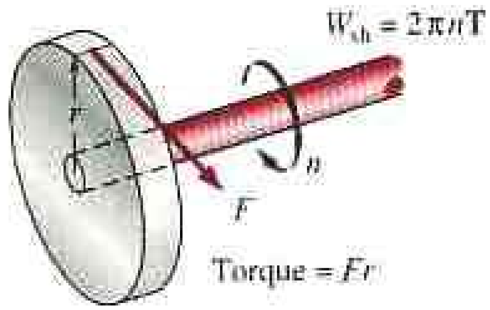


FIGURE 3–28
Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

This force acts through a distance s, which is related to th

$$s = (2\pi r)n$$

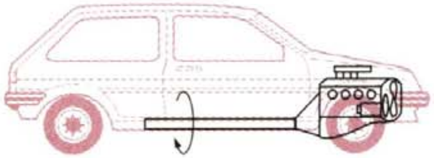
Then the shaft work is determined from

$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi rn) = 2\pi n\mathbf{T} \qquad \text{(kJ)}$$

The power transmitted through the shaft is the shaft work done per unit ti which can be expressed as

$$\dot{W}_{sh} = 2\pi\dot{n}\mathbf{T} \qquad \text{(kW)} \qquad \textbf{(3-}$$

where $\dot{n}$ is the number of revolutions per unit time.



$n = 4000$ rpm

$\tau = 200$ Nm

FIGURE 3–29

Schematic for Example 3–8.

EXAMPLE 3–8 Power Transmission by the Shaft of a Car

Determine the power transmitted through the shaft of a car when the torque ap plied is 200 N · m and the shaft rotates at a rate of 4000 revolutions per minut (rpm).

SOLUTION The torque and the rpm for a car engine are given. The power trans mitted is to be determined.

Analysis A sketch of the car is given in Fig. 3–29. The shaft power is deter mined directly from

$$\dot{W}_{sh} = 2\pi\dot{n}\mathbf{T} = (2\pi)\left(4000\ \frac{1}{\text{min}}\right)(200\ \text{N}\cdot\text{m})\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{1\ \text{kJ}}{1000\ \text{N}\cdot\text{m}}\right)$$

$$= \mathbf{83.8\ kW}\ (\text{or } 112.3\ \text{hp})$$

Spring Work

is common knowledge that when a force is applied on a spring, the length the spring changes (Fig. 3–30). When the length of the spring changes by a fferential amount *dx* under the influence of a force *F*, the work done is

$$\delta W_{\text{spring}} = F\,dx \qquad \textbf{(3–24)}$$

determine the total spring work, we need to know a functional relationship tween *F* and *x*. For linear elastic springs, the displacement *x* is proportional the force applied (Fig. 3–31). That is,

$$F = kx \qquad \text{(kN)} \qquad \textbf{(3–25)}$$

here *k* is the spring constant and has the unit kN/m. The displacement *x* is easured from the undisturbed position of the spring (that is, $x = 0$ when = 0). Substituting Eq. 3–25 into Eq. 3–24 and integrating yield

$$W_{\text{spring}} = \tfrac{1}{2}k(x_2^2 - x_1^2) \qquad \text{(kJ)} \qquad \textbf{(3–26)}$$

here x_1 and x_2 are the initial and the final displacements of the spring, spectively, measured from the undisturbed position of the spring.

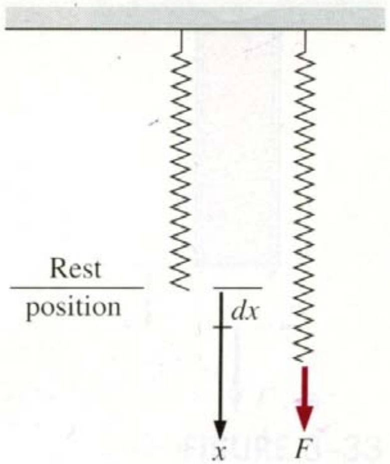


FIGURE 3–30
Elongation of a spring under the influence of a force.

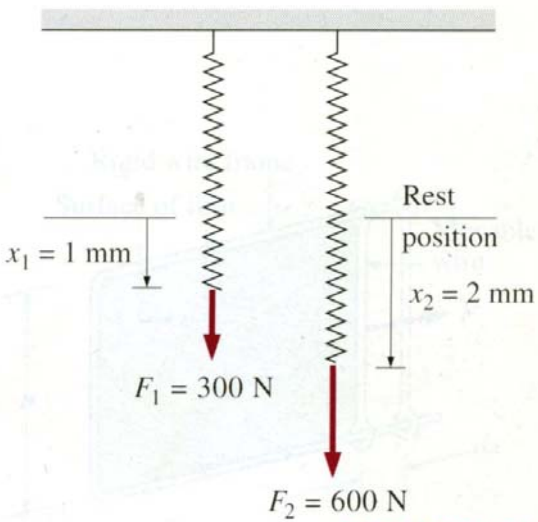
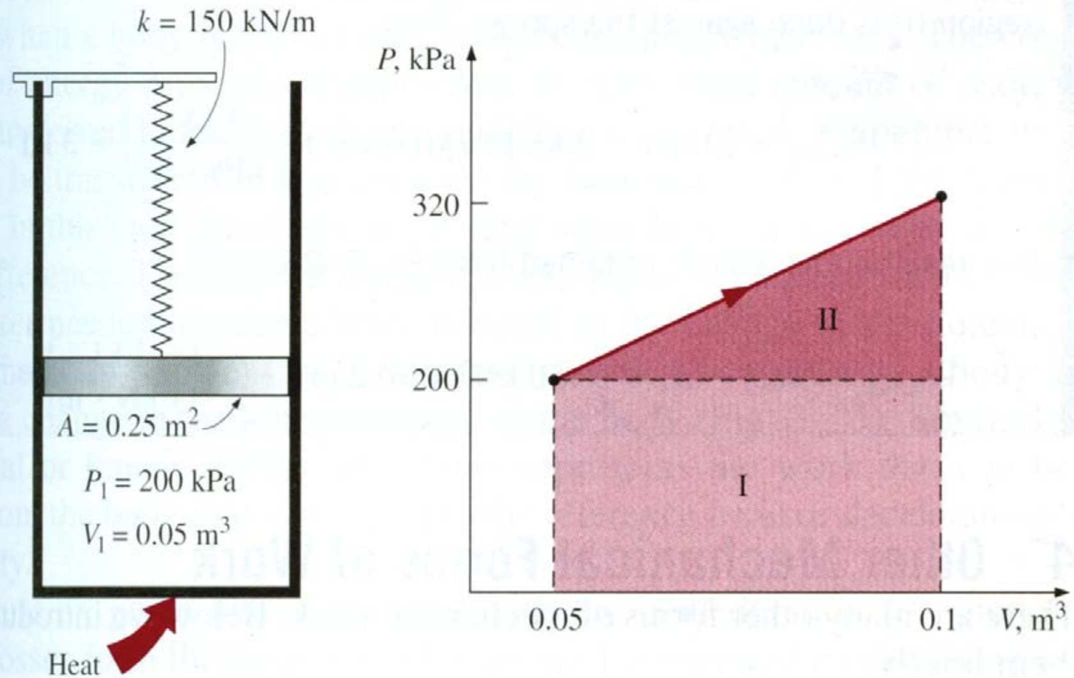


FIGURE 3–31
The displacement of a linear spring doubles when the force is doubled.

XAMPLE 3–9 Expansion of a Gas against a Spring

piston-cylinder device contains 0.05 m^3 of a gas initially at 200 kPa. At this ate, a linear spring that has a spring constant of 150 kN/m is touching the pis- n but exerting no force on it. Now heat is transferred to the gas, causing the ston to rise and to compress the spring until the volume inside the cylinder oubles. If the cross-sectional area of the piston is 0.25 m^2, determine (*a*) the nal pressure inside the cylinder, (*b*) the total work done by the gas, and (*c*) the action of this work done against the spring to compress it.

OLUTION A sketch of the system and the *P-V* diagram of the process are own in Fig. 3–32.



Assumptions **1** The expansion process is quasi-equilibrium. **2** The spring is linear in the range of interest.

Analysis (*a*) The enclosed volume at the final state is

$$V_2 = 2V_1 = (2)(0.05\ \text{m}^3) = 0.1\ \text{m}^3$$

Then the displacement of the piston (and of the spring) becomes

$$x = \frac{\Delta V}{A} = \frac{(0.1 - 0.05)\ \text{m}^3}{0.25\ \text{m}^2} = 0.2\ \text{m}$$

The force applied by the linear spring at the final state is

$$F = kx = (150\ \text{kN/m})(0.2\ \text{m}) = 30\ \text{kN}$$

The additional pressure applied by the spring on the gas at this state is

$$P = \frac{F}{A} = \frac{30\ \text{kN}}{0.25\ \text{m}^2} = 120\ \text{kPa}$$

Without the spring, the pressure of the gas would remain constant at 200 kPa while the piston is rising. But under the effect of the spring, the pressure rises linearly from 200 kPa to

$$200 + 120 = \mathbf{320\ kPa}$$

at the final state.

(*b*) An easy way of finding the work done is to plot the process on a *P-V* diagram and find the area under the process curve. From Fig. 3–32 the area under the process curve (a trapezoid) is determined to be

$$W = \text{area} = \frac{(200 + 320)\ \text{kPa}}{2}[(0.1 - 0.05)\ \text{m}^3]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = \mathbf{13\ kJ}$$

Note that the work is done by the system.

(*c*) The work represented by the rectangular area (region I) is done against the piston and the atmosphere, and the work represented by the triangular area (region II) is done against the spring. Thus,

$$W_{\text{spring}} = \tfrac{1}{2}[(320 - 200)\ \text{kPa}](0.05\ \text{m}^3)\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = 3\ \text{kJ}$$

This result could also be obtained from Eq. 3-26:

$$W_{\text{spring}} = \tfrac{1}{2}k(x_2^2 - x_1^2) = \tfrac{1}{2}(150\ \text{kN/m})[(0.2\ \text{m})^2 - 0^2]\left(\frac{1\ \text{kJ}}{1\ \text{kN}\cdot\text{m}}\right) = 3\ \text{kJ}$$

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