Chapter 2: ENERGY, ENERGY TRANSFER & GENERAL ENERGY ANALYSIS

Objectives

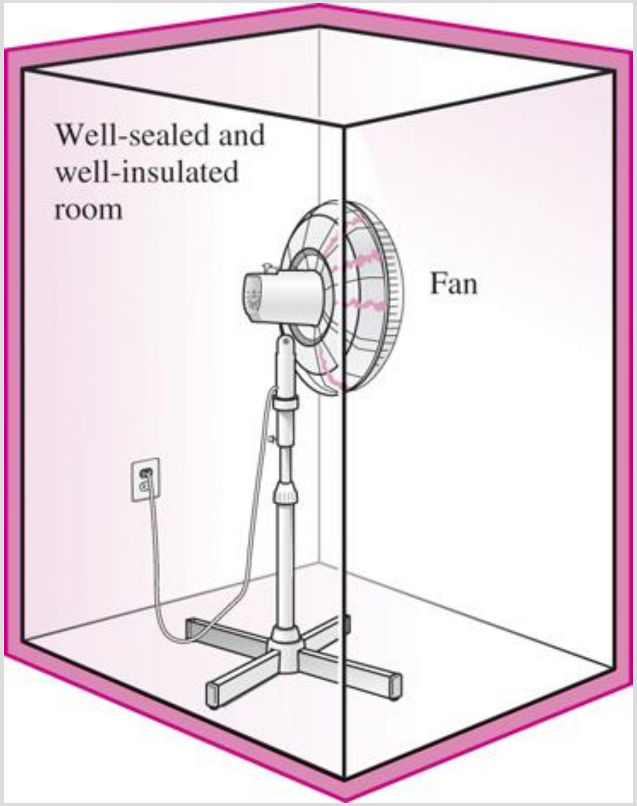
- Introduce the concept of energy and define its various forms.
- Discuss the nature of internal energy.
- Define the concept of heat and the terminology associated with energy transfer by heat.
- Discuss the three mechanisms of heat transfer: conduction, convection, and radiation.
- Define the concept of work, including electrical work and several forms of mechanical work.
- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.
- Determine that a fluid flowing across a control surface of a control volume carries energy across the control surface in addition to any energy transfer across the control surface that may be in the form of heat and/or work.
- Define energy conversion efficiencies.
- Discuss the implications of energy conversion on the environment.

INTRODUCTION

- If we take the entire room—including the air and the refrigerator (or fan)—as the system, which is an adiabatic closed system since the room is well-sealed and well-insulated, the only energy interaction involved is the electrical energy crossing the system boundary and entering the room.
- As a result of the conversion of electric energy consumed by the device to heat, **the room temperature will rise**.

A refrigerator operating with its door open in a well-sealed and well-insulated room

A fan running in a well-sealed and well-insulated room will raise the temperature of air in the room.



FORMS OF ENERGY

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy, *E*** of a system.
- Thermodynamics deals only with the ***change*** of the total energy.
- **Macroscopic forms of energy**: Those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.
- **Microscopic forms of energy**: Those related to the molecular structure of a system and the degree of the molecular activity.
- **Internal energy, *U***: The sum of all the microscopic forms of energy.
- **Kinetic energy, KE**: The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy, PE:** The energy that a system possesses as a result of its elevation in a gravitational field.

The macroscopic energy of an object changes with velocity and elevation.

$$KE = m\frac{V^2}{2} \qquad (kJ)$$

Kinetic energy

$$ke = \frac{V^2}{2} \qquad (kJ/kg)$$

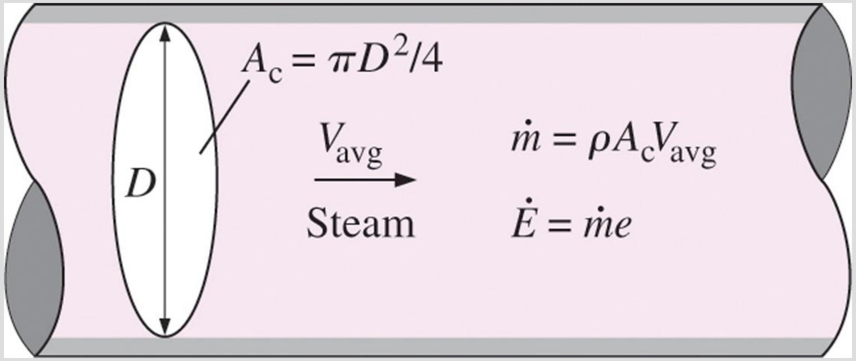
Kinetic energy per unit mass

$$PE = mgz \qquad (kJ)$$

Potential energy

$$pe = gz \qquad (kJ/kg)$$

Potential energy per unit mass



Mass flow rate

$$\dot{m} = \rho \dot{V} = \rho A_c V_{avg} \qquad (kg/s)$$

Energy flow rate

$$\dot{E} = \dot{m}e \qquad (kJ/s \text{ or } kW)$$

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \qquad (kJ)$$

Total energy of a system

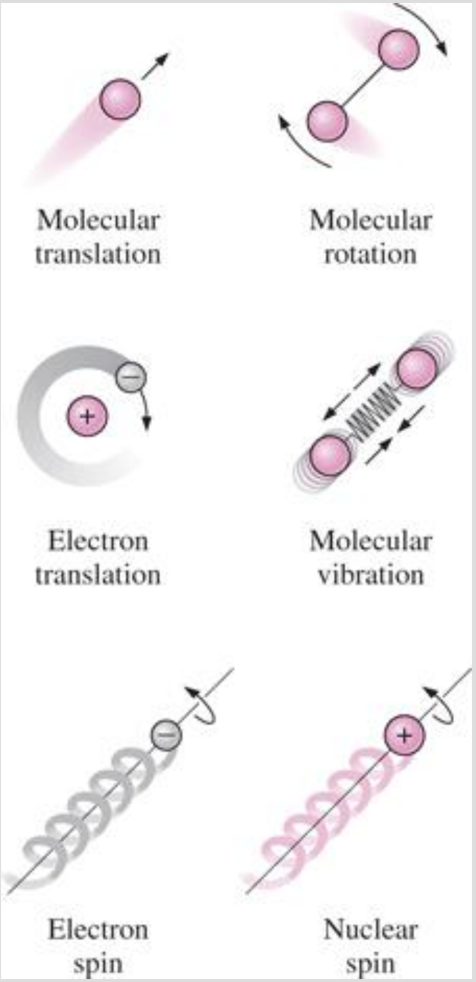
$$e = u + ke + pe = u + \frac{V^2}{2} + gz \qquad (kJ/kg)$$

Energy of a system per unit mass

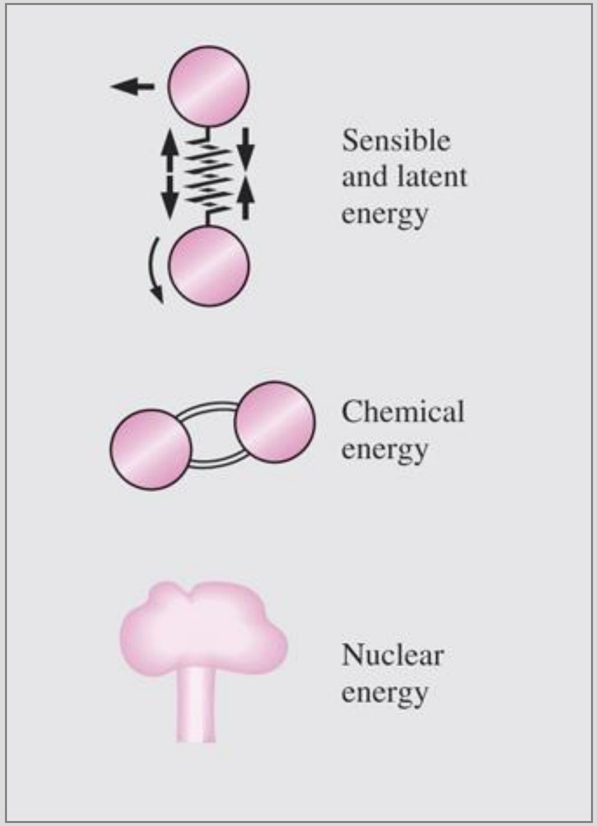
$$e = \frac{E}{m} \qquad (kJ/kg)$$

Total energy per unit mass

Some Physical Insight to Internal Energy



The various forms of microscopic energies that make up *sensible* energy.



The internal energy of a system is the sum of all forms of the microscopic energies.

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

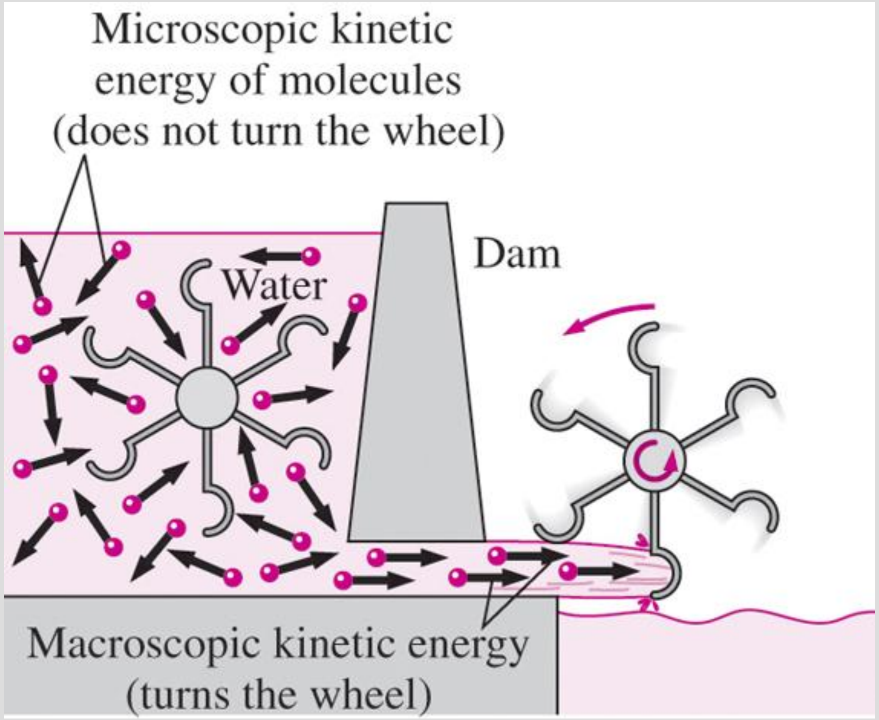
Chemical energy: The internal energy associated with the atomic bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself.

Thermal = Sensible + Latent

Internal = Sensible + Latent + Chemical + Nuclear

- The total energy of a system, can be *contained* or *stored* in a system, and thus can be viewed as the ***static* forms of energy**.
- The forms of energy not stored in a system can be viewed as the ***dynamic* forms of energy** or as ***energy interactions***.
- The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.
- The only two forms of energy interactions associated with a closed system are **heat transfer** and **work**.

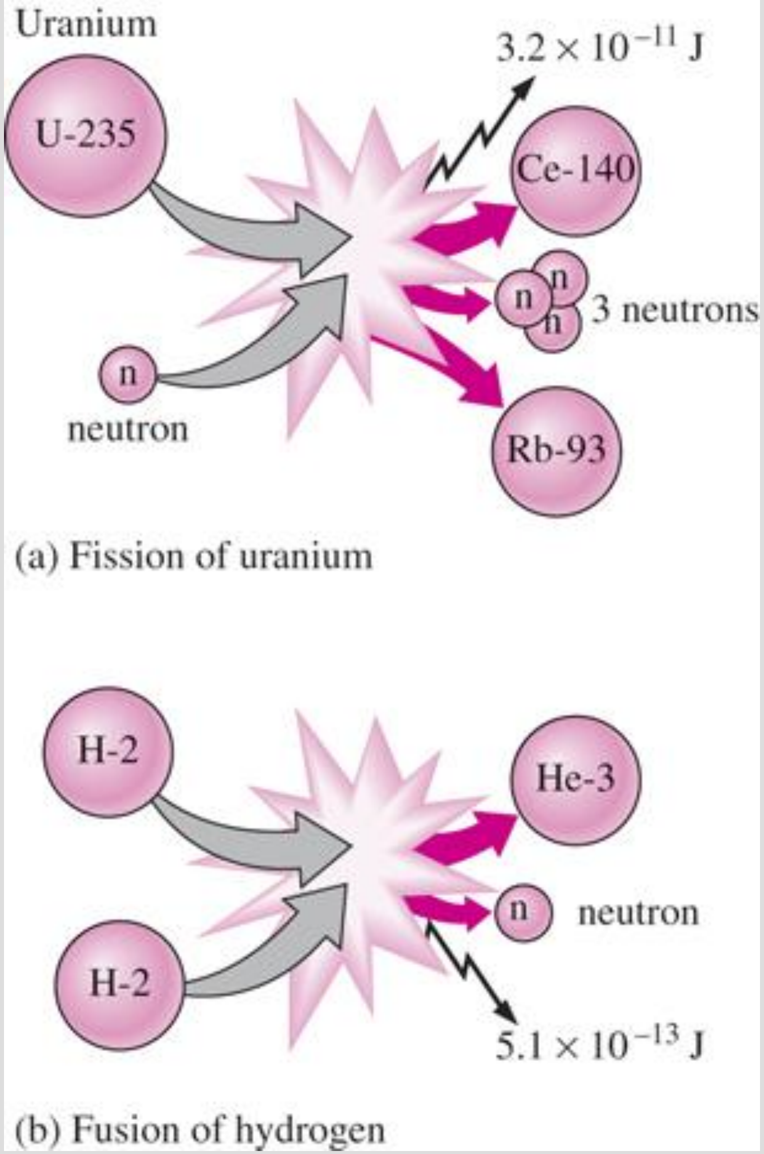


The *macroscopic* kinetic energy is an organized form of energy and is much more useful than the disorganized *microscopic* kinetic energies of the molecules.

- **The difference between heat transfer and work:** An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise it is work.

More on Nuclear Energy

- The best known **fission** reaction involves the split of the uranium atom (the U-235 isotope) into other elements and is commonly used to generate electricity in nuclear power plants (440 of them in 2004, generating 363,000 MW worldwide), to power nuclear submarines and aircraft carriers, and even to power spacecraft as well as building nuclear bombs.
- Nuclear energy by **fusion** is released when two small nuclei combine into a larger one.
- The uncontrolled fusion reaction was achieved in the early 1950s, but all the efforts since then to achieve controlled fusion by massive lasers, powerful magnetic fields, and electric currents to generate power have failed.



The fission of uranium and the fusion of hydrogen during nuclear reactions, and the release of nuclear energy.

EXAMPLE 2–1 A Car Powered by Nuclear Fuel

An average car consumes about 5 L of gasoline a day, and the capacity of the fuel tank of a car is about 50 L. Therefore, a car needs to be refueled once every 10 days. Also, the density of gasoline ranges from 0.68 to 0.78 kg/L, and its lower heating value is about 44,000 kJ/kg (that is, 44,000 kJ of heat is released when 1 kg of gasoline is completely burned). Suppose all the problems associated with the radioactivity and waste disposal of nuclear fuels are resolved, and a car is to be powered by U-235. If a new car comes equipped with 0.1-kg of the nuclear fuel U-235, determine if this car will ever need refueling under average driving conditions (Fig. 2–9).

Solution A car powered by nuclear energy comes equipped with nuclear fuel. It is to be determined if this car will ever need refueling.

Assumptions **1** Gasoline is an incompressible substance with an average density of 0.75 kg/L. **2** Nuclear fuel is completely converted to thermal energy.

Analysis The mass of gasoline used per day by the car is

$$m_{\text{gasoline}} = (\rho V)_{\text{gasoline}} = (0.75\ \text{kg/L})(5\ \text{L/day}) = 3.75\ \text{kg/day}$$

Noting that the heating value of gasoline is 44,000 kJ/kg, the energy supplied to the car per day is

$$E = (m_{\text{gasoline}})(\text{Heating value})$$

The complete fission of 0.1 kg of uranium-235 releases

$$(6.73 \times 10^{10}\ \text{kJ/kg})(0.1\ \text{kg}) = 6.73 \times 10^{9}\ \text{kJ}$$

of heat, which is sufficient to meet the energy needs of the car for

$$\text{No. of days} = \frac{\text{Energy content of fuel}}{\text{Daily energy use}} = \frac{6.73 \times 10^{9}\ \text{kJ}}{165{,}000\ \text{kJ/day}} = \mathbf{40{,}790\ days}$$

which is equivalent to about 112 years. Considering that no car will last more than 100 years, this car will never need refueling. It appears that nuclear fuel of the size of a cherry is sufficient to power a car during its lifetime.

Mechanical Energy

Mechanical energy: The form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.

Kinetic and potential energies: The familiar forms of mechanical energy.

$$e_{mech} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Mechanical energy of a flowing fluid per unit mass

$$\dot{E}_{mech} = \dot{m}e_{mech} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Rate of mechanical energy of a flowing fluid

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{mech} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

Rate of mechanical energy change of a fluid during incompressible flow

$$\Delta \dot{E}_{mech} = \dot{m}\Delta e_{mech} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$

EXAMPLE 2–2 Wind Energy

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–10). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

Solution A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(*a*) Wind energy per unit mass of air is

$$e = \mathrm{ke} = \frac{V^2}{2} = \frac{(8.5\ \mathrm{m/s})^2}{2}\left(\frac{1\ \mathrm{J/kg}}{1\ \mathrm{m^2/s^2}}\right) = \mathbf{36.1\ J/kg}$$

(*b*) Wind energy for an air mass of 10 kg is

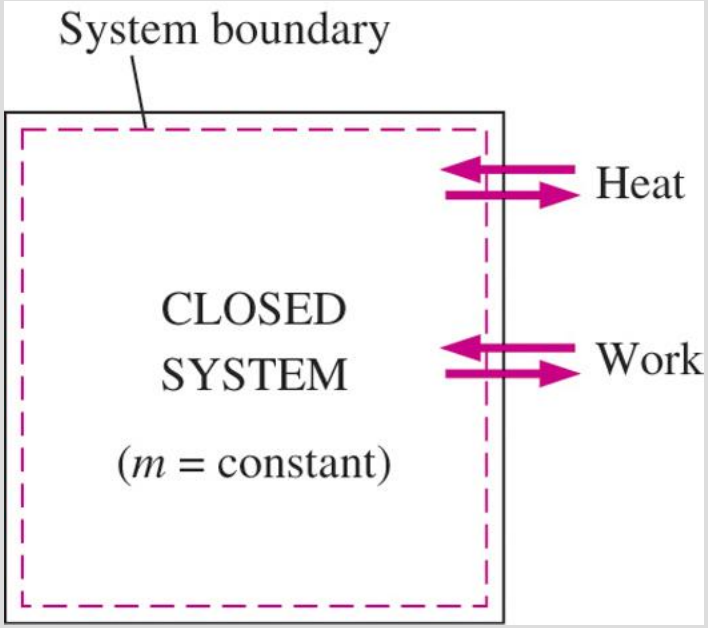
$$E = me = (10\ \mathrm{kg})(36.1\ \mathrm{J/kg}) = \mathbf{361\ J}$$

(*c*) Wind energy for a mass flow rate of 1154 kg/s is

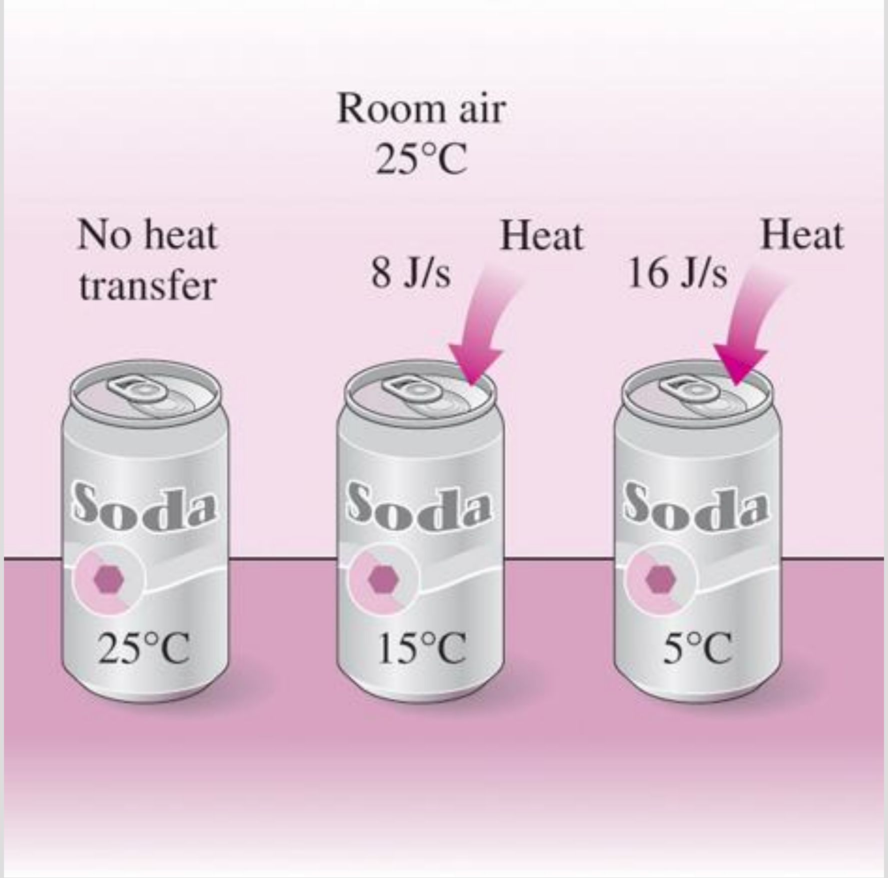
$$\dot{E} = \dot{m}e = (1154\ \mathrm{kg/s})(36.1\ \mathrm{J/kg})\left(\frac{1\ \mathrm{kW}}{1000\ \mathrm{J/s}}\right) = \mathbf{41.7\ kW}$$

ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.



Energy can cross the boundaries of a closed system in the form of heat and work.



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

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

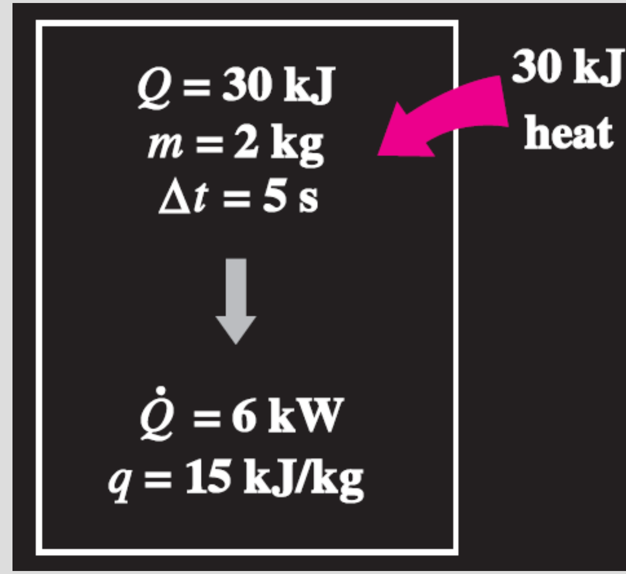
Heat transfer per unit mass

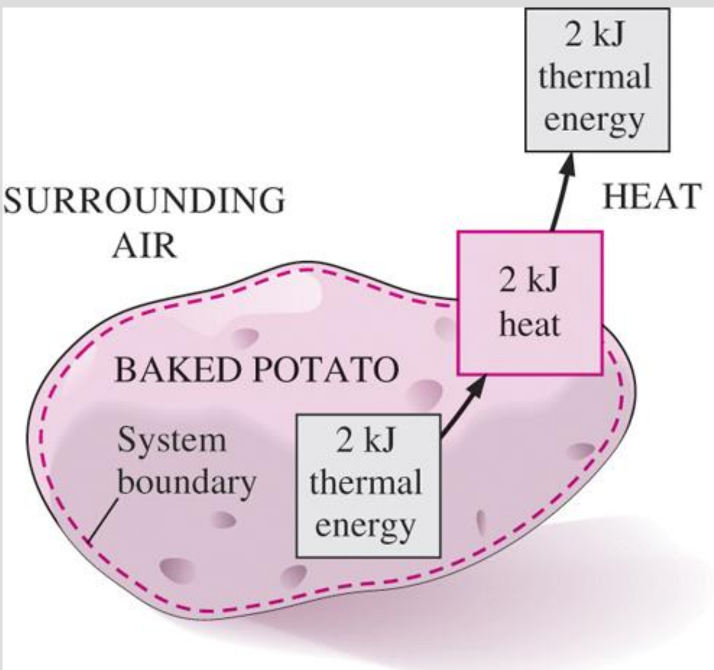
$$Q = \dot{Q}\,\Delta t \qquad (\text{kJ})$$

Amount of heat transfer when heat transfer rate is constant

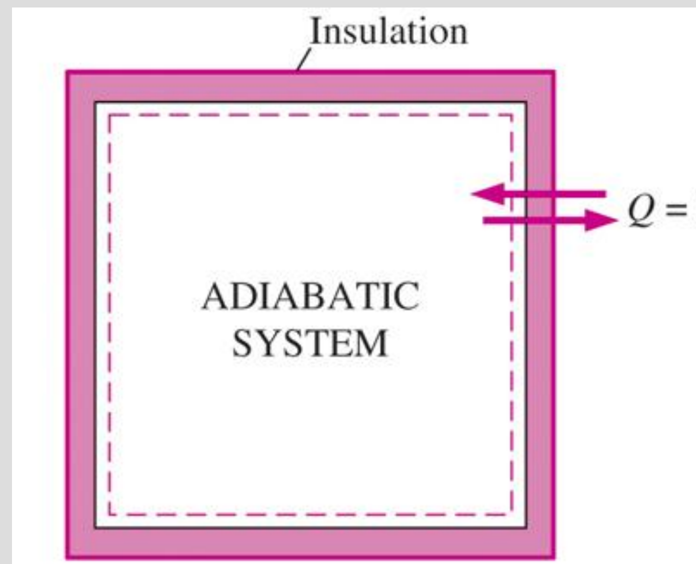
$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \qquad (\text{kJ})$$

Amount of heat transfer when heat transfer rate changes with time





Energy is recognized as heat transfer only as it crosses the system boundary.



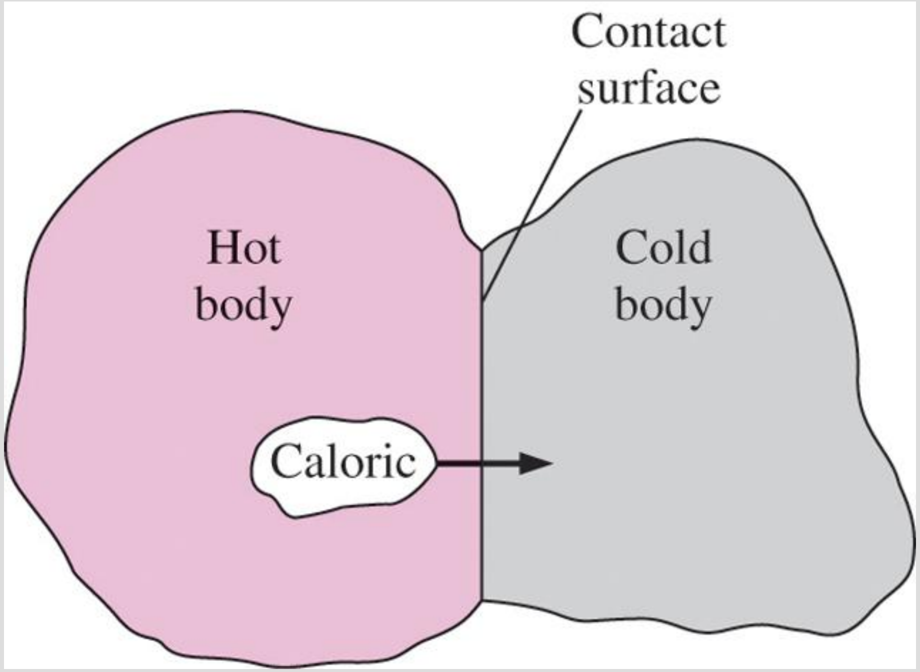
During an adiabatic process, a system exchanges no heat with its surroundings.

Historical Background on Heat

- **Kinetic theory**: Treats molecules as tiny balls that are in motion and thus possess kinetic energy.
- **Heat**: The energy associated with the random motion of atoms and molecules.

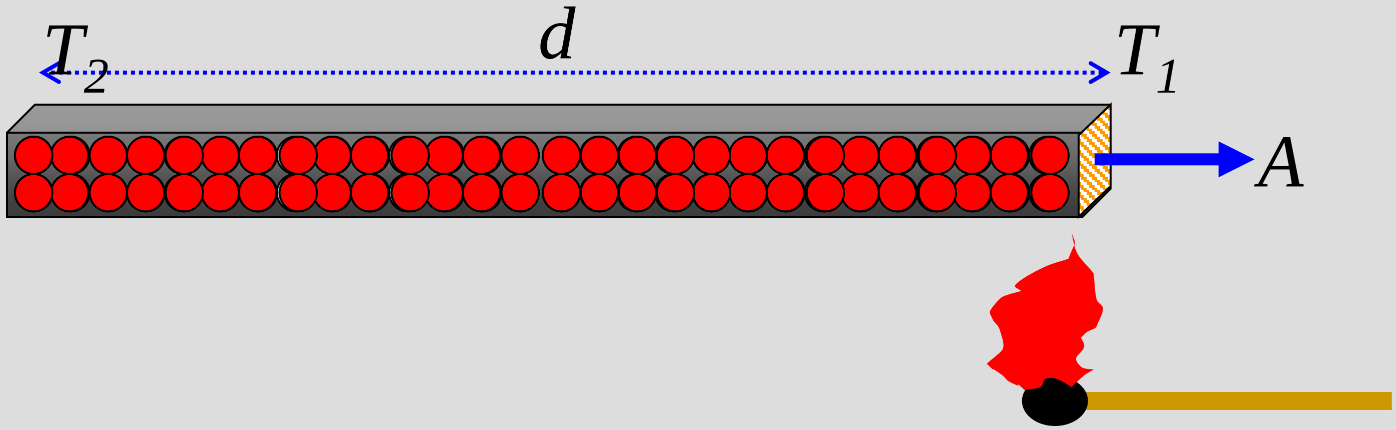
Heat transfer mechanisms:

- **Conduction:** The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.
- **Convection:** The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.
- **Radiation:** The transfer of energy due to the emission of electromagnetic waves (or photons).



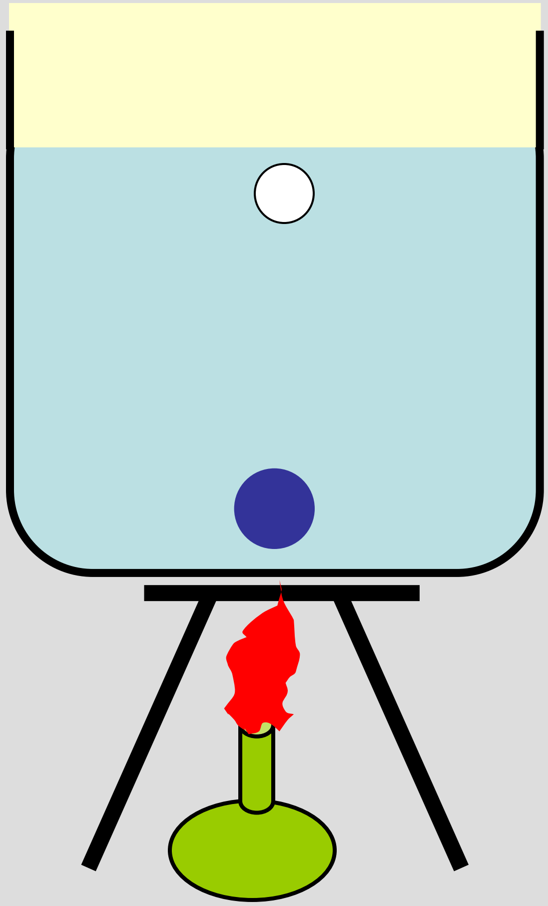
In the early nineteenth century, heat was thought to be an invisible fluid called the ***caloric*** that flowed from warmer bodies to the cooler ones.

Conduction:



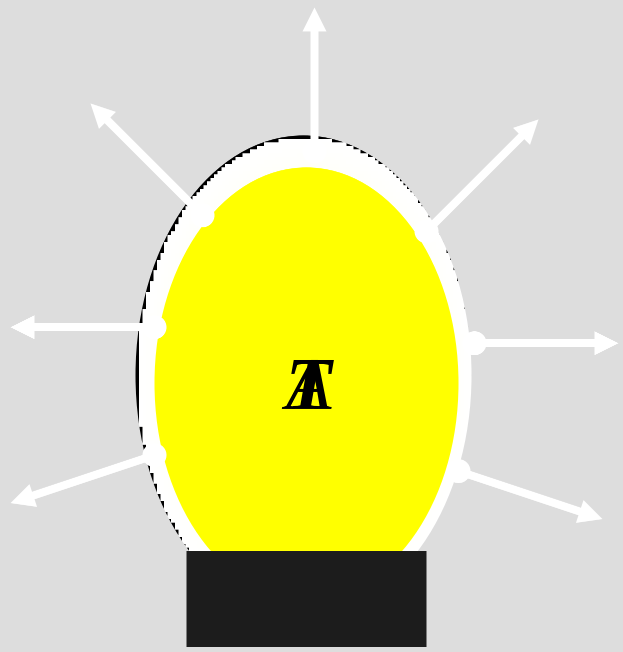
Perpindahan kalor yang tanpa disertai perpindahan zat perantara.

Convection:



Perpindahan kalor yang disertai perpindahan zat perantara.

Radiation:



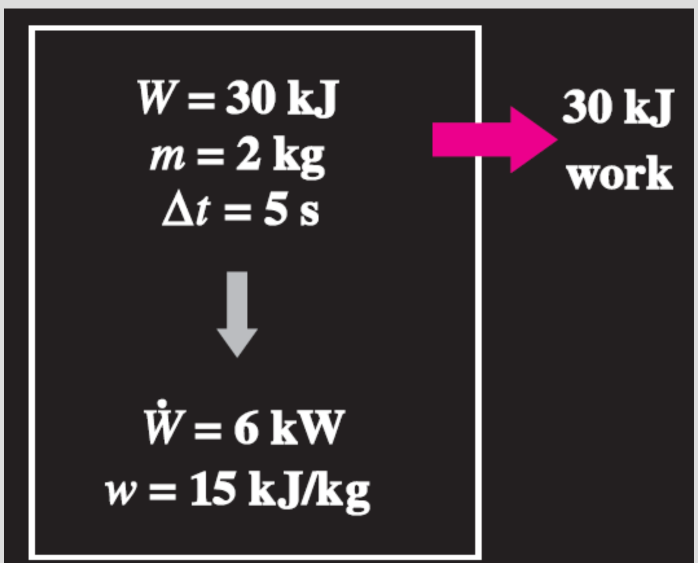
Perpindahan kalor tanpa zat perantara.

ENERGY TRANSFER BY WORK

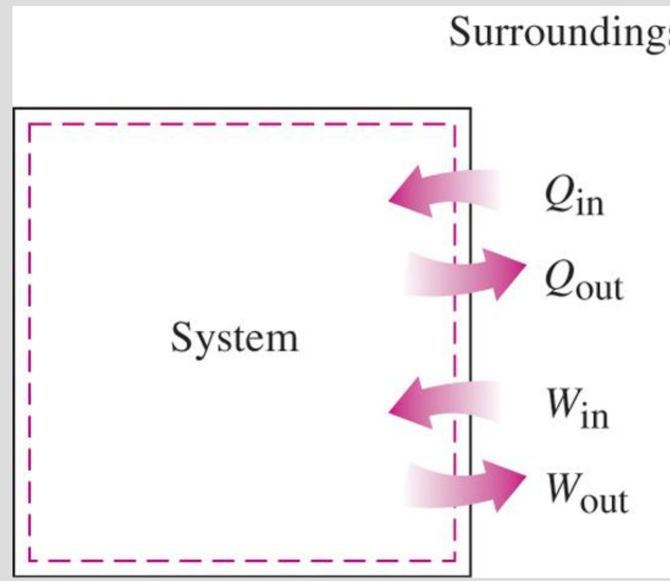
- **Work**: The energy transfer associated with a force acting through a distance.
  - ✓ **A rising piston, a rotating shaft,** and **an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention**: *Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative*.
- Alternative to sign convention is to use the subscripts ***in*** and ***out*** to indicate direction. This is the primary approach in this text.

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

Work done per unit mass



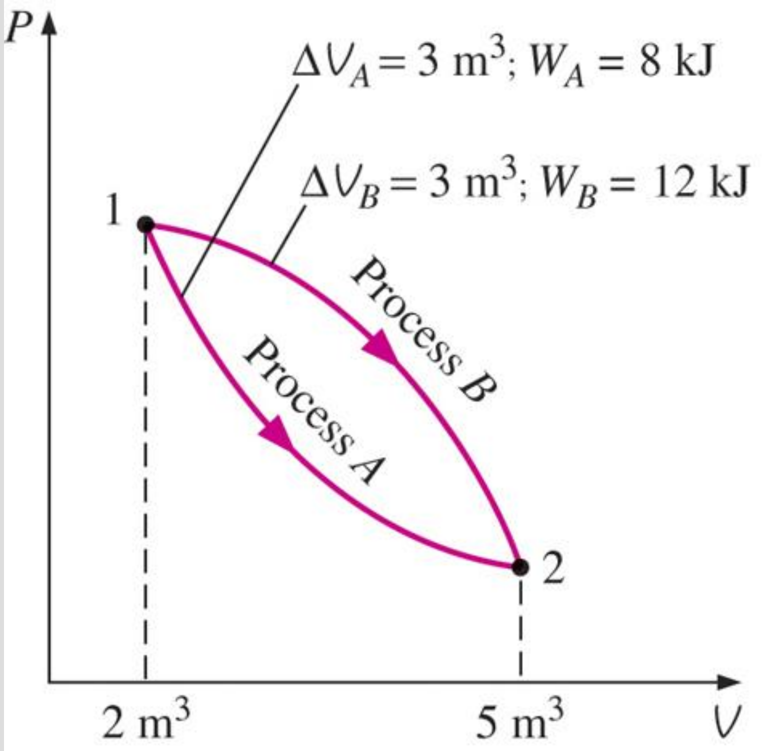
Power is the work done per unit time (kW)



Specifying the directions of heat and work.

Heat vs. Work

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a *process*, not a state.
- Unlike properties, heat or work has no meaning at a state.
- Both are *path functions* (i.e., their magnitudes depend on the path followed during a process as well as the end states).



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

Properties are point functions have exact differentials (d).

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

Path functions have inexact differentials (δ)

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

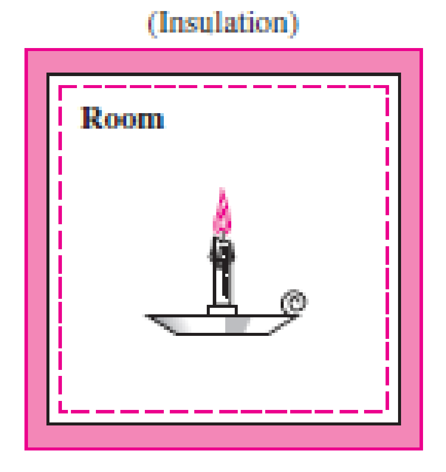
EXAMPLE 2–3 Burning of a Candle in an Insulated Room

A candle is burning in a well-insulated room. Taking the room (the air plus the candle) as the system, determine (*a*) if there is any heat transfer during this burning process and (*b*) if there is any change in the internal energy of the system.

Solution A candle burning in a well-insulated room is considered. It is to be determined whether there is any heat transfer and any change in internal energy.

Analysis (*a*) The interior surfaces of the room form the system boundary, as indicated by the dashed lines in Fig. 2–20. As pointed out earlier, heat is recognized as it crosses the boundaries. Since the room is well insulated, we have an adiabatic system and no heat will pass through the boundaries. Therefore, $Q = 0$ for this process.

(*b*) The internal energy involves energies that exist in various forms (sensible, latent, chemical, nuclear). During the process just described, part of the chemical energy is converted to sensible energy. Since there is no increase or decrease in the total internal energy of the system, $\Delta U = 0$ for this process.

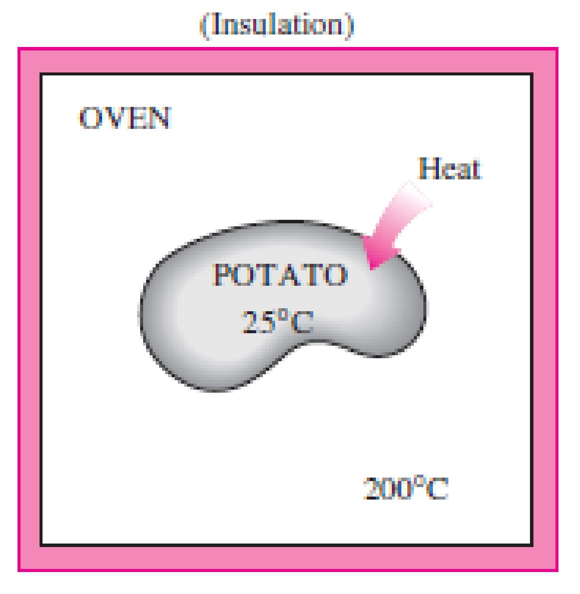


EXAMPLE 2–4 **Heating of a Potato in an Oven**

A potato initially at room temperature (25°C) is being baked in an oven that is maintained at 200°C, as shown in Fig. 2–21. Is there any heat transfer during this baking process?

Solution A potato is being baked in an oven. It is to be determined whether there is any heat transfer during this process.

Analysis This is not a well-defined problem since the system is not specified. Let us assume that we are observing the potato, which will be our system. Then the skin of the potato can be viewed as the system boundary. Part of the energy in the oven will pass through the skin to the potato. Since the driving force for this energy transfer is a temperature difference, this is a heat transfer process.

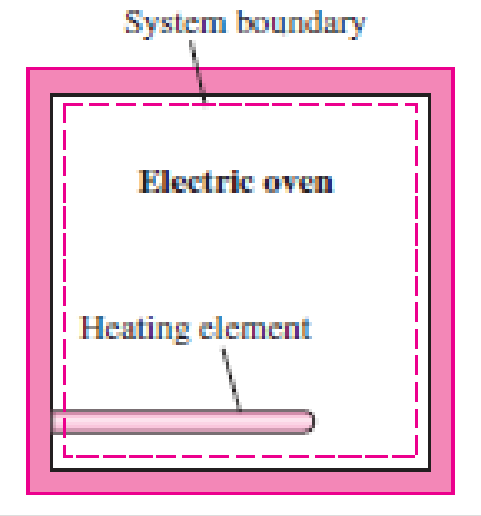


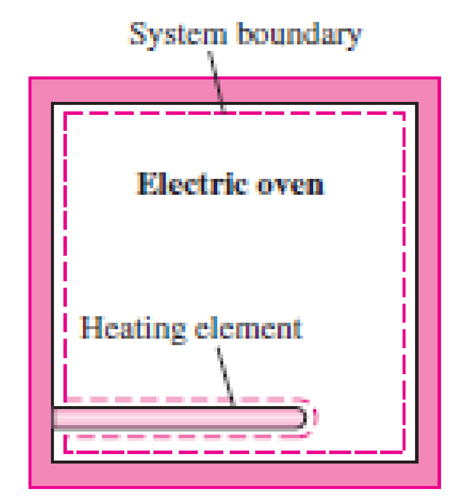
EXAMPLE 2–5 Heating of an Oven by Work Transfer

A well-insulated electric oven is being heated through its heating element. If the entire oven, including the heating element, is taken to be the system, determine whether this is a heat or work interaction.

Solution A well-insulated electric oven is being heated by its heating element. It is to be determined whether this is a heat or work interaction.

Analysis For this problem, the interior surfaces of the oven form the system boundary, as shown in Fig. 2–22. The energy content of the oven obviously increases during this process, as evidenced by a rise in temperature. This energy transfer to the oven is not caused by a temperature difference between the oven and the surrounding air. Instead, it is caused by *electrons* crossing the system boundary and thus doing work. Therefore, this is a work interaction.





EXAMPLE 2–6 **Heating of an Oven by Heat Transfer**

Answer the question in Example 2–5 if the system is taken as only the air in the oven without the heating element.

Solution The question in Example 2–5 is to be reconsidered by taking the system to be only the air in the oven.

Analysis This time, the system boundary will include the outer surface of the heating element and will not cut through it, as shown in Fig. 2–23. Therefore, no electrons will be crossing the system boundary at any point. Instead, the energy generated in the interior of the heating element will be transferred to the air around it as a result of the temperature difference between the heating element and the air in the oven. Therefore, this is a heat transfer process.

Discussion For both cases, the amount of energy transfer to the air is the same. These two examples show that an energy transfer can be heat or work, depending on how the system is selected.

Electrical Work

Electrical work

$$W_e = \mathbf{V}N$$

Electrical power

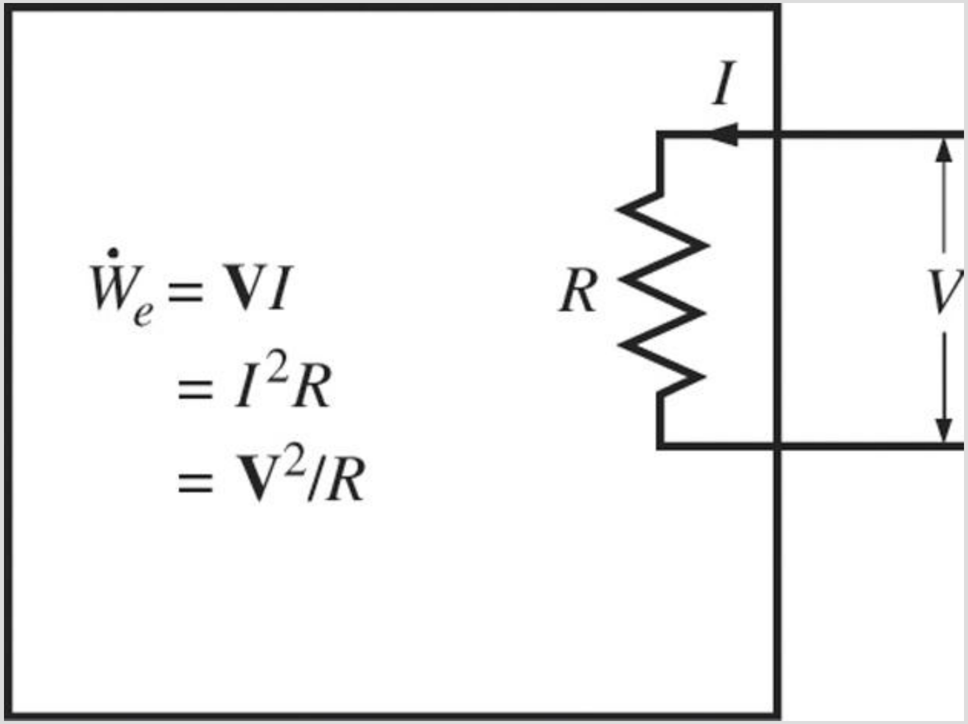
$$\dot{W}_e = \mathbf{V}I \qquad \text{(W)}$$

When potential difference and current change with time

$$W_e = \int_1^2 \mathbf{V}I\,dt \qquad \text{(kJ)}$$

When potential difference and current remain constant

$$W_e = \mathbf{V}I\,\Delta t \qquad \text{(kJ)}$$



Electrical power in terms of resistance *R*, current *I*, and potential difference **V**.

MECHANICAL FORMS OF WORK

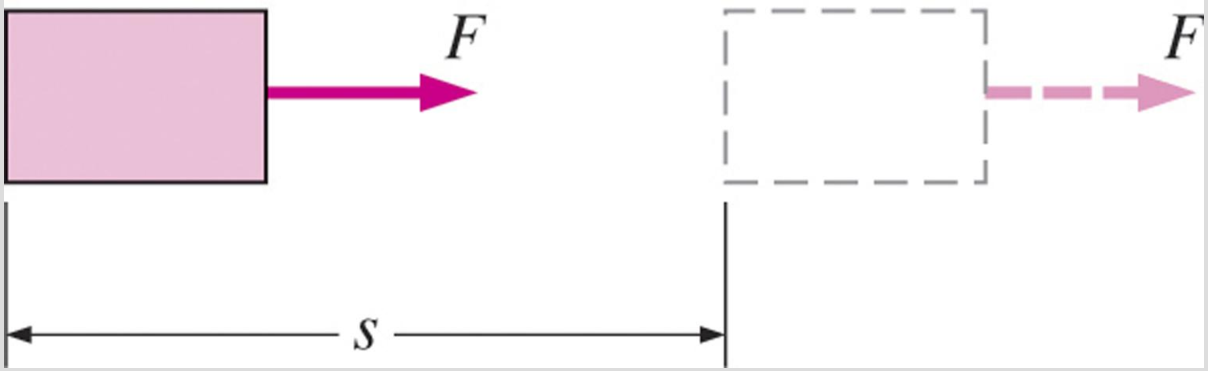
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - ✓ there must be a ***force*** acting on the boundary.
  - ✓ the boundary must ***move***.

When force is not constant

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

Work = Force × Distance

$$W = Fs \qquad (\text{kJ})$$



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

If there is no movement, no work is done.

Shaft Work

A force *F* acting through a moment arm *r* generates a torque T

$$T = Fr \quad \rightarrow \quad F = \frac{T}{r}$$

This force acts through a distance *s*

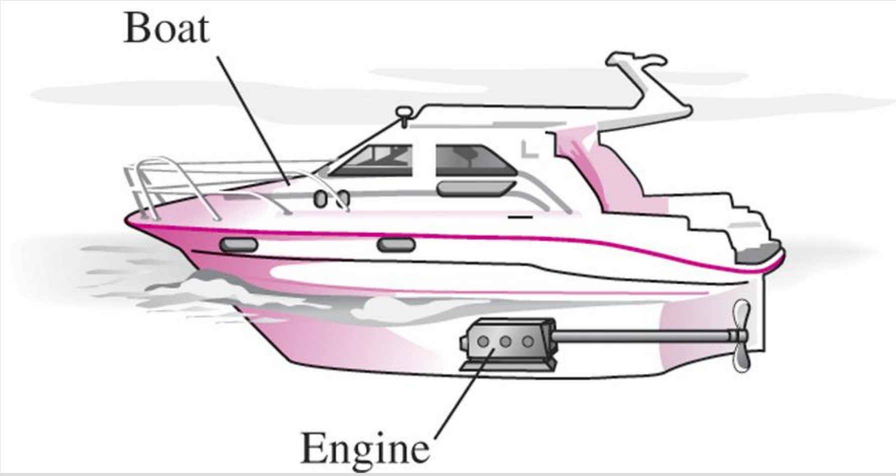
$$s = (2\pi r)n$$

Shaft work

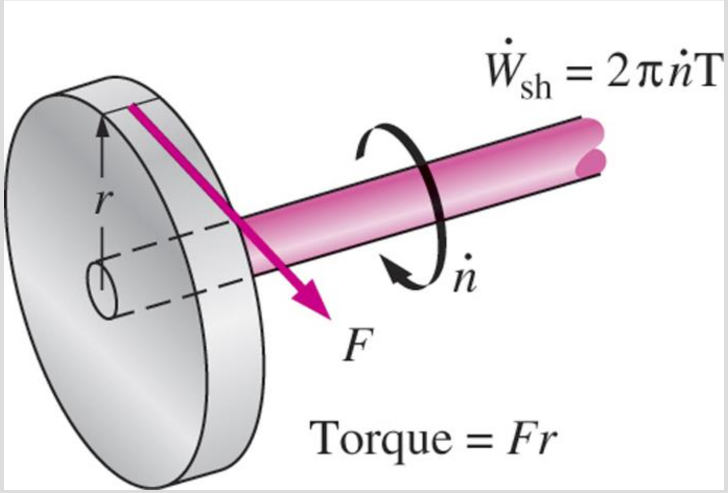
$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi rn) = 2\pi nT \qquad (kJ)$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi\dot{n}T \qquad (kW)$$



Energy transmission through rotating shafts is commonly encountered in practice.



Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

Spring Work

When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is

$$\delta W_{\text{spring}} = F\,dx$$

For linear elastic springs, the displacement *x* is proportional to the force applied

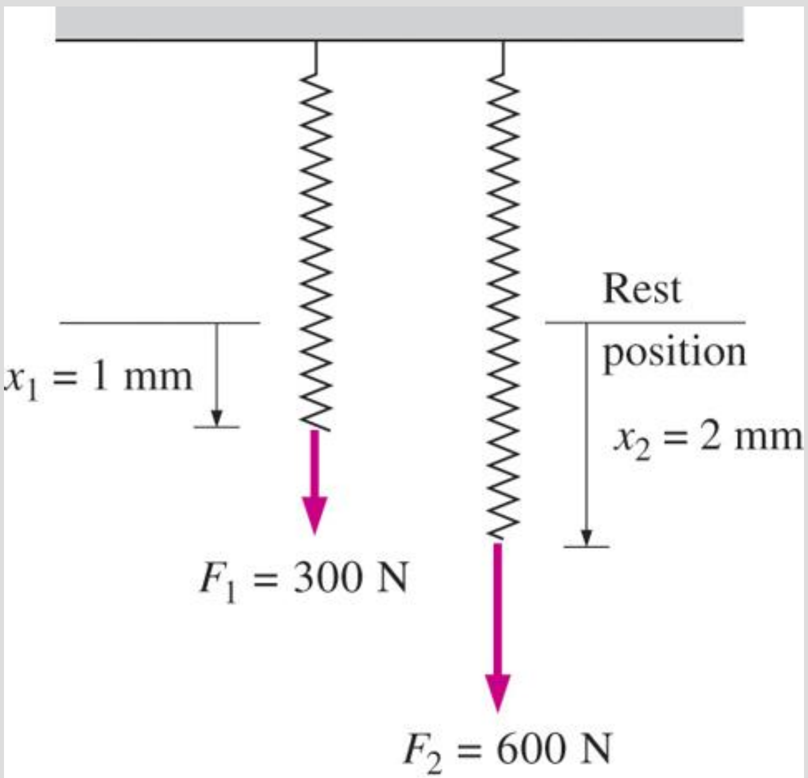
$$F = kx \qquad (\text{kN})$$

k: spring constant (kN/m)

Substituting and integrating yield

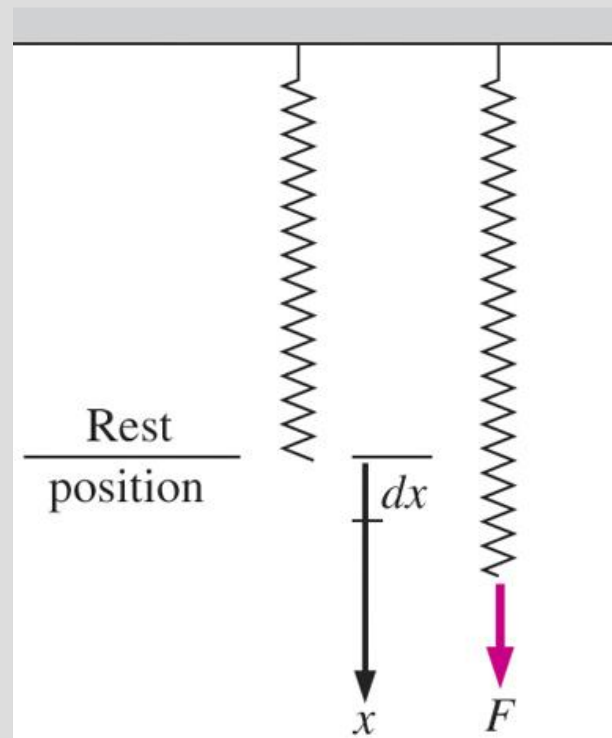
$$W_{\text{spring}} = \tfrac{1}{2}k\left(x_2^2 - x_1^2\right) \qquad (\text{kJ})$$

x_1 and x_2: the initial and the final displacements



The displacement of a linear spring doubles when the force is doubled.

Elongation of a spring under the influence of a force.



EXAMPLE 2–7 Power Transmission by the Shaft of a Car

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

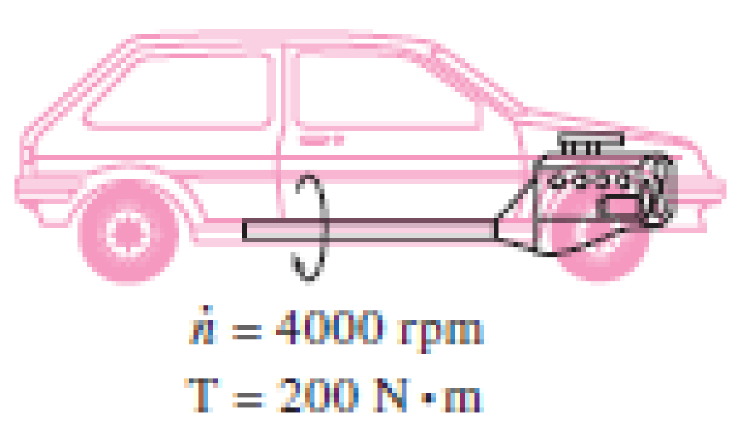
Solution The torque and the rpm for a car engine are given. The power transmitted is to be determined.

Analysis A sketch of the car is given in Fig. 2–29. The shaft power is determined directly from

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

$$= \mathbf{83.8\ kW} \qquad \text{(or 112 hp)}$$

Discussion Note that power transmitted by a shaft is proportional to torque and the rotational speed.

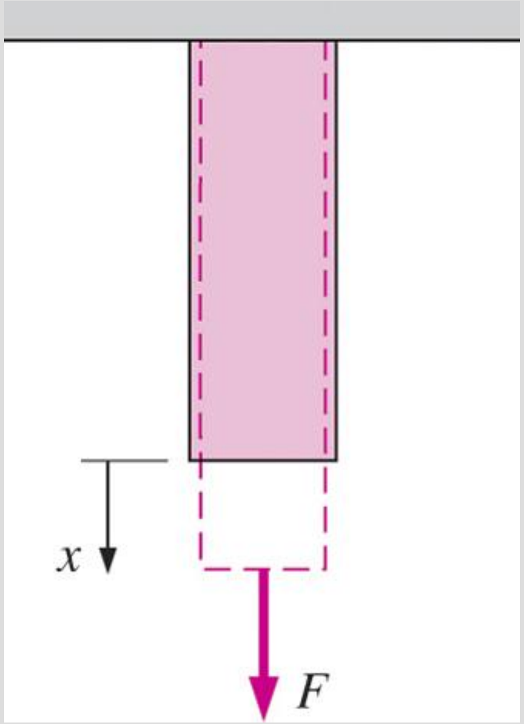


Work Done on Elastic Solid Bars

$$W_{\text{elastic}} = \int_1^2 F\,dx = \int_1^2 \sigma_n A\,dx \qquad \text{(kJ)}$$

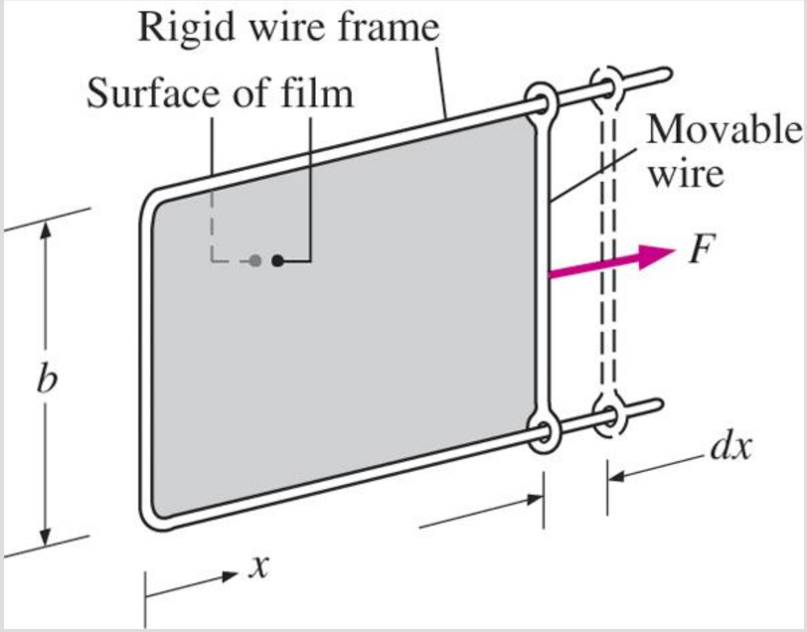
Work Associated with the Stretching of a Liquid Film

$$W_{\text{surface}} = \int_1^2 \sigma_s\,dA \qquad \text{(kJ)}$$



Solid bars behave as springs under the influence of a force.

Stretching a liquid film with a movable wire.



Work Done to Raise or to Accelerate a Body

1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.
2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.

Nonmechanical Forms of Work

Electrical work: The generalized force is the *voltage* (the electrical potential) and the generalized displacement is the *electrical charge.*

Magnetic work: The generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment*.

Electrical polarization work: The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium*.

The energy transferred to a body while being raised is equal to the change in its potential energy.

EXAMPLE 2–8 Power Needs of a Car to Climb a Hill

Consider a 1200-kg car cruising steadily on a level road at 90 km/h. Now the car starts climbing a hill that is sloped 30° from the horizontal (Fig. 2–35). If the velocity of the car is to remain constant during climbing, determine the additional power that must be delivered by the engine.

Solution A car is to climb a hill while maintaining a constant velocity. The additional power needed is to be determined.

Analysis The additional power required is simply the work that needs to be done per unit time to raise the elevation of the car, which is equal to the change in the potential energy of the car per unit time:

$$\dot{W}_g = mg\ \Delta z/\Delta t = mgV_{\text{vertical}}$$

$$= (1200\text{ kg})(9.81\text{ m/s}^2)(90\text{ km/h})(\sin 30°)\left(\frac{1\text{ m/s}}{3.6\text{ km/h}}\right)\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)$$

$$= 147\text{ kJ/s} = \mathbf{147\ kW} \qquad \text{(or 197 hp)}$$

EXAMPLE 2–9 Power Needs of a Car to Accelerate

Determine the power required to accelerate a 900-kg car shown in Fig. 2–36 from rest to a velocity of 80 km/h in 20 s on a level road.

Solution The power required to accelerate a car to a specified velocity is to be determined.

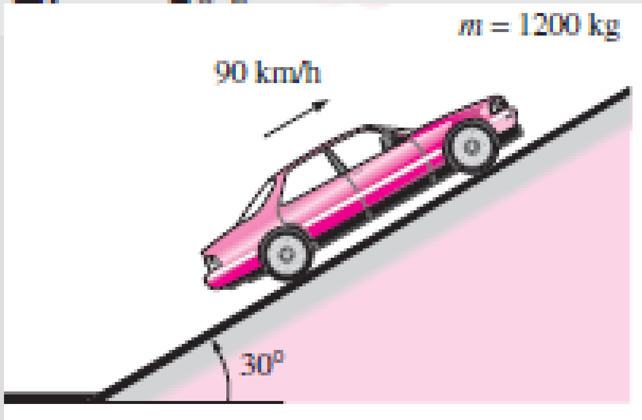
Analysis The work needed to accelerate a body is simply the change in the kinetic energy of the body,

$$W_a = \tfrac{1}{2}m(V_2^2 - V_1^2) = \tfrac{1}{2}(900\text{ kg})\left[\left(\frac{80{,}000\text{ m}}{3600\text{ s}}\right)^2 - 0^2\right]\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)$$

$$= 222\text{ kJ}$$

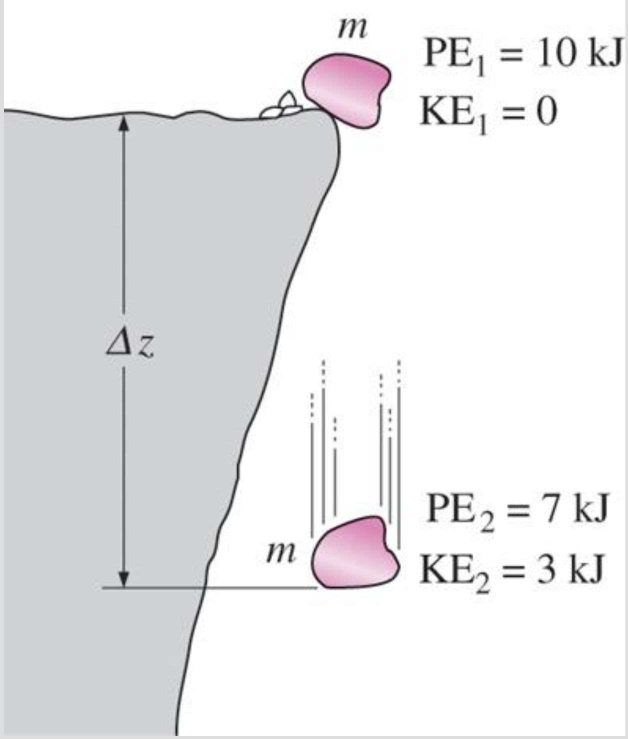
The average power is determined from

$$\dot{W}_a = \frac{W_a}{\Delta t} = \frac{222\text{ kJ}}{20\text{ s}} = \mathbf{11.1\ kW} \qquad \text{(or 14.9 hp)}$$

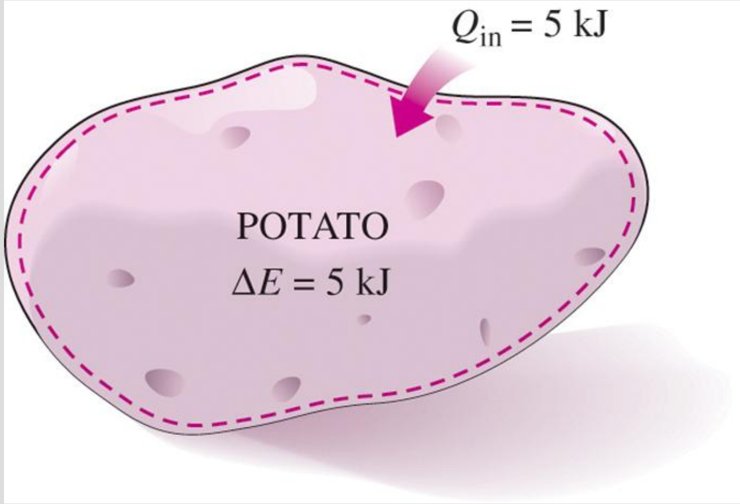


THE FIRST LAW OF THERMODYNAMICS

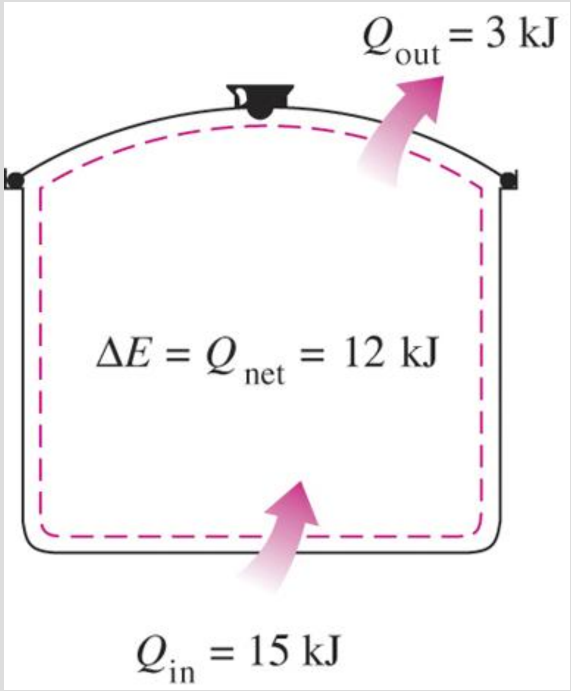
- **The *first law of thermodynamics* (*the conservation of energy principle*)** provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that ***energy can be neither created nor destroyed during a process; it can only change forms.***
- **The *First Law*:** For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.



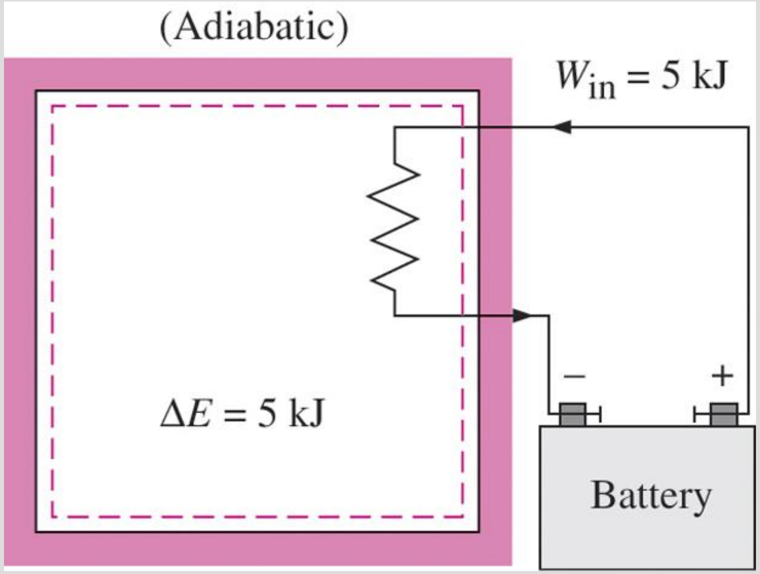
Energy cannot be created or destroyed; it can only change forms.



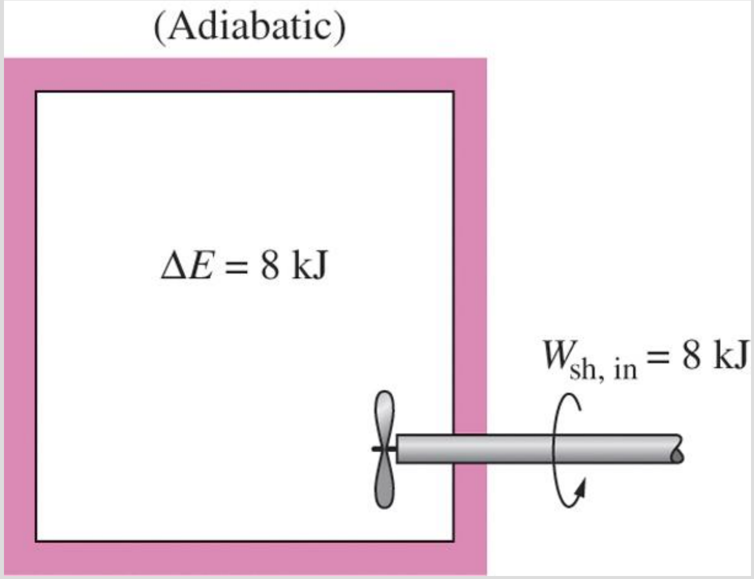
The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.



In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.



The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



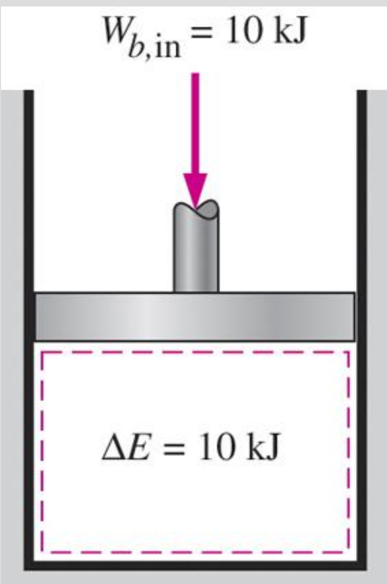
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

Energy Balance

The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

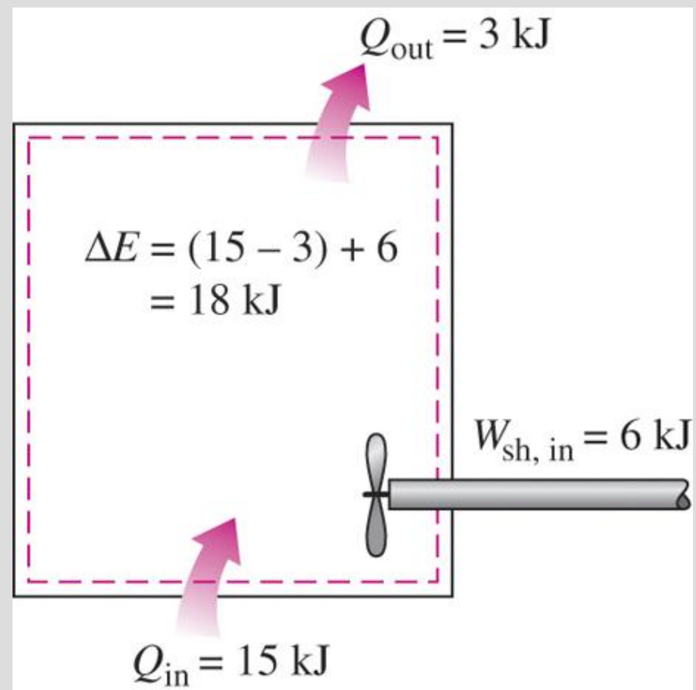
$$E_{in} - E_{out} = \Delta E_{system}$$



(Adiabatic)

The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.



Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{\text{system}} = E_{\text{final}} - E_{\text{initial}} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

Internal, kinetic, and potential energy changes

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

$$\Delta \text{KE} = \tfrac{1}{2} m(V_2^2 - V_1^2)$$

$$\Delta \text{PE} = mg(z_2 - z_1)$$

Stationary Systems

$$z_1 = z_2 \rightarrow \Delta \text{PE} = 0$$

$$V_1 = V_2 \rightarrow \Delta \text{KE} = 0$$

$$\Delta E = \Delta U$$

Mechanisms of Energy Transfer, E_{in} and E_{out}

- Heat transfer
- Work transfer
- Mass flow

A closed mass involves only *heat transfer* and *work.*

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

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

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal,}\\ \text{kinetic, potential, etc., energies}}} \quad (\text{kW})$$

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

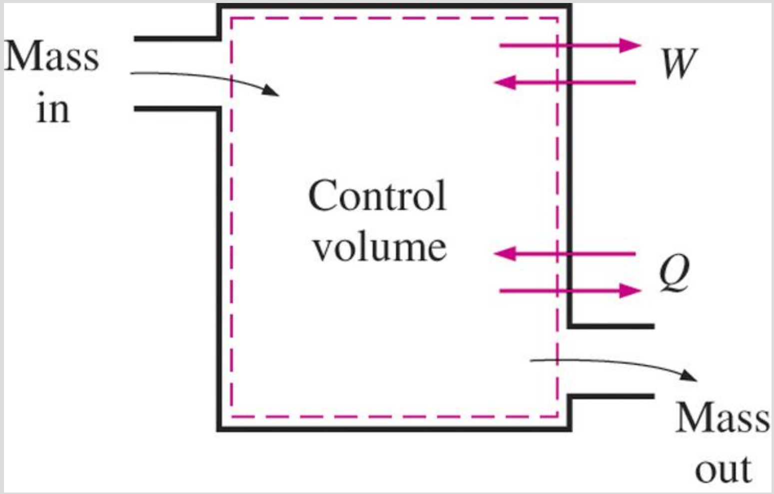
$$W = \dot{W}\,\Delta t$$

$$\Delta E = (dE/dt)\,\Delta t$$

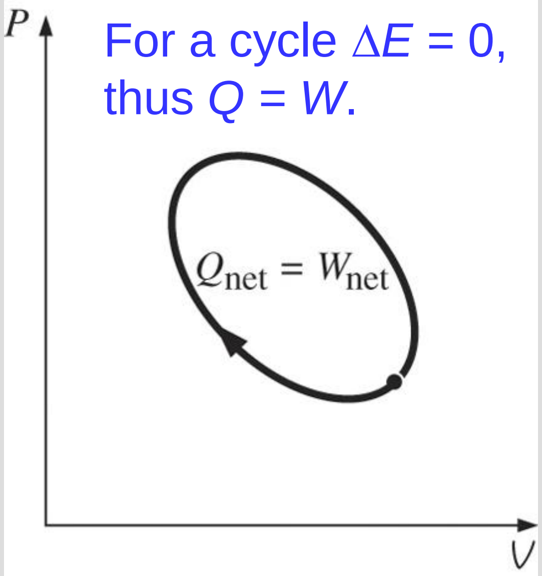
$$e_{in} - e_{out} = \Delta e_{system} \quad (\text{kJ/kg})$$

$$\delta E_{in} - \delta E_{out} = dE_{system} \qquad \delta e_{in} - \delta e_{out} = de_{system}$$

$$\dot{W}_{net,out} = \dot{Q}_{net,in} \quad (\text{for a cycle})$$



The energy content of a control volume can be changed by mass flow as well as heat and work interactions.



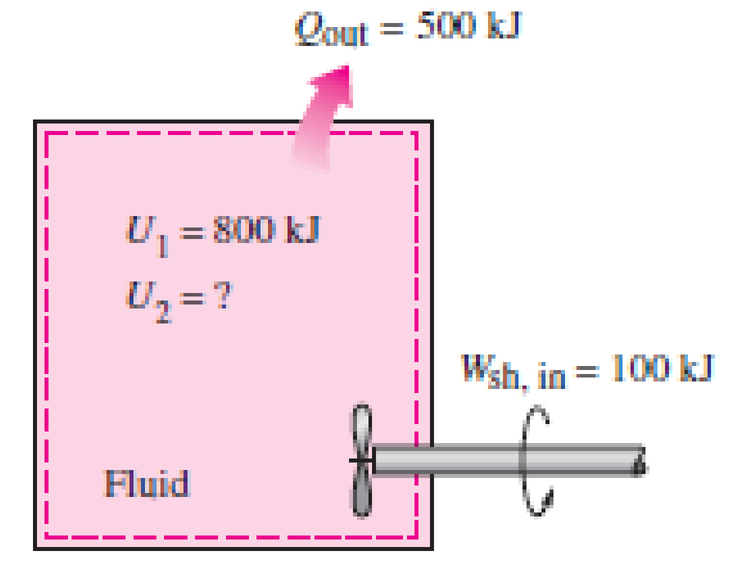
For a cycle $\Delta E = 0$, thus $Q = W$.

EXAMPLE 2–10 Cooling of a Hot Fluid in a Tank

A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

Solution A fluid in a rigid tank looses heat while being stirred. The final internal energy of the fluid is to be determined.

Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of the system's energy that may change during this process. **2** Energy stored in the paddle wheel is negligible.



Analysis Take the contents of the tank as the *system* (Fig. 2–47). This is a *closed system* since no mass crosses the boundary during the process. We observe that the volume of a rigid tank is constant, and thus there is no moving boundary work. Also, heat is lost from the system and shaft work is done on the system. Applying the energy balance on the system gives

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

$$W_{sh,in} - Q_{out} = \Delta U = U_2 - U_1$$

$$100 \text{ kJ} - 500 \text{ kJ} = U_2 - 800 \text{ kJ}$$

$$U_2 = \mathbf{400\ kJ}$$

Therefore, the final internal energy of the system is 400 kJ.

EXAMPLE 2–11 Acceleration of Air by a Fan

A fan that consumes 20 W of electric power when operating is claimed to discharge air from a ventilated room at a rate of 0.25 kg/s at a discharge velocity of 8 m/s (Fig. 2–48). Determine if this claim is reasonable.

Solution A fan is claimed to increase the velocity of air to a specified value while consuming electric power at a specified rate. The validity of this claim is to be investigated.

Assumptions The ventilating room is relatively calm, and air velocity in it is negligible.

Analysis First, let's examine the energy conversions involved: The motor of the fan converts part of the electrical power it consumes to mechanical (shaft) power, which is used to rotate the fan blades in air. The blades are shaped such that they impart a large fraction of the mechanical power of the shaft to air by mobilizing it. In the limiting ideal case of no losses (no conversion of electrical and mechanical energy to thermal energy) in steady operation, the electric power input will be equal to the rate of increase of the kinetic energy of air. Therefore, for a control volume that encloses the fan-motor unit, the energy balance can be written as

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

$$\dot{W}_{elect,\,in} = \dot{m}_{air}\,\mathrm{ke}_{out} = \dot{m}_{air}\frac{V_{out}^2}{2}$$

Solving for V_{out} and substituting gives the maximum air outlet velocity to be

$$V_{out} = \sqrt{\frac{\dot{W}_{elect,in}}{2\dot{m}_{air}}} = \sqrt{\frac{20\ \mathrm{J/s}}{2(0.25\ \mathrm{kg/s})}\left(\frac{1\ \mathrm{m^2/s^2}}{1\ \mathrm{J/kg}}\right)} = 6.3\ \mathrm{m/s}$$

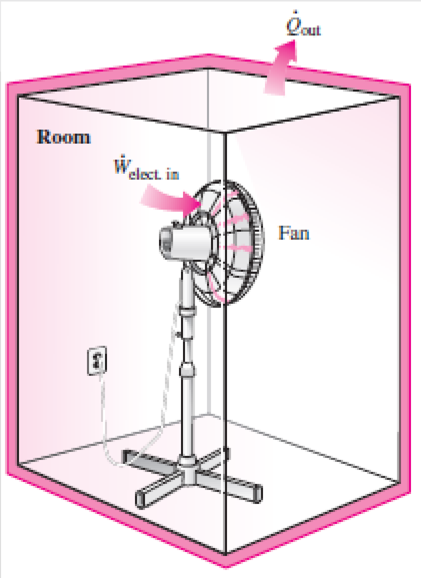
which is less than 8 m/s. Therefore, the claim is **false.**

EXAMPLE 2–12 Heating Effect of a Fan

A room is initially at the outdoor temperature of 25°C. Now a large fan that consumes 200 W of electricity when running is turned on (Fig. 2–49). The heat transfer rate between the room and the outdoor air is given as $\dot{Q} = UA(T_i - T_o)$ where $U = 6\ \text{W/m}^2 \cdot {}^\circ\text{C}$ is the overall heat transfer coefficient, $A = 30\ \text{m}^2$ is the exposed surface area of the room, and T_i and T_o are the indoor and outdoor air temperatures, respectively. Determine the indoor air temperature when steady operating conditions are established.

Solution A large fan is turned on and kept on in a room that looses heat to the outdoors. The indoor air temperature is to be determined when steady operation is reached.

Assumptions **1** Heat transfer through the floor is negligible. **2** There are no other energy interactions involved.



Analysis The electricity consumed by the fan is energy input for the room, and thus the room gains energy at a rate of 200 W. As a result, the room air temperature tends to rise. But as the room air temperature rises, the rate of heat loss from the room increases until the rate of heat loss equals the electric power consumption. At that point, the temperature of the room air, and thus the energy content of the room, remains constant, and the conservation of energy for the room becomes

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

$$\dot{W}_{elect,in} = \dot{Q}_{out} = UA(T_i - T_o)$$

Substituting,

$$200\ \text{W} = (6\ \text{W/m}^2 \cdot {}^\circ\text{C})(30\ \text{m}^2)(T_i - 25^\circ\text{C})$$

It gives

$$T_i = 26.1^\circ\text{C}$$

Therefore, the room air temperature will remain constant after it reaches 26.1°C.

EXAMPLE 2–13 Annual Lighting Cost of a Classroom

The lighting needs of a classroom are met by 30 fluorescent lamps, each consuming 80 W of electricity (Fig. 2–50). The lights in the classroom are kept on for 12 hours a day and 250 days a year. For a unit electricity cost of 7 cents per kWh, determine annual energy cost of lighting for this classroom. Also, discuss the effect of lighting on the heating and air-conditioning requirements of the room.

Solution The lighting of a classroom by fluorescent lamps is considered. The annual electricity cost of lighting for this classroom is to be determined, and the lighting's effect on the heating and air-conditioning requirements is to be discussed.

Assumptions The effect of voltage fluctuations is negligible so that each fluorescent lamp consumes its rated power.

Analysis The electric power consumed by the lamps when all are on and the number of hours they are kept on per year are

$$\text{Lighting power} = (\text{Power consumed per lamp}) \times (\text{No. of lamps})$$
$$= (80\ \text{W/lamp})(30\ \text{lamps})$$
$$= 2400\ \text{W} = 2.4\ \text{kW}$$
$$\text{Operating hours} = (12\ \text{h/day})(250\ \text{days/year}) = 3000\ \text{h/year}$$

Then the amount and cost of electricity used per year become

$$\text{Lighting energy} = (\text{Lighting power})(\text{Operating hours})$$
$$= (2.4\ \text{kW})(3000\ \text{h/year}) = 7200\ \text{kWh/year}$$
$$\text{Lighting cost} = (\text{Lighting energy})(\text{Unit cost})$$
$$= (7200\ \text{kWh/year})(\$0.07/\text{kWh}) = \mathbf{\$504/year}$$

Light is absorbed by the surfaces it strikes and is converted to thermal energy. Disregarding the light that escapes through the windows, the entire 2.4 kW of electric power consumed by the lamps eventually becomes part of thermal energy of the classroom. Therefore, the lighting system in this room reduces the heating requirements by 2.4 kW, but increases the air-conditioning load by 2.4 kW.

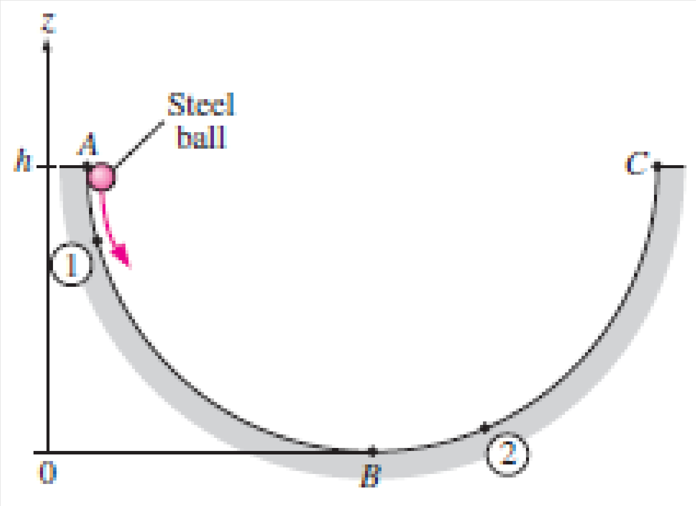
EXAMPLE 2–14 Conservation of Energy for an Oscillating Steel Ball

The motion of a steel ball in a hemispherical bowl of radius *h* shown in Fig. 2–51 is to be analyzed. The ball is initially held at the highest location at point *A*, and then it is released. Obtain relations for the conservation of energy of the ball for the cases of frictionless and actual motions.

Solution A steel ball is released in a bowl. Relations for the energy balance are to be obtained.

Assumptions The motion is frictionless, and thus friction between the ball, the bowl, and the air is negligible.

Analysis When the ball is released, it accelerates under the influence of gravity, reaches a maximum velocity (and minimum elevation) at point *B* at



the bottom of the bowl, and moves up toward point *C* on the opposite side. In the ideal case of frictionless motion, the ball will oscillate between points *A* and *C*. The actual motion involves the conversion of the kinetic and potential energies of the ball to each other, together with overcoming resistance to motion due to friction (doing frictional work). The general energy balance for any system undergoing any process is

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

Then the energy balance for the ball for a process from point 1 to point 2 becomes

$$-w_{\text{friction}} = (\text{ke}_2 + \text{pe}_2) - (\text{ke}_1 + \text{pe}_1)$$

or

$$\frac{V_1^2}{2} + gz_1 = \frac{V_2^2}{2} + gz_2 + w_{\text{friction}}$$

since there is no energy transfer by heat or mass and no change in the internal energy of the ball (the heat generated by frictional heating is dissipated to the surrounding air). The frictional work term w_{friction} is often expressed as e_{loss} to represent the loss (conversion) of mechanical energy into thermal energy.

For the idealized case of frictionless motion, the last relation reduces to

$$\frac{V_1^2}{2} + gz_1 = \frac{V_2^2}{2} + gz_2 \quad \text{or} \quad \frac{V^2}{2} + gz = C = \text{constant}$$

ENERGY CONVERSION EFFICIENCIES

Efficiency is one of the most frequently used terms in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished.

The definition of performance is not limited to thermodynamics only.

$$\text{Performance} = \frac{\text{Desired output}}{\text{Required input}}$$

Efficiency of a water heater: The ratio of the energy delivered to the house by hot water to the energy supplied to the water heater.

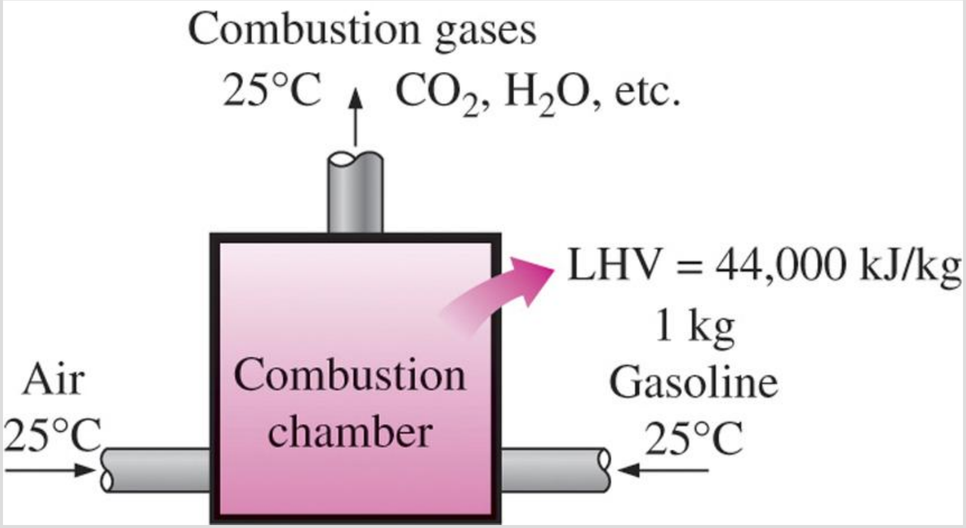
Type	Efficiency
Gas, conventional	55%
Gas, high-efficiency	62%
Electric, conventional	90%
Electric, high-efficiency	94%

$$\eta_{\text{combustion}} = \frac{Q}{\text{HV}} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.



The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the **annual fuel utilization efficiency (AFUE)**, which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cooldown losses.

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:** The ratio of the net electrical power output to the rate of fuel energy input.

$$\eta_{\text{overall}} = \eta_{\text{combustion}}\,\eta_{\text{thermal}}\,\eta_{\text{generator}} = \frac{\dot{W}_{\text{net,electric}}}{\text{HHV} \times \dot{m}_{\text{net}}}$$

Overall efficiency of a power plant

TABLE 2–1

The efficacy of different lighting systems

Type of lighting	Efficacy, lumens/W
Combustion	
Candle	0.2
Incandescent	
Ordinary	6–20
Halogen	16–25
Fluorescent	
Ordinary	40–60
High output	70–90
Compact	50–80
High-intensity discharge	
Mercury vapor	50–60
Metal halide	56–125
High-pressure sodium	100–150
Low-pressure sodium	up to 200

Lighting efficacy: The amount of light output in lumens per W of electricity consumed.

A 15-W compact fluorescent lamp provides as much light as a 60-W incandescent lamp.

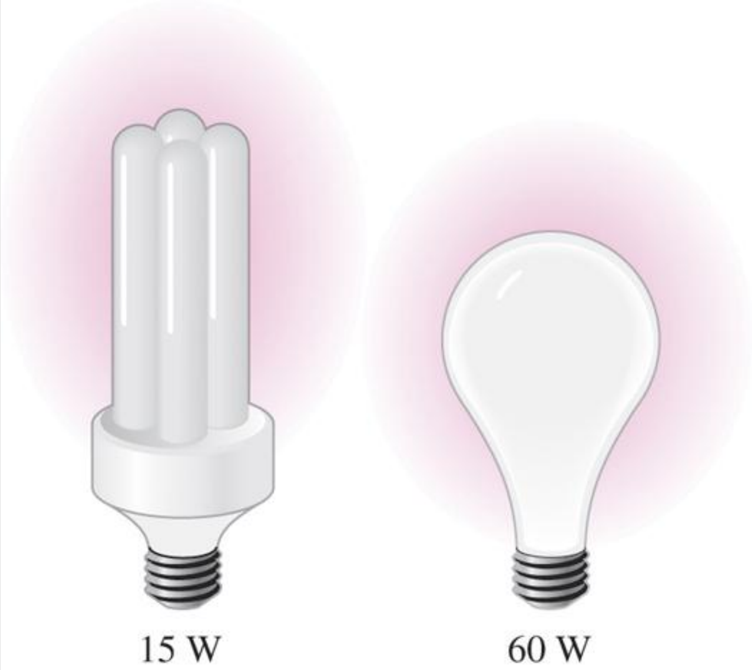


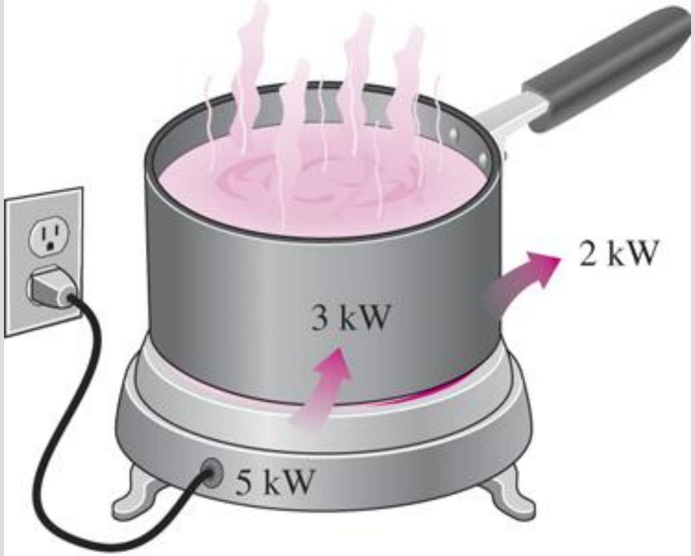
TABLE 2–2

Energy costs of cooking a casserole with different appliances*

[From A. Wilson and J. Morril, *Consumer Guide to Home Energy Savings*, Washington, DC: American Council for an Energy-Efficient Economy, 1996, p. 192.]

Cooking appliance	Cooking temperature	Cooking time	Energy used	Cost of energy
Electric oven	350°F (177°C)	1 h	2.0 kWh	$0.16
Convection oven (elect.)	325°F (163°C)	45 min	1.39 kWh	$0.11
Gas oven	350°F (177°C)	1 h	0.112 therm	$0.07
Frying pan	420°F (216°C)	1 h	0.9 kWh	$0.07
Toaster oven	425°F (218°C)	50 min	0.95 kWh	$0.08
Electric slow cooker	200°F (93°C)	7 h	0.7 kWh	$0.06
Microwave oven	"High"	15 min	0.36 kWh	$0.03

*Assumes a unit cost of $0.08/kWh for electricity and $0.60/therm for gas.



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}} = \frac{3\text{ kWh}}{5\text{ kWh}} = 0.60$$

- Using energy-efficient appliances conserve energy.
- It helps the **environment** by reducing the amount of pollutants emitted to the atmosphere during the combustion of fuel.
- The combustion of fuel produces
  - carbon dioxide, causes global warming
  - nitrogen oxides and hydrocarbons, cause smog
  - carbon monoxide, toxic
  - sulfur dioxide, causes acid rain.

The efficiency of a cooking appliance represents the fraction of the energy supplied to the appliance that is transferred to the food.

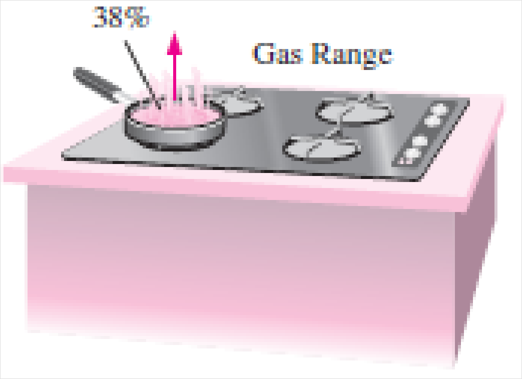
EXAMPLE 2–15 Cost of Cooking with Electric and Gas Ranges

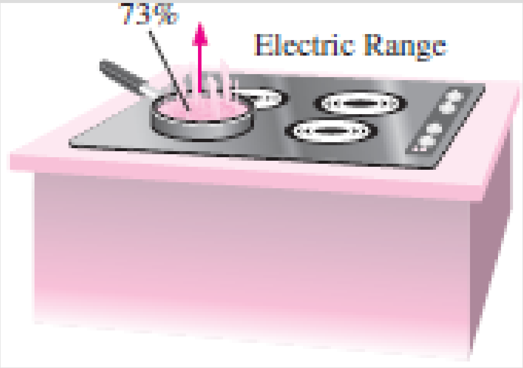
The efficiency of cooking appliances affects the internal heat gain from them since an inefficient appliance consumes a greater amount of energy for the same task, and the excess energy consumed shows up as heat in the living space. The efficiency of open burners is determined to be 73 percent for electric units and 38 percent for gas units (Fig. 2–57). Consider a 2-kW electric burner at a location where the unit costs of electricity and natural gas are \$0.09/kWh and \$0.55/therm, respectively. Determine the rate of energy consumption by the burner and the unit cost of utilized energy for both electric and gas burners.

Solution The operation of electric and gas ranges is considered. The rate of energy consumption and the unit cost of utilized energy are to be determined.

Analysis The efficiency of the electric heater is given to be 73 percent. Therefore, a burner that consumes 2 kW of electrical energy will supply

$$\dot{Q}_{\text{utilized}} = (\text{Energy input}) \times (\text{Efficiency}) = (2\text{ kW})(0.73) = \mathbf{1.46\ kW}$$





Analysis The efficiency of the electric heater is given to be 73 percent. Therefore, a burner that consumes 2 kW of electrical energy will supply

$$\dot{Q}_{\text{utilized}} = (\text{Energy input}) \times (\text{Efficiency}) = (2\text{ kW})(0.73) = \mathbf{1.46\ kW}$$

of useful energy. The unit cost of utilized energy is inversely proportional to the efficiency, and is determined from

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$0.09/\text{kWh}}{0.73} = \mathbf{\$0.123/kWh}$$

Noting that the efficiency of a gas burner is 38 percent, the energy input to a gas burner that supplies utilized energy at the same rate (1.46 kW) is

$$\dot{Q}_{\text{input, gas}} = \frac{\dot{Q}_{\text{utilized}}}{\text{Efficiency}} = \frac{1.46\text{ kW}}{0.38} = \mathbf{3.84\ kW} \qquad (= 13{,}100\text{ Btu/h})$$

since 1 kW = 3412 Btu/h. Therefore, a gas burner should have a rating of at least 13,100 Btu/h to perform as well as the electric unit.

Noting that 1 therm = 29.3 kWh, the unit cost of utilized energy in the case of a gas burner is determined to be

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$0.55/29.3\text{ kWh}}{0.38}$$

$$= \mathbf{\$0.049/kWh}$$

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

$$\eta_{\text{mech}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{\text{mech,out}}}{E_{\text{mech,in}}} = 1 - \frac{E_{\text{mech,loss}}}{E_{\text{mech,in}}}$$

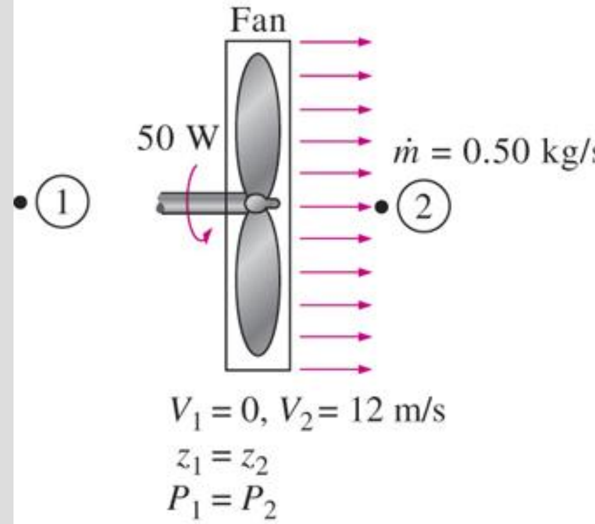
The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the **pump efficiency** and **turbine efficiency**,

$$\eta_{\text{pump}} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{pump}}}$$

$$\Delta \dot{E}_{\text{mech,fluid}} = \dot{E}_{\text{mech,out}} - \dot{E}_{\text{mech,in}}$$

$$\eta_{\text{turbine}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{\text{shaft,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|} = \frac{\dot{W}_{\text{turbine}}}{\dot{W}_{\text{turbine},e}}$$

$$|\Delta \dot{E}_{\text{mech,fluid}}| = \dot{E}_{\text{mech,in}} - \dot{E}_{\text{mech,out}}$$



$$\eta_{\text{mech, fan}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{m} V_2^2/2}{\dot{W}_{\text{shaft,in}}} = \frac{(0.50\ \text{kg/s})(12\ \text{m/s})^2/2}{50\ \text{W}} = 0.72$$

The mechanical efficiency of a fan is the ratio of the kinetic energy of air at the fan exit to the mechanical power input.

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft,out}}}{\dot{W}_{\text{elect,in}}}$$

Pump efficiency

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

Generator efficiency

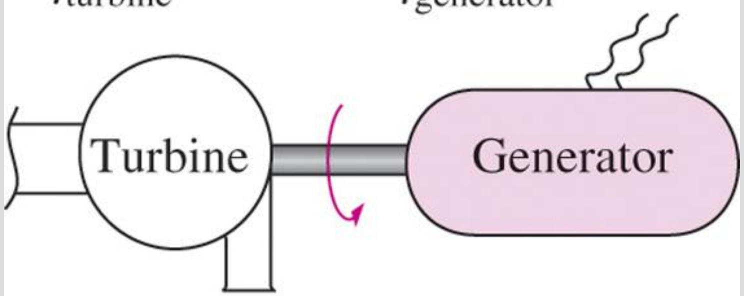
$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|}$$

Turbine-Generator overall efficiency

$\eta_{\text{turbine}} = 0.75$ $\eta_{\text{generator}} = 0.97$



$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = 0.75 \times 0.97 = 0.73$$

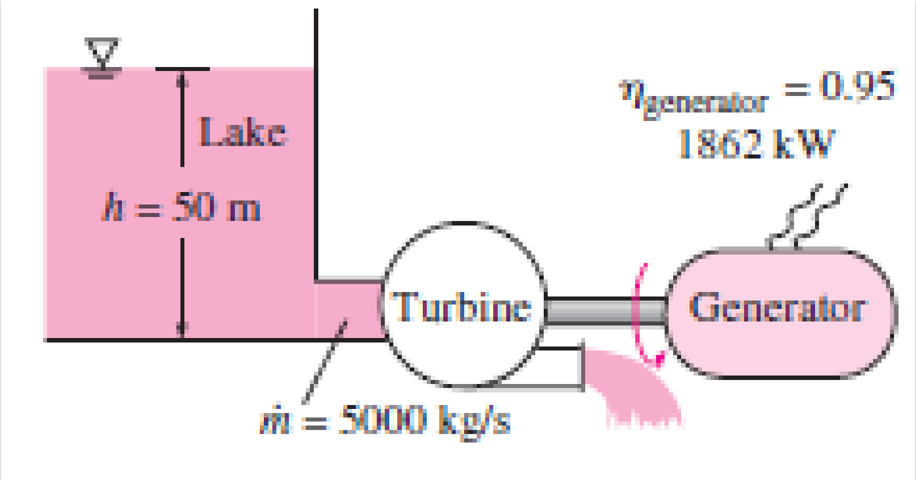
The overall efficiency of a turbine–generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical energy of the fluid converted to electric energy.

EXAMPLE 2–16 Performance of a Hydraulic Turbine–Generator

The water in a large lake is to be used to generate electricity by the installation of a hydraulic turbine–generator at a location where the depth of the water is 50 m (Fig. 2–60). Water is to be supplied at a rate of 5000 kg/s. If the electric power generated is measured to be 1862 kW and the generator efficiency is 95 percent, determine (*a*) the overall efficiency of the turbine–generator, (*b*) the mechanical efficiency of the turbine, and (*c*) the shaft power supplied by the turbine to the generator.

Solution A hydraulic turbine–generator is to generate electricity from the water of a lake. The overall efficiency, the turbine efficiency, and the turbine shaft power are to be determined.

Assumptions **1** The elevation of the lake remains constant. **2** The mechanical energy of water at the turbine exit is negligible.



Properties The density of water can be taken to be $\rho = 1000\ \text{kg/m}^3$.

Analysis (*a*) We take the bottom of the lake as the reference level for convenience. Then kinetic and potential energies of water are zero, and the change in its mechanical energy per unit mass becomes

$$e_{\text{mech,in}} - e_{\text{mech,out}} = \frac{P}{\rho} - 0 = gh = (9.81\ \text{m/s}^2)(50\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$

$$= 0.491\ \text{kJ/kg}$$

Then the rate at which mechanical energy is supplied to the turbine by the fluid and the overall efficiency become

$$|\Delta \dot{E}_{\text{mech,fluid}}| = \dot{m}(e_{\text{mech,in}} - e_{\text{mech,out}}) = (5000\ \text{kg/s})(0.491\ \text{kJ/kg}) = 2455\ \text{kW}$$

$$\eta_{\text{overall}} = \eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|} = \frac{1862\ \text{kW}}{2455\ \text{kW}} = \mathbf{0.76}$$

(*b*) Knowing the overall and generator efficiencies, the mechanical efficiency of the turbine is determined from

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} \rightarrow \eta_{\text{turbine}} = \frac{\eta_{\text{turbine-gen}}}{\eta_{\text{generator}}} = \frac{0.76}{0.95} = \mathbf{0.80}$$

(*c*) The shaft power output is determined from the definition of mechanical efficiency,

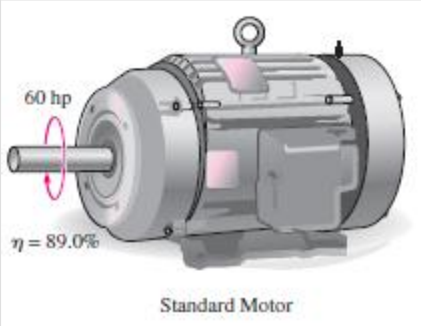
$$\dot{W}_{\text{shaft,out}} = \eta_{\text{turbine}}|\Delta \dot{E}_{\text{mech,fluid}}| = (0.80)(2455\ \text{kW}) = \mathbf{1964\ kW}$$

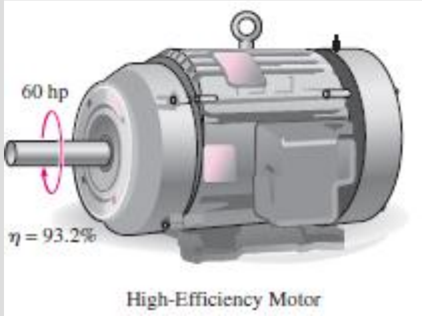
EXAMPLE 2–17 **Cost Savings Associated with High-Efficiency Motors**

A 60-hp electric motor (a motor that delivers 60 hp of shaft power at full load) that has an efficiency of 89.0 percent is worn out and is to be replaced by a 93.2 percent efficient high-efficiency motor (Fig. 2–61). The motor operates 3500 hours a year at full load. Taking the unit cost of electricity to be $0.08/kWh, determine the amount of energy and money saved as a result of installing the high-efficiency motor instead of the standard motor. Also, determine the simple payback period if the purchase prices of the standard and high-efficiency motors are $4520 and $5160, respectively.

Solution A worn-out standard motor is to be replaced by a high-efficiency one. The amount of electrical energy and money saved as well as the simple payback period are to be determined.

Assumptions The load factor of the motor remains constant at 1 (full load) when operating.





Analysis The electric power drawn by each motor and their difference can be expressed as

$$\dot{W}_{\text{electric in,standard}} = \dot{W}_{\text{shaft}}/\eta_{\text{st}} = (\text{Rated power})(\text{Load factor})/\eta_{\text{st}}$$

$$\dot{W}_{\text{electric in,efficient}} = \dot{W}_{\text{shaft}}/\eta_{\text{eff}} = (\text{Rated power})(\text{Load factor})/\eta_{\text{eff}}$$

$$\text{Power savings} = \dot{W}_{\text{electric in,standard}} - \dot{W}_{\text{electric in,efficient}}$$

$$= (\text{Rated power})(\text{Load factor})(1/\eta_{\text{st}} - 1/\eta_{\text{eff}})$$

where η_{st} is the efficiency of the standard motor, and η_{eff} is the efficiency of the comparable high-efficiency motor. Then the annual energy and cost savings associated with the installation of the high-efficiency motor become

$$\begin{aligned}\text{Energy savings} &= (\text{Power savings})(\text{Operating hours})\\ &= (\text{Rated power})(\text{Operating hours})(\text{Load factor})(1/\eta_{st} - 1/\eta_{eff})\\ &= (60\text{ hp})(0.7457\text{ kW/hp})(3500\text{ h/year})(1)(1/0.89 - 1/0.93.2)\\ &= \mathbf{7929\ kWh/year}\end{aligned}$$

$$\begin{aligned}\text{Cost savings} &= (\text{Energy savings})(\text{Unit cost of energy})\\ &= (7929\text{ kWh/year})(\$0.08/\text{ kWh})\\ &= \mathbf{\$634/year}\end{aligned}$$

Also,

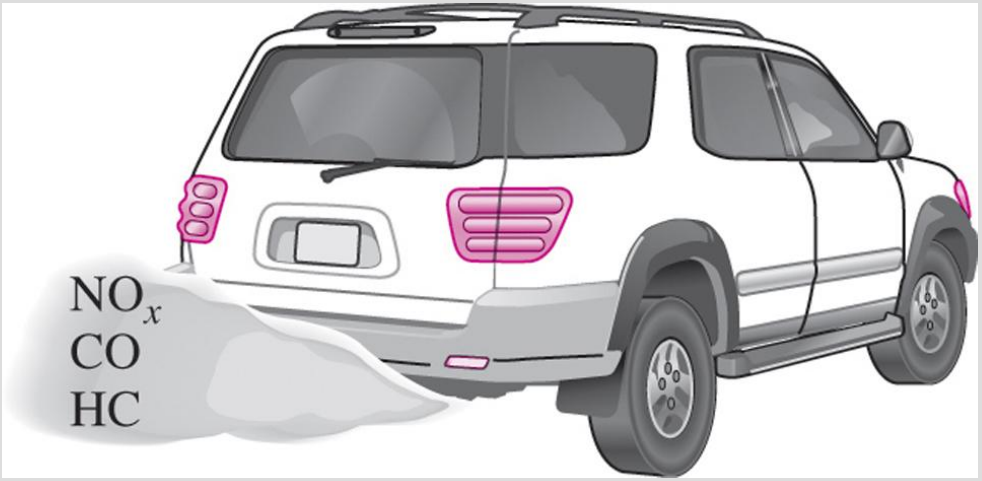
$$\text{Excess initial cost} = \text{Purchase price differential} = \$5160 - \$4520 = \$640$$

This gives a simple payback period of

$$\text{Simple payback period} = \frac{\text{Excess initial cost}}{\text{Annual cost savings}} = \frac{\$640}{\$634/\text{year}} = \mathbf{1.01\ year}$$

ENERGY AND ENVIRONMENT

- The conversion of energy from one form to another often affects the environment and the air we breathe in many ways, and thus the study of energy is not complete without considering its impact on the environment.
- Pollutants emitted during the combustion of fossil fuels are responsible for **smog**, **acid rain**, and **global warming**.
- The environmental pollution has reached such high levels that it became a serious threat to **vegetation**, **wild life**, and **human health**.

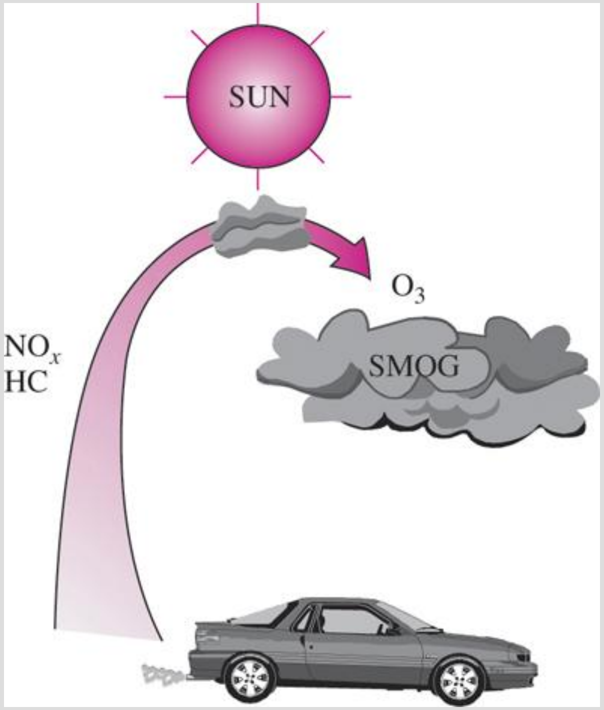


Motor vehicles are the largest source of air pollution.

Energy conversion processes are often accompanied by environmental pollution.

Ozone and Smog

- **Smog**: Made up mostly of ground-level ozone (O_3), but it also contains numerous other chemicals, including carbon monoxide (CO), particulate matter such as soot and dust, volatile organic compounds (VOCs) such as benzene, butane, and other hydrocarbons.
- **Hydrocarbons** and **nitrogen oxides** react in the presence of sunlight on hot calm days to form ground-level ozone.
- **Ozone** irritates eyes and damages the air sacs in the lungs where oxygen and carbon dioxide are exchanged, causing eventual hardening of this soft and spongy tissue.
- It also causes shortness of breath, wheezing, fatigue, headaches, and nausea, and aggravates respiratory problems such as asthma.

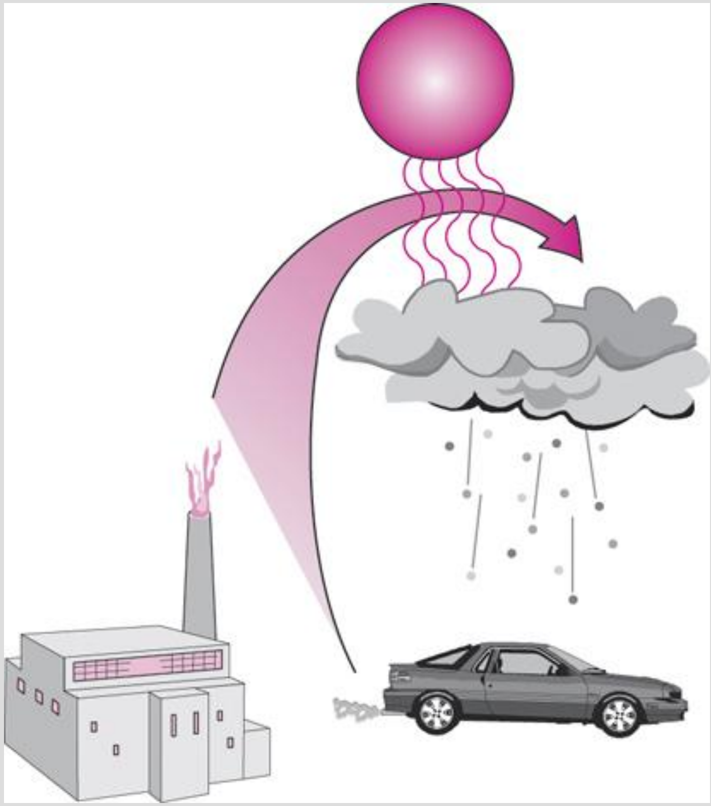


- The other serious pollutant in smog is **carbon monoxide**, which is a colorless, odorless, poisonous gas.
- It is mostly emitted by motor vehicles.
- It deprives the body's organs from getting enough oxygen by binding with the red blood cells that would otherwise carry oxygen. It is fatal at high levels.
- Suspended particulate matter such as dust and soot are emitted by vehicles and industrial facilities. Such particles irritate the eyes and the lungs.

Ground-level ozone, which is the primary component of smog, forms when HC and NO_x react in the presence of sunlight in hot calm days.

Acid Rain

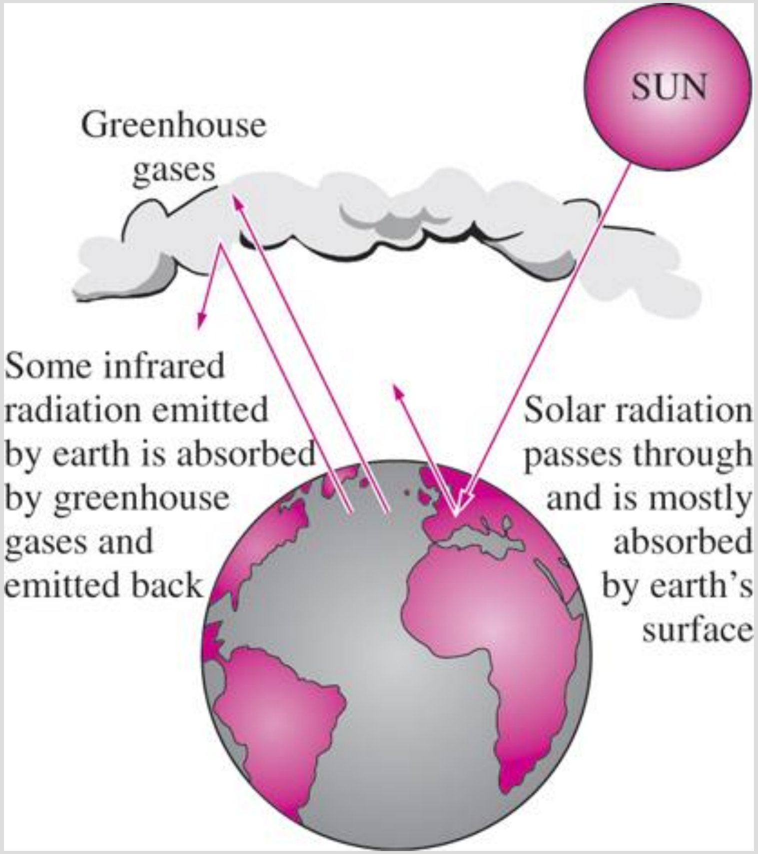
- The sulfur in the fuel reacts with oxygen to form sulfur dioxide (SO_2), which is an air pollutant.
- The main source of SO_2 is the electric power plants that burn high-sulfur coal.
- Motor vehicles also contribute to SO_2 emissions since gasoline and diesel fuel also contain small amounts of sulfur.



- The sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight to form sulfuric and nitric acids.
- The acids formed usually dissolve in the suspended water droplets in clouds or fog.
- These acid-laden droplets, which can be as acidic as lemon juice, are washed from the air on to the soil by rain or snow. This is known as **acid rain**.

Sulfuric acid and **nitric acid** are formed when sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight.

The Greenhouse Effect: Global Warming



The greenhouse effect on earth.

- **Greenhouse effect**: Glass allows the solar radiation to enter freely but blocks the infrared radiation emitted by the interior surfaces. This causes a rise in the interior temperature as a result of the thermal energy buildup in a space (i.e., car).
- The surface of the earth, which warms up during the day as a result of the absorption of solar energy, cools down at night by radiating part of its energy into deep space as infrared radiation.
- **Carbon dioxide (CO_2),** water vapor, and trace amounts of some other gases such as methane and nitrogen oxides act like a blanket and keep the earth warm at night by blocking the heat radiated from the earth. The result is **global warming**.
- These gases are called "**greenhouse gases**," with CO_2 being the primary component.
- CO_2 is produced by the burning of fossil fuels such as **coal, oil, and natural gas**.

Greenhouse effect

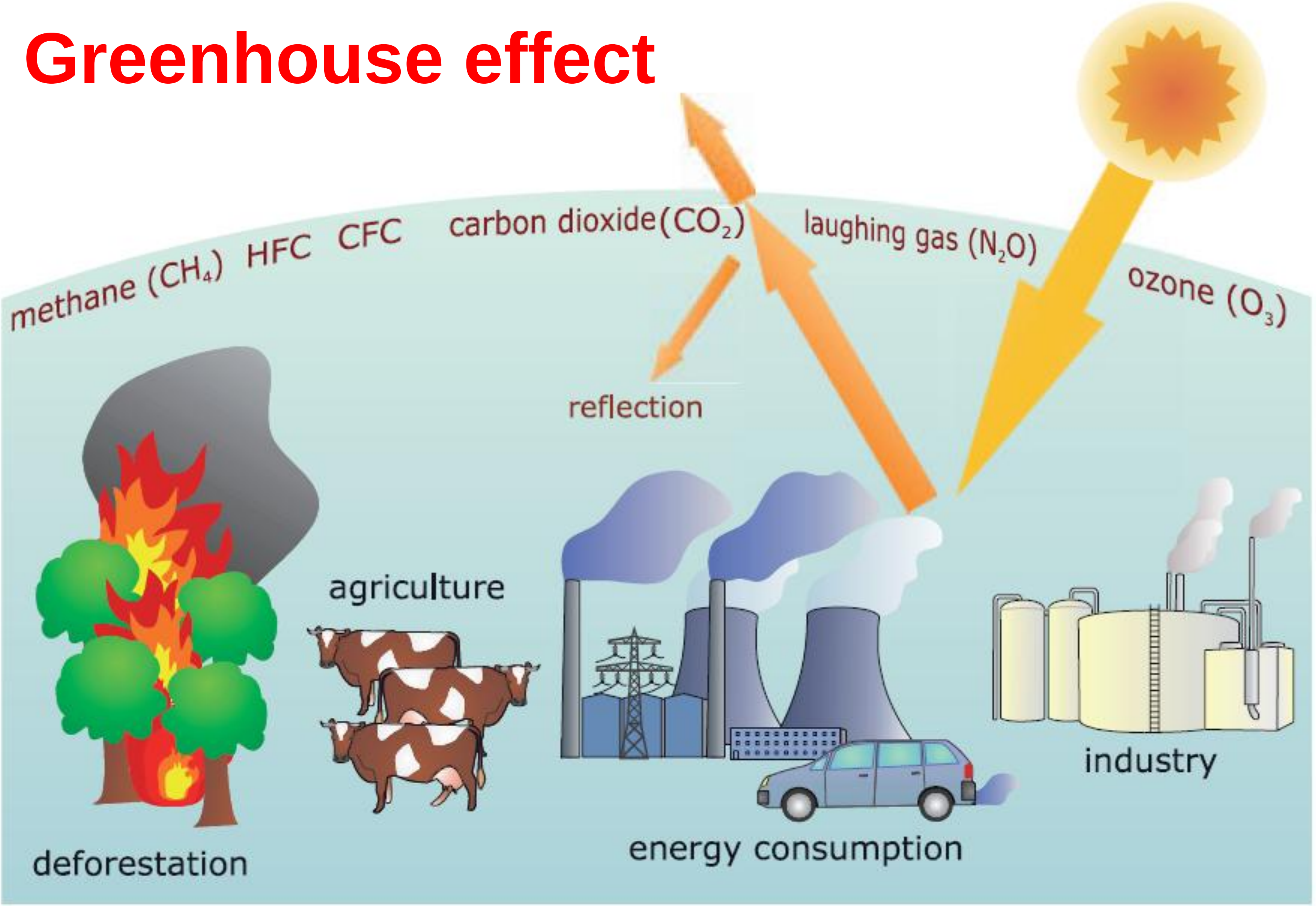


Figure Causes of anthropogenic greenhouse effects due to human activities.

- **A 1995 report**: The earth has already warmed about **0.5° C** during the last century, and they estimate that the earth's temperature will rise another **2° C** by the year 2100.
- A rise of this magnitude can cause **severe changes in weather patterns** with storms and heavy rains and flooding at some parts and drought in others, major floods due to the melting of ice at the poles, loss of wetlands and coastal areas due to rising sea levels, and other negative results.
- **Improved energy efficiency, energy conservation, and using renewable energy sources** help minimize global warming.

The average car produces several times its weight in CO_2 every year (it is driven 20,000 km a year, consumes 2300 liters of gasoline, and produces 2.5 kg of CO_2 per liter).

Renewable energies such as wind are called "green energy" since they emit no pollutants or greenhouse gases.

EXAMPLE 2–18 Reducing Air Pollution by Geothermal Heating

A geothermal power plant in Nevada is generating electricity using geothermal water extracted at 180°C, and reinjected back to the ground at 85°C. It is proposed to utilize the reinjected brine for heating the residential and commercial buildings in the area, and calculations show that the geothermal heating system can save 18 million therms of natural gas a year. Determine the amount of NO_x and CO_2 emissions the geothermal system will save a year. Take the average NO_x and CO_2 emissions of gas furnaces to be 0.0047 kg/therm and 6.4 kg/therm, respectively.

Solution The gas heating systems in an area are being replaced by a geothermal district heating system. The amounts of NO_x and CO_2 emissions saved per year are to be determined.

Analysis The amounts of emissions saved per year are equivalent to the amounts emitted by furnaces when 18 million therms of natural gas are burned,

$$NO_x \text{ savings} = (NO_x \text{ emission per therm})(\text{No. of therms per year})$$
$$= (0.0047 \text{ kg/therm})(18 \times 10^6 \text{ therm/year})$$
$$= \mathbf{8.5 \times 10^4 \text{ kg/year}}$$

$$CO_2 \text{ savings} = (CO_2 \text{ emission per therm})(\text{No. of therms per year})$$
$$= (6.4 \text{ kg/therm})(18 \times 10^6 \text{ therm/year})$$
$$= \mathbf{1.2 \times 10^8 \text{ kg/year}}$$

EXAMPLE 2–19 Heat Transfer from a Person

Consider a person standing in a breezy room at 20°C. Determine the total rate of heat transfer from this person if the exposed surface area and the average outer surface temperature of the person are 1.6 m^2 and 29°C, respectively, and the convection heat transfer coefficient is 6 $W/m^2 \cdot °C$ (Fig. 2–75).

Solution A person is standing in a breezy room. The total rate of heat loss from the person is to be determined.

Assumptions **1** The emissivity and heat transfer coefficient are constant and uniform. **2** Heat conduction through the feet is negligible. **3** Heat loss by evaporation is disregarded.

Analysis The heat transfer between the person and the air in the room will be by convection (instead of conduction) since it is conceivable that the air in the vicinity of the skin or clothing will warm up and rise as a result of heat transfer from the body, initiating natural convection currents. It appears that the experimentally determined value for the rate of convection heat transfer in this case is 6 W per unit surface area (m^2) per unit temperature difference (in K or °C) between the person and the air away from the person. Thus, the rate of convection heat transfer from the person to the air in the room is, from Eq. 2–53,

$$\dot{Q}_{conv} = hA(T_s - T_f)$$
$$= (6\ W/m^2 \cdot °C)(1.6\ m^2)(29 - 20)\ °C$$
$$= 86.4\ W$$

The person will also lose heat by radiation to the surrounding wall surfaces. We take the temperature of the surfaces of the walls, ceiling, and the floor to be equal to the air temperature in this case for simplicity, but we recognize that this does not need to be the case. These surfaces may be at a higher or lower temperature than the average temperature of the room air, depending on the outdoor conditions and the structure of the walls. Considering that air does not intervene with radiation and the person is completely enclosed by the surrounding surfaces, the net rate of radiation heat transfer from the person to the surrounding walls, ceiling, and the floor is, from Eq. 2–57,

$$\dot{Q}_{rad} = \varepsilon\sigma A(T_s^4 - T_{surr}^4)$$
$$= (0.95)(5.67 \times 10^{-8}\ W/m^2 \cdot K^4)(1.6\ m^2) \times [(29 + 273)^4 - (20 + 273)^4]K^4$$
$$= 81.7\ W$$

Note that we must use *absolute* temperatures in radiation calculations. Also note that we used the emissivity value for the skin and clothing at room temperature since the emissivity is not expected to change significantly at a slightly higher temperature.

Then the rate of total heat transfer from the body is determined by adding these two quantities to be

$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad} = 86.4 + 81.7 = \mathbf{168.1\ W}$$

The heat transfer would be much higher if the person were not dressed since the exposed surface temperature would be higher. Thus, an important function of the clothes is to serve as a barrier against heat transfer.

Summary

- Forms of energy
  - ✓ Macroscopic = kinetic + potential
  - ✓ Microscopic = Internal energy (sensible + latent + chemical + nuclear)
- Energy transfer by heat
- Energy transfer by work
- Mechanical forms of work
- The first law of thermodynamics
  - ✓ Energy balance
  - ✓ Energy change of a system
  - ✓ Mechanisms of energy transfer (heat, work, mass flow)
- Energy conversion efficiencies
  - ✓ Efficiencies of mechanical and electrical devices (turbines, pumps)
- Energy and environment
  - ✓ Ozone and smog
  - ✓ Acid rain
  - ✓ The Greenhouse effect: Global warming

TUGAS

- Kerjakan Soal di Bab 2 minimal 2 nomer setiap sub bab
- Hitung kesetimbangan energi di salah satu bagian rumah. Kirim ke OCW
- Bikin makalah tentang pengaruh mobil elektrik terhadap lingkungan dan ekonomi negara. Setuju atau tidak. Kirim ke OCW