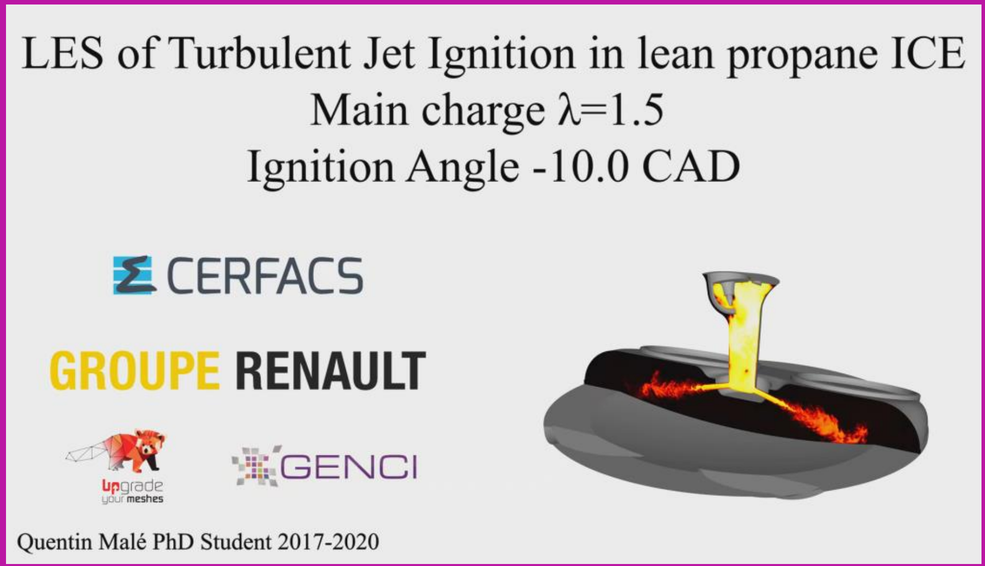
Thermodynamics

An Engineering Approach

Lecture 2: Energy and the First Law of Thermodynamics

Qiang Cheng (Jonny)

Aalto University
School of Engineering



Learning Outcomes

When you complete your study of this chapter, you will be able to…

- **explain key concepts related to energy and the first law of thermodynamics . . . including internal, kinetic, and potential energy, work and power, heat transfer and heat transfer modes, heat transfer rate, power cycle, refrigeration cycle, and heat pump cycle.**

- **analyze closed systems including applying energy balances, appropriately modeling the case at hand, and correctly observing sign conventions for work and heat transfer.**

- **conduct energy analyses of systems undergoing thermodynamic cycles, evaluating as appropriate thermal efficiencies of power cycles and coefficients of performance of refrigeration and heat pump cycles.**

Reviewing Mechanical Concepts of Energy

Work and Kinetic Energy

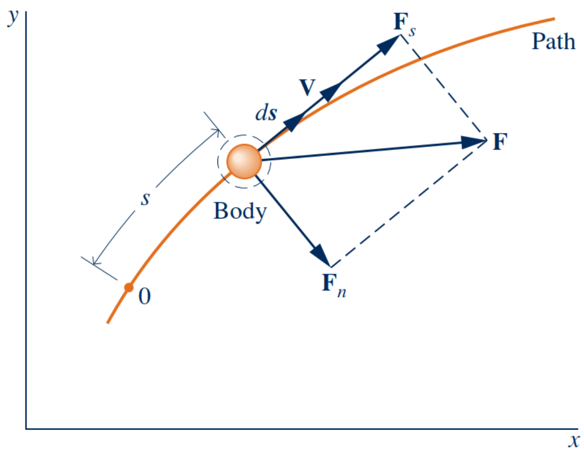


Fig. 2.1 Forces acting on a moving system.

By Newton's second law of motion, the magnitude of the component $\mathbf{F}_s$ is related to the change in the magnitude of $\mathbf{V}$ by

$$F_s = m\frac{dV}{dt} \tag{2.1}$$

Using the chain rule, this can be written as

$$F_s = m\frac{dV}{ds}\frac{ds}{dt} = mV\frac{dV}{ds} \tag{2.2}$$

where $V = ds/dt$. Rearranging Eq. 2.2 and integrating from s_1 to s_2 gives

$$\int_{V_1}^{V_2} mV\,dV = \int_{s_1}^{s_2} F_s\,ds \tag{2.3}$$

Reviewing Mechanical Concepts of Energy

Work and Kinetic Energy

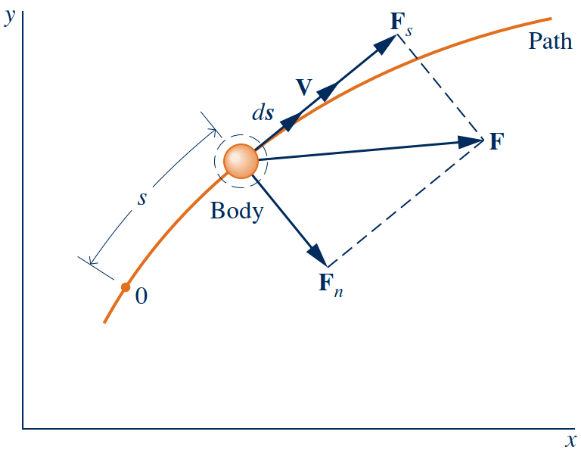


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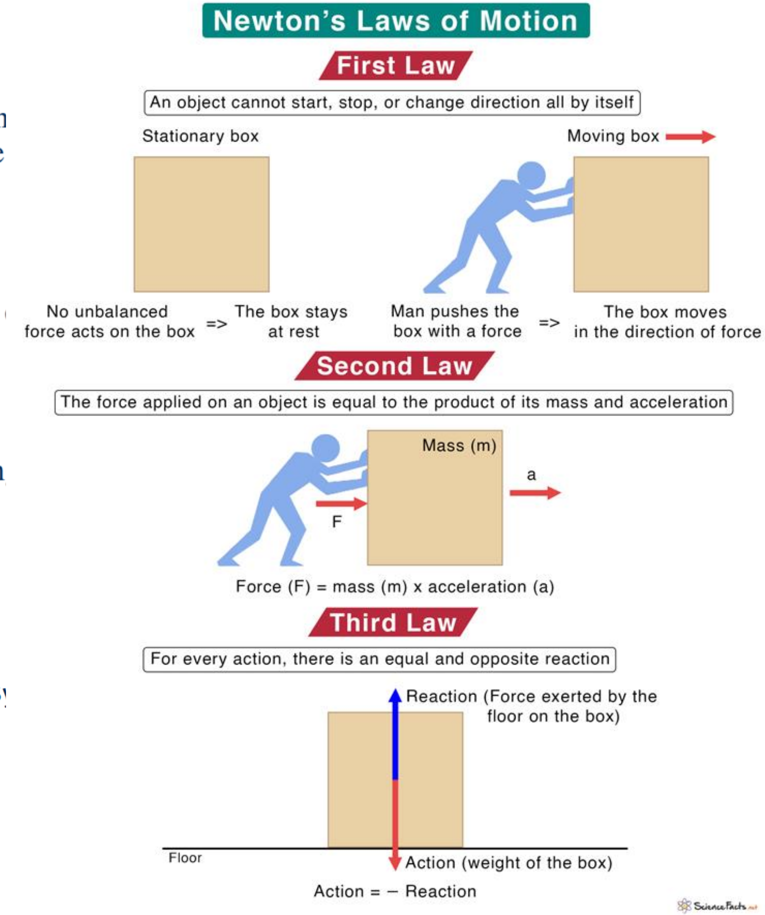
Fig. 2.1 Forces acting on a moving sy



Reviewing Mechanical Concepts of Energy

The integral on the left of Eq. 2.3 is evaluated as follows

$$\int_{V_1}^{V_2} mV\,dV = \frac{1}{2}mV^2\Big]_{V_1}^{V_2} = \frac{1}{2}m(V_2^2 - V_1^2) \tag{2.4}$$

The quantity $\frac{1}{2}mV^2$ is the **kinetic energy**, KE, of the body. Kinetic energy is a scalar quantity. The *change* in kinetic energy, ΔKE, of the body is

kinetic energy

$$\Delta KE = KE_2 - KE_1 = \frac{1}{2}m(V_2^2 - V_1^2) \tag{2.5}$$

TAKE NOTE...

The symbol Δ always means "final value minus initial value."

The integral on the right of Eq. 2.3 is the *work* of the force F_s as the body moves from s_1 to s_2 along the path. Work is also a scalar quantity.

With Eq. 2.4, Eq. 2.3 becomes

$$\frac{1}{2}m(V_2^2 - V_1^2) = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s} \tag{2.6}$$

Potential Energy

gravitational potential energy

The quantity mgz is the gravitational potential energy, PE. The change in gravitational potential energy, ΔPE, is

$$\Delta \mathrm{PE} = \mathrm{PE}_2 - \mathrm{PE}_1 = mg(z_2 - z_1)$$

The work of each force acting on the body shown in Fig. 2.2 can be determined by using the definition previously given. The total work is the algebraic sum of these individual values. In accordance with Eq. 2.6, the total work equals the change in kinetic energy. That is,

$$\frac{1}{2}m(\mathrm{V}_2^2 - \mathrm{V}_1^2) = \int_{z_1}^{z_2} R\,dz - \int_{z_1}^{z_2} mg\,dz \quad \textbf{(2.7)}$$

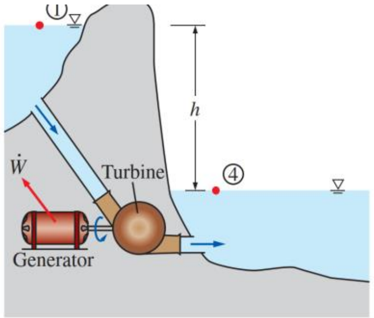
A minus sign is introduced before the second term on the right because the gravitational force is directed downward and z is taken as positive upward.

The first integral on the right of Eq. 2.7 represents the work done by the force **R** on the body as it moves vertically from z_1 to z_2. The second integral can be evaluated as follows:

$$\int_{z_1}^{z_2} mg\,dz = mg(z_2 - z_1) \quad \textbf{(2.8)}$$

where the acceleration of gravity has been assumed to be constant with elevation. By incorporating Eq. 2.8 into Eq. 2.7 and rearranging

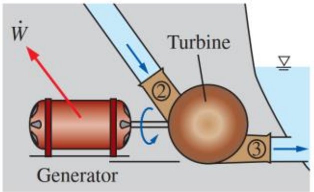
$$\frac{1}{2}m(\mathrm{V}_2^2 - \mathrm{V}_1^2) + mg(z_2 - z_1) = \int_{z_1}^{z_2} R\,dz \quad \textbf{(2.9)}$$



$$\dot{W}_{\max} = \dot{m}\,\Delta e_{\text{mech}} = \dot{m}g\,(z_1 - z_4) = \dot{m}gh$$

since $P_1 \approx P_4 = P_{\text{atm}}$ and $V_1 = V_4 \approx 0$

(*a*)



$$\dot{W}_{\max} = \dot{m}\,\Delta e_{\text{mech}} = \dot{m}\frac{P_2 - P_3}{\rho} = \dot{m}\frac{\Delta P}{\rho}$$

since $V_1 \approx V_3$ and $z_2 = z_3$

(*b*)

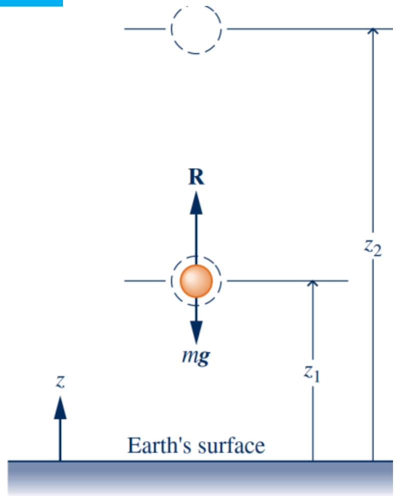


Fig. 2.2 Illustration used to introduce the potential energy concept.

TAKE NOTE...

Throughout this book it is assumed that the acceleration of gravity, g, can be assumed constant.

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Broadening Our Understanding of Work

The work W done by, or on, a system evaluated in terms of macroscopically observable forces and displacements is

$$W = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s}$$

thermodynamic definition of work

A particular interaction is categorized as a work interaction if it satisfies the following criterion, which can be considered the thermodynamic definition of work: Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight.

Sign Convention and Notation

$W > 0$: work done *by* the system

$W < 0$: work done *on* the system

Power

The rate of energy transfer by work is called power and is denoted by $\dot{W}$.

When a work interaction involves a macroscopically observable force, the rate of energy transfer by work is equal to the product of the force and the velocity at the point of application of the force

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$$\dot{W} = \mathbf{F} \cdot \mathbf{V}$$

$$W = \int_{t_1}^{t_2} \dot{W}\, dt = \int_{t_1}^{t_2} \mathbf{F} \cdot \mathbf{V}\, dt$$

Broadening Our Understanding of Work

▸ FOR EXAMPLE to illustrate the use of Eq. 2.13, let us evaluate the power required for a bicyclist traveling at 20 miles per hour to overcome the drag force imposed by the surrounding air. This *aerodynamic drag* force is given by

$$F_d = \tfrac{1}{2} C_d A \rho V^2$$

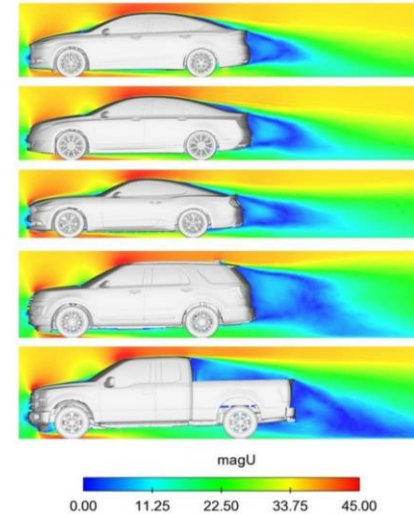
where C_d is a constant called the *drag coefficient,* A is the frontal area of the bicycle and rider, and ρ is the air density. By Eq. 2.13 the required power is $\mathbf{F}_d \cdot \mathbf{V}$ or

$$\begin{aligned}\dot{W} &= (\tfrac{1}{2} C_d A \rho V^2) V \\ &= \tfrac{1}{2} C_d A \rho V^3\end{aligned}$$

Using typical values: $C_d = 0.88$, $A = 3.9\ \text{ft}^2$, and $\rho = 0.075\ \text{lb/ft}^3$, together with $V = 20\ \text{mi/h} = 29.33\ \text{ft/s}$, and also converting units to horsepower, the power required is

$$\begin{aligned}\dot{W} &= \frac{1}{2}(0.88)(3.9\ \text{ft}^2)\left(0.075 \frac{\text{lb}}{\text{ft}^3}\right)\left(29.33 \frac{\text{ft}}{\text{s}}\right)^3 \left|\frac{1\ \text{lbf}}{32.2\ \text{lb} \cdot \text{ft/s}^2}\right| \left|\frac{1\ \text{hp}}{550\ \text{ft} \cdot \text{lbf/s}}\right| \\ &= 0.183\ \text{hp}\end{aligned}$$

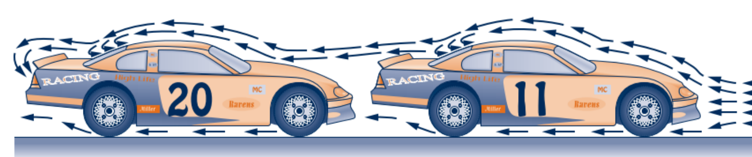
Drag can be reduced by *streamlining* the shape of a moving object and using the strategy known as *drafting* (see box).



Drafting

Drafting occurs when two or more moving vehicles or individuals align closely to reduce the overall effect of drag. Drafting is seen in competitive events such as auto racing, bicycle racing, speed-skating, and running.

Studies show that air flow over a single vehicle or individual in motion is characterized by a high-pressure region in front and a low-pressure region behind. The difference between these pressures creates a force, called drag, impeding motion. During drafting, as seen in the sketch below, a second vehicle or individual is closely aligned with another, and air flows over the pair nearly as if they were a single entity, thereby altering the pressure between them and reducing the drag each experiences. While race-car drivers use drafting to increase speed, non–motor sport competitors usually aim to reduce demands on their bodies while maintaining the same speed.



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Modeling Expansion or Compression Work

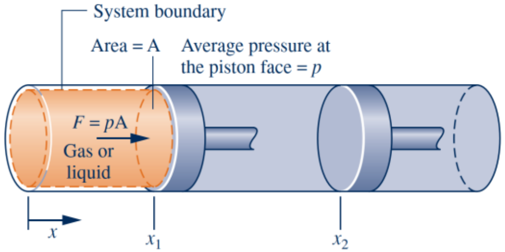
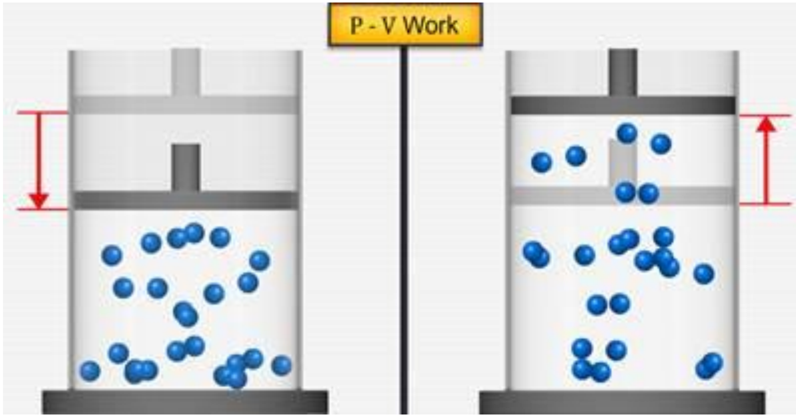


Fig. 2.4 Expansion or compression of a gas or liquid.



$$\delta W = p\mathrm{A}\,dx \tag{2.15}$$

The product A dx in Eq. 2.15 equals the change in volume of the system, dV. Thus, the work expression can be written as

$$\delta W = p\,dV \tag{2.16}$$

Since dV is positive when volume increases, the work at the moving boundary is positive when the gas expands. For a compression, dV is negative, and so is work found from Eq. 2.16. These signs are in agreement with the previously stated sign convention for work.

For a change in volume from V_1 to V_2, the work is obtained by integrating Eq. 2.16

$$W = \int_{V_1}^{V_2} p\,dV \tag{2.17}$$

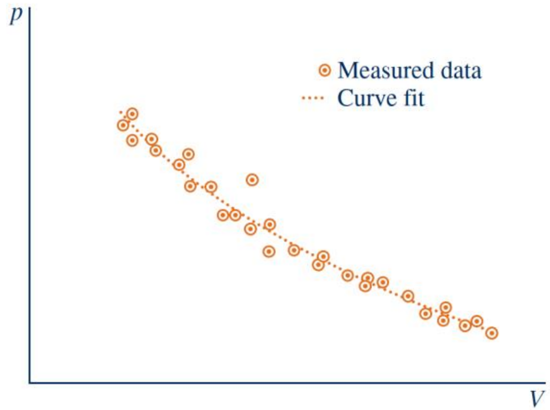


Fig. 2.5 Pressure at the piston face versus cylinder volume.

Expansion or Compression Work in Quasiequilibrium Processes

quasiequilibrium process

Processes are sometime modeled as an idealized type of process called a quasiequilibrium (or quasistatic) process. A quasiequilibrium process is one in which the departure from thermodynamic equilibrium is at most infinitesimal.

polytropic process

A quasiequilibrium process described by $PV^n = constant$, where n is a constant, is called a polytropic process.

Using the Quasiequilibrium Process Concept

Our interest in the quasiequilibrium process concept stems mainly from two considerations:

- Simple thermodynamic models giving at least *qualitative* information about the behavior of actual systems of interest often can be developed using the quasiequilibrium process concept. This is akin to the use of idealizations such as the point mass or the frictionless pulley in mechanics for the purpose of simplifying an analysis.
- The quasiequilibrium process concept is instrumental in deducing relationships that exist among the properties of systems at equilibrium (Chaps. 3, 6, and 11).

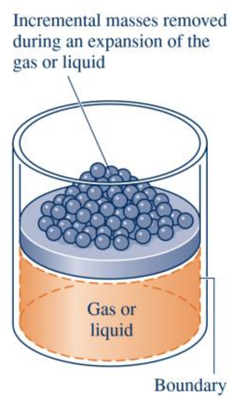


Fig. 2.6 Illustration of a quasiequilibrium expansion or compression.

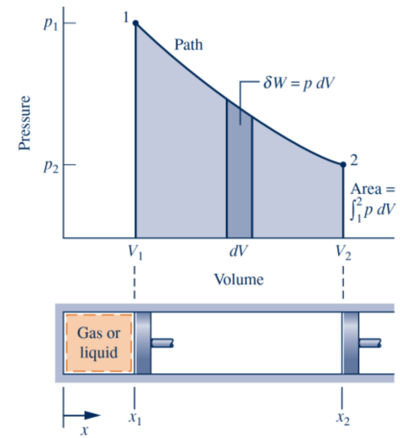


Fig. 2.7 Work of a quasiequilibrium expansion or compression process.

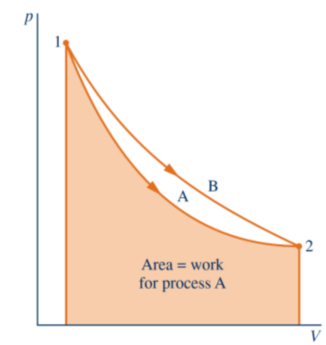


Fig. 2.8 Illustration that work depends on the process.

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Expansion or Compression Work in Quasiequilibrium Processes

quasiequilibrium process

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Polytropic Index

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Polytropic processes are usually categorized either by what variable remains constant in the process, or by the shape of its corresponding graph (e.g. linear)

When n is less than 0: Negative n values represent a large amount of heat added to the system is much greater than the work done by the system

Constant	n	Equation	Associated with
Temperature (Isothermic)	1 (unless saturated)	$PV^1 = C$	Non-insulated systems
Pressure (Isobaric)	0 (unless saturated)	$PV^0 = C$	Pistons/Cylinders
Volume (Isochoric)	∞	$PV^\infty = C$	Rigid containers
Linear	-1	$PV^{-1} = C$	Work and Heat flow in/out
Entropy (Isentropic)	γ	$PV^\gamma = C$	Expansion Valves

For isentropic processes, $n = \gamma = C_p/C_v$, where C_p is the heat capacity of an ideal gas at constant pressure, and C_v is the heat capacity of an ideal gas at constant volume.

EXAMPLE 2.1

Evaluating Expansion Work

A gas in a piston–cylinder assembly undergoes an expansion process for which the relationship between pressure and volume is given by

$$pV^n = constant$$

The initial pressure is 3 bar, the initial volume is 0.1 m^3, and the final volume is 0.2 m^3. Determine the work for the process, in kJ, if **(a)** $n = 1.5$, **(b)** $n = 1.0$, and **(c)** $n = 0$.

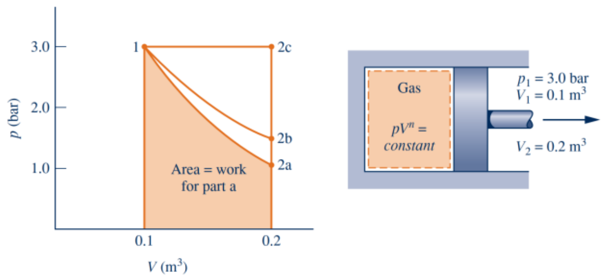
SOLUTION

Known: A gas in a piston–cylinder assembly undergoes an expansion for which $pV^n = constant$.

Find: Evaluate the work if (a) $n = 1.5$, (b) $n = 1.0$, (c) $n = 0$.

Schematic and Given Data: The given p–V relationship and the given data for pressure and volume can be used to construct the accompanying pressure–volume diagram of the process.

1



Engineering Model:

1. The gas is a closed system.
2. The moving boundary is the only work mode.
3. The expansion is a polytropic process. 2

Fig. E2.1

Analysis: The required values for the work are obtained by integration of Eq. 2.17 using the given pressure–volume relation.

(a) Introducing the relationship $p = constant/V^n$ into Eq. 2.17 and performing the integration

$$W = \int_{V_1}^{V_2} p\, dV = \int_{V_1}^{V_2} \frac{constant}{V^n} dV$$

$$= \frac{(constant)V_2^{1-n} - (constant)V_1^{1-n}}{1-n}$$

The constant in this expression can be evaluated at either end state: $constant = p_1V_1^n = p_2V_2^n$. The work expression then becomes

$$W = \frac{(p_2V_2^n)V_2^{1-n} - (p_1V_1^n)V_1^{1-n}}{1-n} = \frac{p_2V_2 - p_1V_1}{1-n} \tag{a}$$

This expression is valid for all values of n except $n = 1.0$. The case $n = 1.0$ is taken up in part (b).

To evaluate W, the pressure at state 2 is required. This can be found by using $p_1V_1^n = p_2V_2^n$, which on rearrangement yields

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^n = (3\text{ bar})\left(\frac{0.1}{0.2}\right)^{1.5} = 1.06\text{ bar}$$

Accordingly,

3

$$W = \left(\frac{(1.06\text{ bar})(0.2\text{ m}^3) - (3)(0.1)}{1 - 1.5}\right)\left|\frac{10^5\text{ N/m}^2}{1\text{ bar}}\right|\left|\frac{1\text{ kJ}}{10^3\text{ N}\cdot\text{m}}\right|$$
$$= +17.6\text{ kJ}$$

(b) For $n = 1.0$, the pressure–volume relationship is $pV = constant$ or $p = constant/V$. The work is

$$W = constant\int_{V_1}^{V_2}\frac{dV}{V} = (constant)\ln\frac{V_2}{V_1} = (p_1V_1)\ln\frac{V_2}{V_1} \tag{b}$$

Substituting values

$$W = (3\text{ bar})(0.1\text{ m}^3)\left|\frac{10^5\text{ N/m}^2}{1\text{ bar}}\right|\left|\frac{1\text{ kJ}}{10^3\text{ N}\cdot\text{m}}\right|\ln\left(\frac{0.2}{0.1}\right) = +20.79\text{ kJ}$$

(c) For $n = 0$, the pressure–volume relation reduces to $p = constant$, and the integral becomes $W = p(V_2 - V_1)$, which is a special case of the expression found in part (a). Substituting values and converting units as above, $W = +30$ kJ.

1 In each case, the work for the process can be interpreted as the area under the curve representing the process on the accompanying p–V diagram. Note that the relative areas are in agreement with the numerical results.

2 The assumption of a polytropic process is significant. If the given pressure–volume relationship were obtained as a fit to experimental pressure–volume data, the value of $\int p\, dV$ would provide a plausible estimate of the work only when the measured pressure is essentially equal to that exerted at the piston face.

3 Observe the use of unit conversion factors here and in part (b).

4 In each of the cases considered, it is not necessary to identify the gas (or liquid) contained within the piston–cylinder assembly. The calculated values for W are determined by the process path and the end states. However, if it is desired to evaluate a property such as temperature, both the nature and amount of the substance must be provided because appropriate relations among the properties of the particular substance would then be required.

Skills Developed

Ability to...

- ❑ apply the problem-solving methodology.
- ❑ define a closed system and identify interactions on its boundary.
- ❑ evaluate work using Eq. 2.17.
- ❑ apply the pressure–volume relation $pV^n = constant$.

Quick Quiz Evaluate the work, in kJ, for a two-step process consisting of an expansion with $n = 1.0$ from $p_1 = 3$ bar, $V_1 = 0.1$ m^3 to $V = 0.15$ m^3, followed by an expansion with $n = 0$ from $V = 0.15$ m^3 to $V_2 = 0.2$ m^3. **Ans.** 22.16 kJ.

Further Examples of Work

Extension of a Solid Bar

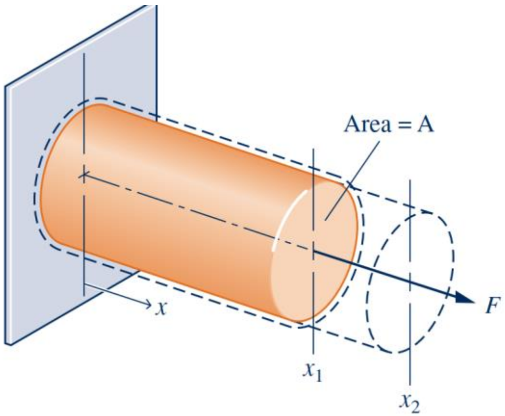
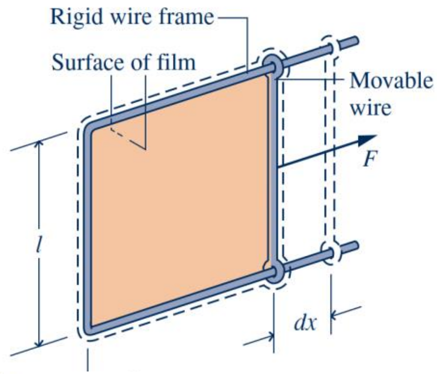


Fig. 2.9 Elongation of a solid bar.

Stretching of a Liquid Film



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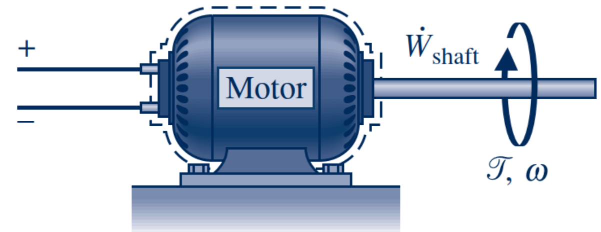
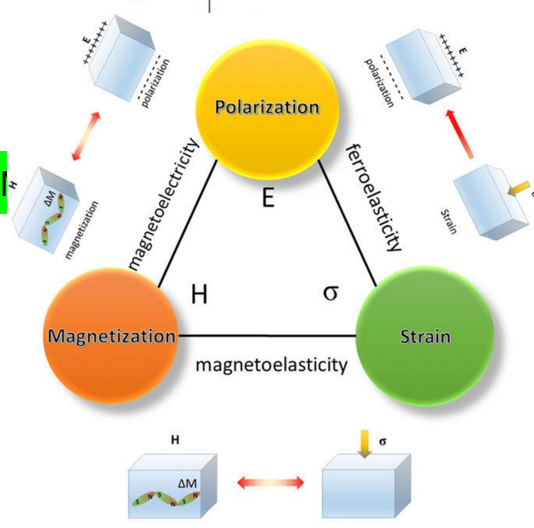
Power Transmitted by a Shaft



Work Due to Polarization or



Electric Power

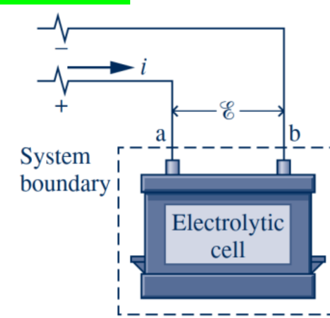


Fig. 2.11 Electrolytic cell used to discuss electric power.

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Broadening Our Understanding of Energy

In engineering thermodynamics, the change in the total energy of a system is considered to be made up of three macroscopic contributions.

- One is the change in kinetic energy, associated with the motion of the system as a whole relative to an external coordinate frame.
- Another is the change in gravitational potential energy, associated with the position of the system as a whole in Earth's gravitational field.
- All other energy changes are lumped together in the internal energy of the system.
- Like kinetic energy and gravitational potential energy, internal energy is an extensive property of the system, as is the total energy.

The change in the total energy of a system is

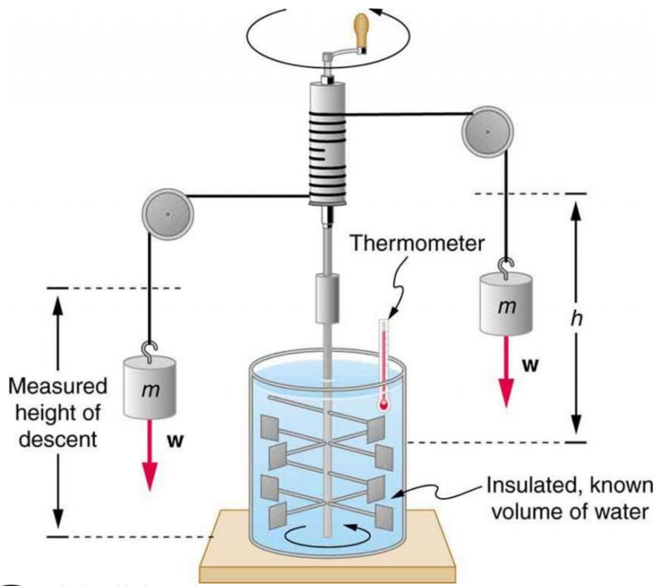
$$E_2 - E_1 = (U_2 - U_1) + (\mathrm{KE}_2 - \mathrm{KE}_1) + (\mathrm{PE}_2 - \mathrm{PE}_1) \quad (2.27a)$$

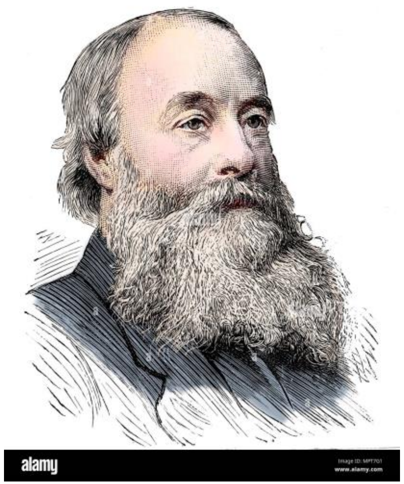
or

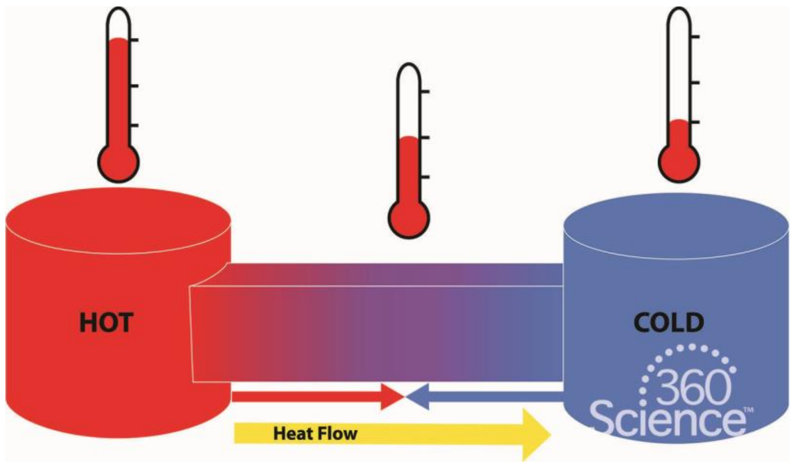
$$\Delta E = \Delta U + \Delta \mathrm{KE} + \Delta \mathrm{PE} \quad (2.27b)$$

Energy Transfer by Heat

On the basis of experiment, beginning with the work of Joule in the early part of the 19th century, we know that energy transfers by heat are induced only as a result of a temperature difference between the system and its surroundings and occur only in the direction of decreasing temperature.







Sign Convention, Notation, and Heat Transfer Rate

sign convention for heat transfer

The symbol Q denotes an amount of energy transferred across the boundary of a system in a heat interaction with the system's surroundings. Heat transfer into a system is taken to be *positive*, and heat transfer from a system is taken as *negative*.

$Q > 0$: heat transfer *to* the system

$Q < 0$: heat transfer *from* the system

heat is not a property

The value of a heat transfer depends on the details of a process and not just the end states. Thus, like work, heat is not a property, and its differential is written as σQ. The amount of energy transfer by heat for a process is given by the integral

$$Q = \int_1^2 \delta Q$$

rate of heat transfer

the amount of energy transfer by heat during a period of time can be found by integrating from time t_1 to time t_2. *In some cases, it is convenient to use the heat flux, q, which is the heat transfer rate per unit of system surface area.*

$$Q = \int_{t_1}^{t_2} \dot{Q}\, dt \qquad \dot{Q} = \int_A \dot{q}\, dA$$

Heat Transfer Modes

Methods based on experiment are available for evaluating energy transfer by heat. These methods recognize two basic transfer mechanisms: ***conduction and thermal radiation***.

Conduction

Energy transfer by conduction can take place in solids, liquids, and gases. Conduction can be thought of as the transfer of energy from the more energetic particles of a substance to adjacent particles that are less energetic due to interactions between particles.

Fourier's law

The time rate of energy transfer by conduction is quantified macroscopically by Fourier's law.

$$\dot{Q}_x = -\kappa A \frac{dT}{dx}$$

where the proportionality constant k is a property called the thermal conductivity. The minus sign is a consequence of energy transfer in the direction of decreasing temperature.

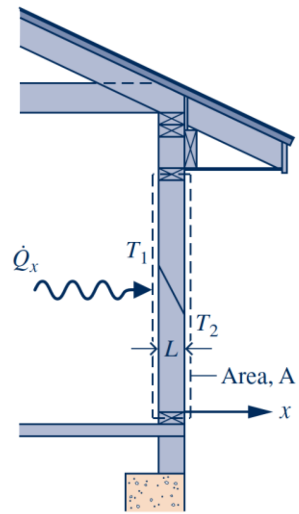


Fig. 2.12 Illustration of Fourier's conduction law.

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Heat Transfer Modes

Radiation

Thermal radiation is emitted by matter as a result of changes in the electronic configurations of the atoms or molecules within it. The energy is transported by electromagnetic waves (or photons). Unlike conduction, thermal radiation requires no intervening medium to propagate and can even take place in a vacuum. Solid surfaces, gases, and liquids all emit, absorb, and transmit thermal radiation to varying degrees.

Stefan–Boltzmann law

The rate at which energy is emitted, $\dot{Q}_e$, from a surface of area A is quantified macroscopically by a modified form of the Stefan–Boltzmann law

$$\dot{Q}_\mathrm{e} = \varepsilon\sigma \mathrm{A} T_\mathrm{b}^4$$

which shows that thermal radiation is associated with the fourth power of the absolute temperature of the surface, T_b. The emissivity, ε, is a property of the surface that indicates how effectively the surface radiates 10 e 1.02 , and is the Stefan–Boltzmann constant:

$$\sigma = 5.67 \times 10^{-8} \mathrm{W/m^2 \cdot K^4} = 0.1714 \times 10^{-8} \mathrm{Btu/h \cdot ft^2 \cdot {}^\circ R^4}$$

net rate of radiant exchange

The net rate of radiant exchange between the smaller surface, whose area is A and emissivity is $\dot{Q}_e$, and the larger surroundings is

$$\dot{Q}_\mathrm{e} = \varepsilon\sigma \mathrm{A}[T_\mathrm{b}^4 - T_\mathrm{s}^4]$$

Heat Transfer Modes

Convection

Energy transfer between a solid surface at a temperature Tb and an adjacent gas or liquid at another temperature T_f plays a prominent role in the performance of many devices of practical interest. This is commonly referred to as convection.

Newton's law of cooling

In this case, energy is transferred in the direction indicated by the arrow due to the combined effects of conduction within the air and the bulk motion of the air.

$$\dot{Q}_c = hA(T_b - T_f)$$

Where, a is the surface area and the proportionality factor h is called the heat transfer coefficient. The heat transfer coefficient is not a thermodynamic property. It is an empirical parameter that incorporates into the heat transfer relationship the nature of the flow pattern near the surface, the fluid properties, and the geometry.

TABLE 2.1

Typical Values of the Convection Heat Transfer Coefficient

Applications	h (W/m^2 · K)	h (Btu/h · ft^2 · °R)
Free convection		
Gases	2–25	0.35–4.4
Liquids	50–1000	8.8–180
Forced convection		
Gases	25–250	4.4–44
Liquids	50–20,000	8.8–3500

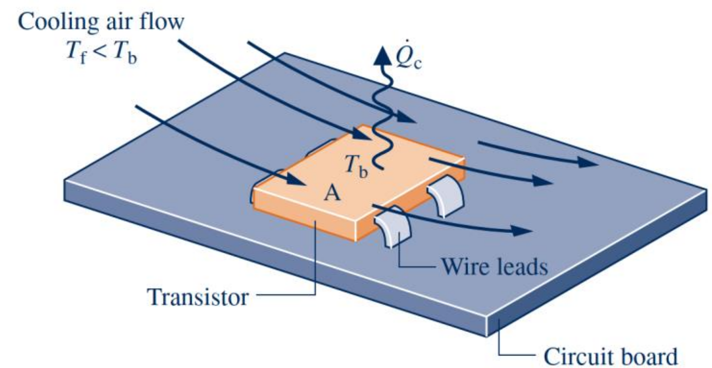


Fig. 2.14 Illustration of Newton's law of cooling.

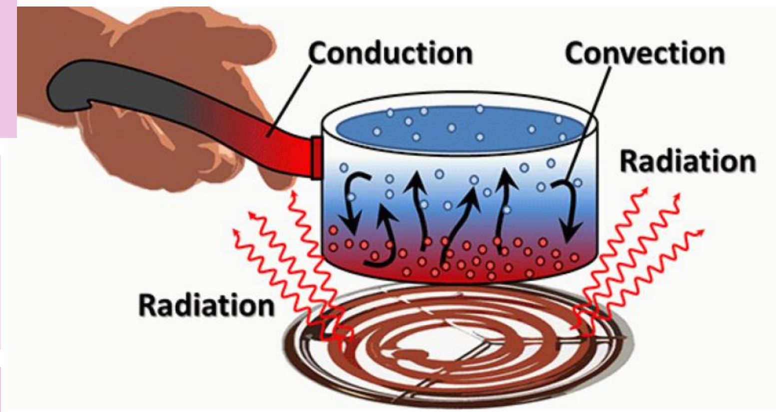
Summary of the Heat Transfer Mechanism

- Heat can be transferred in three different ways: ***conduction, convection, and radiation***.

- Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles, which is known as Fourier's law of heat conduction.

- Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion, which known as Newton's law of cooling.

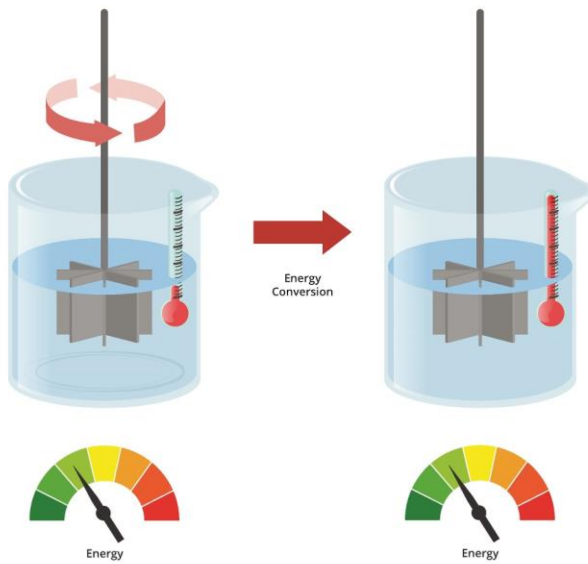
- Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules, which knows as Stefan-Boltzmann law.

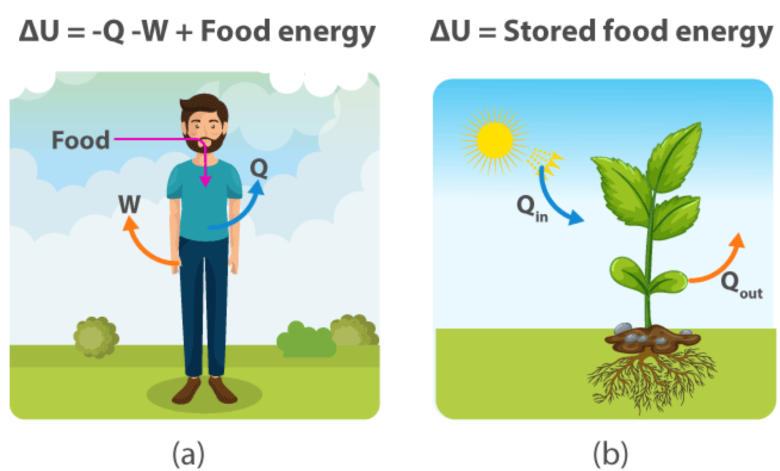


First Law of Thermodynamics

- The first law of thermodynamics, also known as the conservation of energy principle, provides a sound basis for studying the relationships among the various forms of energy and energy interactions.

- Based on experimental observations, the first law of thermodynamics states that energy can be neither created nor destroyed during a process; it can only change forms. Therefore, every bit of energy should be accounted for during a process.





First Law of Thermodynamics

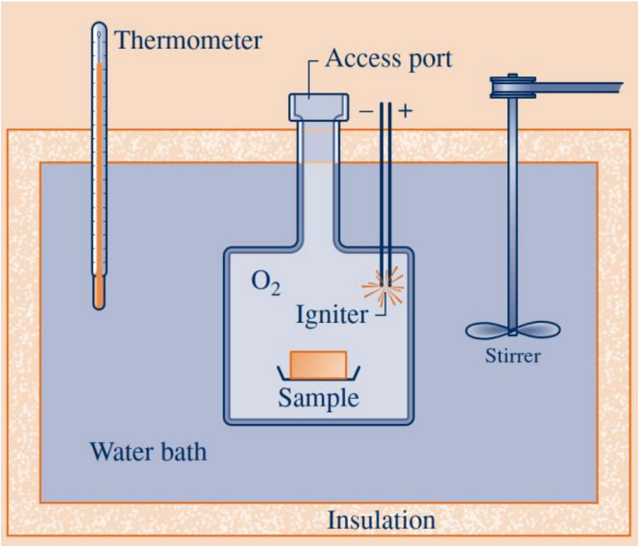
Energy Balance

$$\begin{bmatrix} \textit{change} \text{ in the amount} \\ \text{of energy contained} \\ \text{within a system} \\ \text{during some time} \\ \text{interval} \end{bmatrix} = \begin{bmatrix} \textit{net} \text{ amount of energy} \\ \text{transferred } \textit{in} \text{ across} \\ \text{the system boundary by} \\ \textit{heat} \text{ transfer during} \\ \text{the time interval} \end{bmatrix} - \begin{bmatrix} \textit{net} \text{ amount of energy} \\ \text{transferred } \textit{out} \text{ across} \\ \text{the system boundary} \\ \text{by } \textit{work} \text{ during the} \\ \text{time interval} \end{bmatrix}$$

$$E_2 - E_1 = Q - W$$

$$\Delta KE + \Delta PE + \Delta U = Q - W$$

BIOCONNECTIONS



Constant-volume calorimeter.

First Law of Thermodynamics

energy balance in differential form

$$dE = \delta Q - \delta W$$

time rate form of the energy balance

$$\boxed{\frac{dE}{dt} = \dot{Q} - \dot{W}}$$

$$\begin{bmatrix} \text{time } \textit{rate of change} \\ \text{of the energy} \\ \text{contained within} \\ \text{the system } \textit{at} \\ \textit{time } t \end{bmatrix} = \begin{bmatrix} \text{net } \textit{rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat transfer} \\ \textit{at time } t \end{bmatrix} - \begin{bmatrix} \text{net } \textit{rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work } \textit{at} \\ \textit{time } t \end{bmatrix}$$

Since the time rate of change of energy is given by

$$\frac{dE}{dt} = \frac{d\,\mathrm{KE}}{dt} + \frac{d\,\mathrm{PE}}{dt} + \frac{dU}{dt}$$

or

$$\frac{d\,\mathrm{KE}}{dt} + \frac{d\,\mathrm{PE}}{dt} + \frac{dU}{dt} = \dot{Q} - \dot{W}$$

▸ FOR EXAMPLE consider Fig. 2.16, in which three alternative systems are shown that include a quantity of a gas (or liquid) in a rigid, well-insulated container. In Fig. 2.16*a*, the gas itself is the system. As current flows through the copper plate, there is an energy transfer from the copper plate to the gas. Since this energy transfer occurs as a result of the temperature difference between the plate and the gas, it is classified as a heat transfer. Next, refer to Fig. 2.16*b*, where the boundary is drawn to include the copper plate. It follows from the thermodynamic definition of work that the energy transfer that occurs as current crosses the boundary of this system must be regarded as work. Finally, in Fig. 2.16*c*, the boundary is located so that no energy is transferred across it by heat or work. ◂ ◂ ◂ ◂ ◂

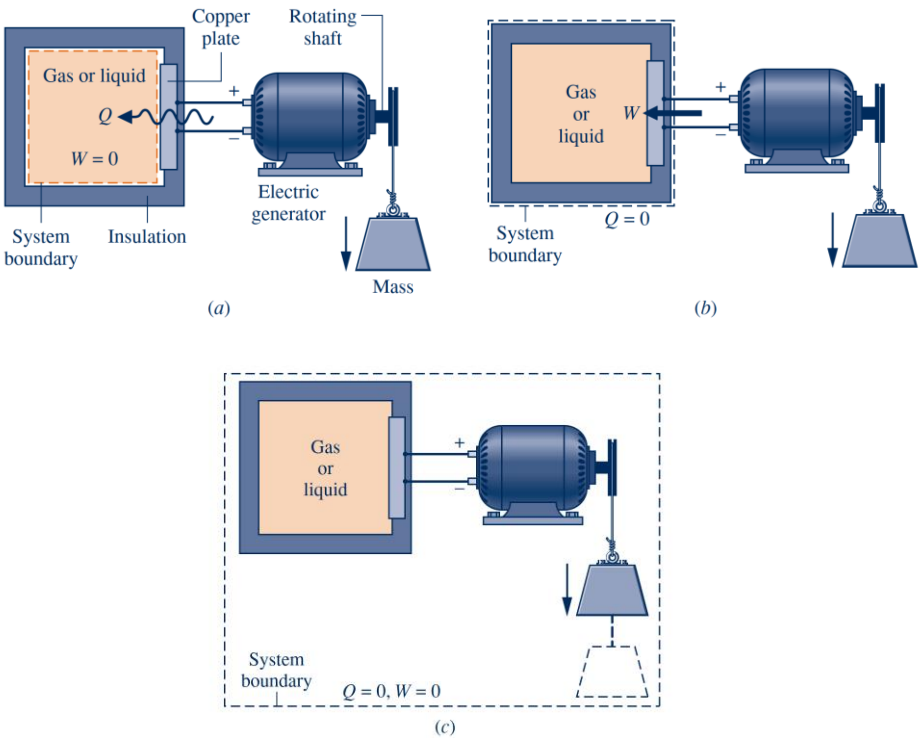


Fig. 2.16 Alternative choices for system boundaries.

Closing Comments

Thus far, we have been careful to emphasize that the quantities symbolized by W and Q in the foregoing equations account for transfers of *energy* and not transfers of work and heat, respectively. The terms *work* and *heat* denote different *means* whereby energy is transferred and not *what* is transferred. However, to achieve economy of expression in subsequent discussions, W and Q are often referred to simply as work and heat transfer, respectively. This less formal manner of speaking is commonly used in engineering practice.

TAKE NOTE...

The terms *heat* and *work* denote *means* whereby energy is transferred. However, W and Q are often referred to informally as work and heat transfer, respectively.

Using the Energy Balance: Processes of Closed Systems

EXAMPLE 2.2

Cooling a Gas in a Piston–Cylinder

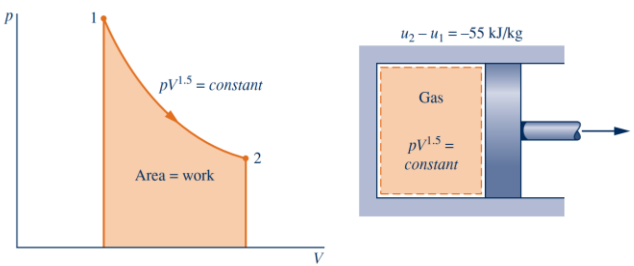
Four-tenths kilogram of a certain gas is contained within a piston–cylinder assembly. The gas undergoes a process for which the pressure–volume relationship is

$$pV^{1.5} = constant$$

The initial pressure is 3 bar, the initial volume is 0.1 m^3, and the final volume is 0.2 m^3. The change in specific internal energy of the gas in the process is $u_2 - u_1 = -55$ kJ/kg. There are no significant changes in kinetic or potential energy. Determine the net heat transfer for the process, in kJ.

Schematic and Given Data:

1



Engineering Model:

1. The gas is a closed system.
2. The process is described by $pV^{1.5} = constant$.
3. There is no change in the kinetic or potential energy of the system.

Fig. E2.2

Analysis: An energy balance for the closed system takes the form

$$\cancel{\Delta KE}^0 + \cancel{\Delta PE}^0 + \Delta U = Q - W$$

where the kinetic and potential energy terms drop out by assumption 3. Then, writing ΔU in terms of specific internal energies, the energy balance becomes

$$m(u_2 - u_1) = Q - W$$

where m is the system mass. Solving for Q

$$Q = m(u_2 - u_1) + W$$

The value of the work for this process is determined in the solution to part (a) of Example 2.1: $W = +17.6$ kJ. The change in internal energy is obtained using given data as

$$m(u_2 - u_1) = 0.4 \text{ kg}\left(-55 \frac{\text{kJ}}{\text{kg}}\right) = -22 \text{ kJ}$$

Substituting values

2 $$Q = -22 + 17.6 = -4.4 \text{ kJ}$$

1 The given relationship between pressure and volume allows the process to be represented by the path shown on the accompanying diagram. The area under the curve represents the work. Since they are not properties, the values of the work and heat transfer depend on the details of the process and cannot be determined from the end states only.

2 The minus sign for the value of Q means that a net amount of energy has been transferred from the system to its surroundings by heat transfer.

Skills Developed

Ability to...

- ❑ define a closed system and identify interactions on its boundary.
- ❑ apply the closed-system energy balance.

Quick Quiz If the gas undergoes a process for which $pV = constant$ and $\Delta u = 0$, determine the heat transfer, in kJ, keeping the initial pressure and given volumes fixed. Ans. 20.79 kJ.

Using the Energy Balance: Processes of Closed Systems

EXAMPLE 2.3

Considering Alternative Systems

Air is contained in a vertical piston–cylinder assembly fitted with an electrical resistor. The atmosphere exerts a pressure of 14.7 lbf/in.^{2} on the top of the piston, which has a mass of 100 lb and a face area of 1 ft^2. Electric current passes through the resistor, and the volume of the air slowly increases by 1.6 ft^3 while its pressure remains constant. The mass of the air is 0.6 lb, and its specific internal energy increases by 18 Btu/lb. The air and piston are at rest initially and finally. The piston–cylinder material is a ceramic composite and thus a good insulator. Friction between the piston and cylinder wall can be ignored, and the local acceleration of gravity is $g = 32.0$ ft/s^2. Determine the heat transfer from the resistor to the air, in Btu, for a system consisting of **(a)** the air alone, **(b)** the air and the piston.

SOLUTION

Known: Data are provided for air contained in a vertical piston–cylinder fitted with an electrical resistor.

Find: Considering each of two alternative systems, determine the heat transfer from the resistor to the air.

Schematic and Given Data:

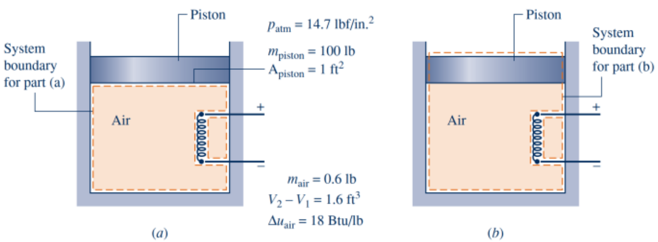


Fig. E2.3

Engineering Model:

1. Two closed systems are under consideration, as shown in the schematic.
2. The only significant heat transfer is from the resistor to the air, during which the air expands slowly and its pressure remains constant.
3. There is no net change in kinetic energy; the change in potential energy of the air is negligible; and since the piston material is a good insulator, the internal energy of the piston is not affected by the heat transfer.
4. Friction between the piston and cylinder wall is negligible.
5. The acceleration of gravity is constant; $g = 32.0$ ft/s^2.

Analysis: (a) Taking the air as the system, the energy balance, Eq. 2.35, reduces with assumption 3 to

$$(\cancel{\Delta KE}^0 + \cancel{\Delta PE}^0 + \Delta U)_{air} = Q - W$$

Or, solving for Q,

$$Q = W + \Delta U_{air}$$

For this system, work is done by the force of the pressure p acting on the *bottom* of the piston as the air expands. With Eq. 2.17 and the assumption of constant pressure

$$W = \int_{V_1}^{V_2} p\, dV = p(V_2 - V_1)$$

To determine the pressure p, we use a force balance on the slowly moving, frictionless piston. The upward force exerted by the air on the *bottom* of the piston equals the weight of the piston plus the downward force of the atmosphere acting on the *top* of the piston. In symbols

$$p\mathrm{A}_{piston} = m_{piston}\, g + p_{atm}\mathrm{A}_{piston}$$

Solving for p and inserting values

$$p = \frac{m_{piston}\, g}{\mathrm{A}_{piston}} + p_{atm}$$
$$= \frac{(100\text{ lb})(32.0\text{ ft/s}^2)}{1\text{ ft}^2}\left|\frac{1\text{ lbf}}{32.2\text{ lb}\cdot\text{ft/s}^2}\right|\left|\frac{1\text{ ft}^2}{144\text{ in.}^2}\right| + 14.7\frac{\text{lbf}}{\text{in.}^2} = 15.4\frac{\text{lbf}}{\text{in.}^2}$$

Thus, the work is

$$W = p(V_2 - V_1)$$
$$= \left(15.4\frac{\text{lbf}}{\text{in.}^2}\right)(1.6\text{ ft}^3)\left|\frac{144\text{ in.}^2}{1\text{ ft}^2}\right|\left|\frac{1\text{ Btu}}{778\text{ ft}\cdot\text{lbf}}\right| = 4.56\text{ Btu}$$

With $\Delta U_{air} = m_{air}(\Delta u_{air})$, the heat transfer is

$$Q = W + m_{air}(\Delta u_{air})$$
$$= 4.56\text{ Btu} + (0.6\text{ lb})\left(18\frac{\text{Btu}}{\text{lb}}\right) = 15.36\text{ Btu}$$

Using the Energy Balance: Processes of Closed Systems

(b) Consider next a system consisting of the air and the piston. The energy change of the overall system is the sum of the energy changes of the air and the piston. Thus, the energy balance, Eq. 2.35, reads

$$(\cancel{\Delta KE}^0 + \cancel{\Delta PE}^0 + \Delta U)_{air} + (\cancel{\Delta KE}^0 + \Delta PE + \cancel{\Delta U}^0)_{piston} = Q - W$$

where the indicated terms drop out by assumption 3. Solving for Q

$$Q = W + (\Delta PE)_{piston} + (\Delta U)_{air}$$

For this system, work is done at the *top* of the piston as it pushes aside the surrounding atmosphere. Applying Eq. 2.17

$$\begin{aligned} W &= \int_{V_1}^{V_2} p\, dV = p_{atm}(V_2 - V_1) \\ &= \left(14.7\,\frac{\text{lbf}}{\text{in.}^2}\right)(1.6\ \text{ft}^3)\left|\frac{144\ \text{in.}^2}{1\ \text{ft}^2}\right|\left|\frac{1\ \text{Btu}}{778\ \text{ft}\cdot\text{lbf}}\right| = 4.35\ \text{Btu} \end{aligned}$$

The elevation change, Δz, required to evaluate the potential energy change of the piston can be found from the volume change of the air and the area of the piston face as

$$\Delta z = \frac{V_2 - V_1}{A_{piston}} = \frac{1.6\ \text{ft}^3}{1\ \text{ft}^2} = 1.6\ \text{ft}$$

Thus, the potential energy change of the piston is

$$\begin{aligned} (\Delta PE)_{piston} &= m_{piston}\, g\Delta z \\ &= (100\ \text{lb})\left(32.0\,\frac{\text{ft}}{\text{s}^2}\right)(1.6\ \text{ft})\left|\frac{1\ \text{lbf}}{32.2\ \text{lb}\cdot\text{ft/s}^2}\right|\left|\frac{1\ \text{Btu}}{778\ \text{ft}\cdot\text{lbf}}\right| = 0.2\ \text{Btu} \end{aligned}$$

Finally,

$$\begin{aligned} Q &= W + (\Delta PE)_{piston} + m_{air}\Delta u_{air} \\ &= 4.35\ \text{Btu} + 0.2\ \text{Btu} + (0.6\ \text{lb})\left(18\,\frac{\text{Btu}}{\text{lb}}\right) = 15.35\ \text{Btu} \end{aligned}$$

1 2 To within round-off, this answer agrees with the result of part (a).

1 Although the value of Q is the same for each system, observe that the values for W differ. Also, observe that the energy changes differ, depending on whether the air alone or the air and the piston is the system.

2 For the system of part (b), the following *energy balance sheet* gives a full accounting of the heat transfer of energy to the system:

Energy In by Heat Transfer

15.35 Btu

Disposition of the Energy In

• Energy stored	
Internal energy of the air	10.8 Btu (70.4%)
Potential energy of the piston	0.2 Btu (1.3%)
• Energy out by work	4.35 Btu (28.3%)
	15.35 Btu (100%)

Skills Developed

Ability to...

- ❑ define alternative closed systems and identify interactions on their boundaries.
- ❑ evaluate work using Eq. 2.17.
- ❑ apply the closed-system energy balance.
- ❑ develop an energy balance sheet.

Quick Quiz What is the change in potential energy of the air, in Btu? **Ans.** 1.23×10^{-3} Btu.

EXAMPLE 2.4

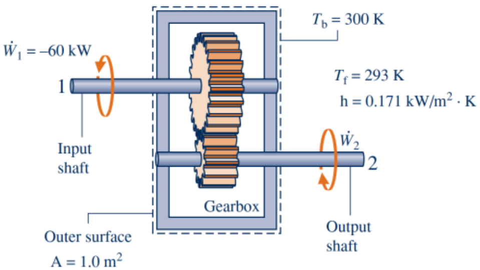
Evaluating Energy Transfer Rates of a Gearbox at Steady State

During steady-state operation, a gearbox receives 60 kW through the input shaft and delivers power through the output shaft. For the gearbox as the system, the rate of energy transfer by convection is

$$\dot{Q} = -hA(T_b - T_f)$$

where $h = 0.171$ kW/m² · K is the heat transfer coefficient, $A = 1.0$ m² is the outer surface area of the gearbox, $T_b = 300$ K (27°C) is the temperature at the outer surface, and $T_f = 293$ K (20°C) is the temperature of the surrounding air away from the immediate vicinity of the gearbox. For the gearbox, evaluate the heat transfer rate and the power delivered through the output shaft, each in kW.

Schematic and Given Data:



Engineering Model:

1. The gearbox is a closed system at steady state.
2. For the gearbox, convection is the dominant hea transfer mode.

Fig. E2.4

Analysis: Using the given expression for $\dot{Q}$ together with known data, the rate of energy transfer by heat is

❶
$$\begin{aligned}\dot{Q} &= -hA(T_b - T_f)\\ &= -\left(0.171\frac{\text{kW}}{\text{m}^2\cdot\text{K}}\right)(1.0\ \text{m}^2)(300 - 293)\ \text{K}\\ &= -1.2\ \text{kW}\end{aligned}$$

The minus sign for $\dot{Q}$ signals that energy is carried *out* of the gearbox by heat transfer.

The energy rate balance, Eq. 2.37, reduces at steady state to

❷
$$\cancel{\frac{dE}{dt}}^{\,0} = \dot{Q} - \dot{W} \quad \text{or} \quad \dot{W} = \dot{Q}$$

The symbol $\dot{W}$ represents the *net* power from the system. The net power is the sum of $\dot{W}_1$ and the output power $\dot{W}_2$

$$\dot{W} = \dot{W}_1 + \dot{W}_2$$

With this expression for $\dot{W}$, the energy rate balance becomes

$$\dot{W}_1 + \dot{W}_2 = \dot{Q}$$

Solving for $\dot{W}_2$, inserting $\dot{Q} = -1.2$ kW, and $\dot{W}_1 = -60$ kW, where the minus sign is required because the input shaft brings energy *into* the system, we have

❸
$$\begin{aligned}\dot{W}_2 &= \dot{Q} - \dot{W}_1\\ &= (-1.2\ \text{kW}) - (-60\ \text{kW})\\ &= +58.8\ \text{kW}\end{aligned}$$

❹ The positive sign for $\dot{W}_2$ indicates that energy is transferred from the system through the output shaft, as expected.

---

❶ In accord with the sign convention for the heat transfer rate in the energy rate balance (Eq. 2.37), Eq. 2.34 is written with a minus sign: $\dot{Q}$ is negative since T_b is greater than T_f.

❷ Properties of a system at steady state do not change with time. Energy E is a property, but heat transfer and work are not properties.

❸ For this system, energy transfer by work occurs at two different locations, and the signs associated with their values differ.

❹ At steady state, the rate of heat transfer from the gearbox accounts for the difference between the input and output power. This can be summarized by the following energy rate "balance sheet" in terms of *magnitudes*:

	Input	Output
	60 kW (input shaft)	58.8 kW (output shaft)
		1.2 kW (heat transfer)
Total:	60 kW	60 kW

Skills Developed

Ability to...

- ❑ define a closed system and identify interactions on its boundary.
- ❑ evaluate the rate of energy transfer by convection.
- ❑ apply the energy rate balance for steady-state operation.
- ❑ develop an energy rate balance sheet.

Quick Quiz For an emissivity of 0.8 and taking $T_s = T_f$, use Eq. 2.33 to determine the net rate at which energy is radiated from the outer surface of the gearbox, in kW. **Ans.** 0.03 kW.

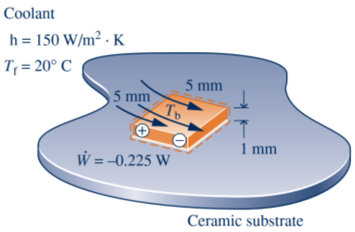
Using the Energy Balance: Processes of Closed Systems

EXAMPLE 2.5

Determining Surface Temperature of a Silicon Chip at Steady State

A silicon chip measuring 5 mm on a side and 1 mm in thickness is embedded in a ceramic substrate. At steady state, the chip has an electrical power input of 0.225 W. The top surface of the chip is exposed to a coolant whose temperature is 20°C. The heat transfer coefficient for convection between the chip and the coolant is 150 W/m² · K. If heat transfer by conduction between the chip and the substrate is negligible, determine the surface temperature of the chip, in °C.

Schematic and Given Data:



Engineering Model:

1. The chip is a closed system at steady state.
2. There is no heat transfer between the chip and the substrate.

Fig. E2.5

Analysis: The surface temperature of the chip, T_b, can be determined using the energy rate balance, Eq. 2.37, which at steady state reduces as follows

❶ $$\cancel{\frac{dE}{dt}}^{0} = \dot{Q} - \dot{W}$$

With assumption 2, the only heat transfer is by convection to the coolant. In this application, Newton's law of cooling, Eq. 2.34, takes the form

❷ $$\dot{Q} = -hA(T_b - T_f)$$

Collecting results

$$0 = -hA(T_b - T_f) - \dot{W}$$

Solving for T_b

$$T_b = \frac{-\dot{W}}{hA} + T_f$$

In this expression, $\dot{W} = -0.225$ W, $A = 25 \times 10^{-6}$ m², $h = 150$ W/m² · K, and $T_f = 293$ K, giving

$$T_b = \frac{-(-0.225\text{ W})}{(150\text{ W/m}^2\cdot\text{K})(25\times10^{-6}\text{ m}^2)} + 293\text{ K}$$
$$= 353\text{ K } (80°\text{C})$$

❶ Properties of a system at steady state do not change with time. Energy E is a property, but heat transfer and work are not properties.

❷ In accord with the sign convention for heat transfer in the energy rate balance (Eq. 2.37), Eq. 2.34 is written with a minus sign: $\dot{Q}$ is negative since T_b is greater than T_f.

Skills Developed

Ability to...

- define a closed system and identify interactions on its boundary.
- evaluate the rate of energy transfer by convection.
- apply the energy rate balance for steady-state operation.

Quick Quiz If the surface temperature of the chip must be no greater than 60°C, what is the corresponding range of values required for the convective heat transfer coefficient, assuming all other quantities remain unchanged? **Ans.** h ≥ 225 W/m² · K.

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Using the Energy Balance: Processes of Closed Systems

EXAMPLE 2.6

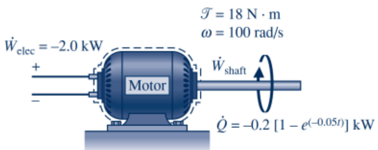
Investigating Transient Operation of a Motor

The rate of heat transfer between a certain electric motor and its surroundings varies with time as

$$\dot{Q} = -0.2[1 - e^{(-0.05t)}]$$

where t is in seconds and $\dot{Q}$ is in kW. The shaft of the motor rotates at a constant speed of $\omega = 100$ rad/s (about 955 revolutions per minute, or RPM) and applies a constant torque of $\mathscr{T} = 18$ N · m to an external load. The motor draws a constant electric power input equal to 2.0 kW. For the motor, plot $\dot{Q}$ and $\dot{W}$, each in kW, and the change in energy ΔE, in kJ, as functions of time from $t = 0$ to $t = 120$ s. Discuss.

Schematic and Given Data:



Engineering Model: The system shown in the accompanying sketch is a closed system.

Fig. E2.6a

Analysis: The time rate of change of system energy is

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

$\dot{W}$ represents the *net* power *from* the system: the sum of the power associated with the rotating shaft, $\dot{W}_{shaft}$, and the power associated with the electricity flow, $\dot{W}_{elec}$:

$$\dot{W} = \dot{W}_{shaft} + \dot{W}_{elec}$$

The rate $\dot{W}_{elec}$ is known from the problem statement: $\dot{W}_{elec} = -2.0$ kW, where the negative sign is required because energy is carried into the system by electrical work. The term $\dot{W}_{shaft}$ can be evaluated with Eq. 2.20 as

$$\dot{W}_{shaft} = \mathscr{T}\omega = (18 \text{ N} \cdot \text{m})(100 \text{ rad/s}) = 1800 \text{ W} = +1.8 \text{ kW}$$

Because energy exits the system along the rotating shaft, this energy transfer rate is positive.

In summary,

$$\dot{W} = \dot{W}_{elec} + \dot{W}_{shaft} = (-2.0 \text{ kW}) + (+1.8 \text{ kW}) = -0.2 \text{ kW}$$

where the minus sign means that the electrical power input is greater than the power transferred out along the shaft.

With the foregoing result for $\dot{W}$ and the given expression for $\dot{Q}$, the energy rate balance becomes

$$\frac{dE}{dt} = -0.2[1 - e^{(-0.05t)}] - (-0.2) = 0.2e^{(-0.05t)}$$

Integrating

$$\Delta E = \int_0^t 0.2e^{(-0.05t)}dt$$

$$= \frac{0.2}{(-0.05)}e^{(-0.05t)}\Big]_0^t = 4[1 - e^{(-0.05t)}]$$

1 The accompanying plots, Figs. E2.6*b* and *c*, are developed using the given expression for $\dot{Q}$ and the expressions for $\dot{W}$ and ΔE obtained in the analysis. Because of our sign conventions for heat and work, the values

Energy Analysis of Cycles

thermodynamic cycle

A ***thermodynamic cycle*** is a sequence of processes that begins and ends at the same state.

Cycle Energy Balance

$$\Delta E_{\text{cycle}} = Q_{\text{cycle}} - W_{\text{cycle}}$$

$$W_{\text{cycle}} = Q_{\text{cycle}}$$

power cycle

Systems undergoing cycles of the type shown in Fig. 2.17a deliver a net work transfer of energy to their surroundings during each cycle. Any such cycle is called a ***power cycle***.

$$W_{\text{cycle}} = Q_{\text{in}} - Q_{\text{out}} \qquad \text{(power cycle)}$$

thermal efficiency

The extent of the energy conversion from heat to work is expressed by the following ratio, commonly called the thermal efficiency:

$$\eta = \frac{W_{\text{cycle}}}{Q_{\text{in}}} \qquad \text{(power cycle)}$$

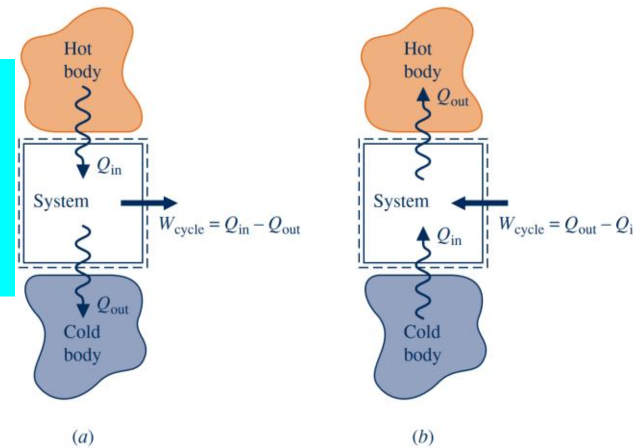
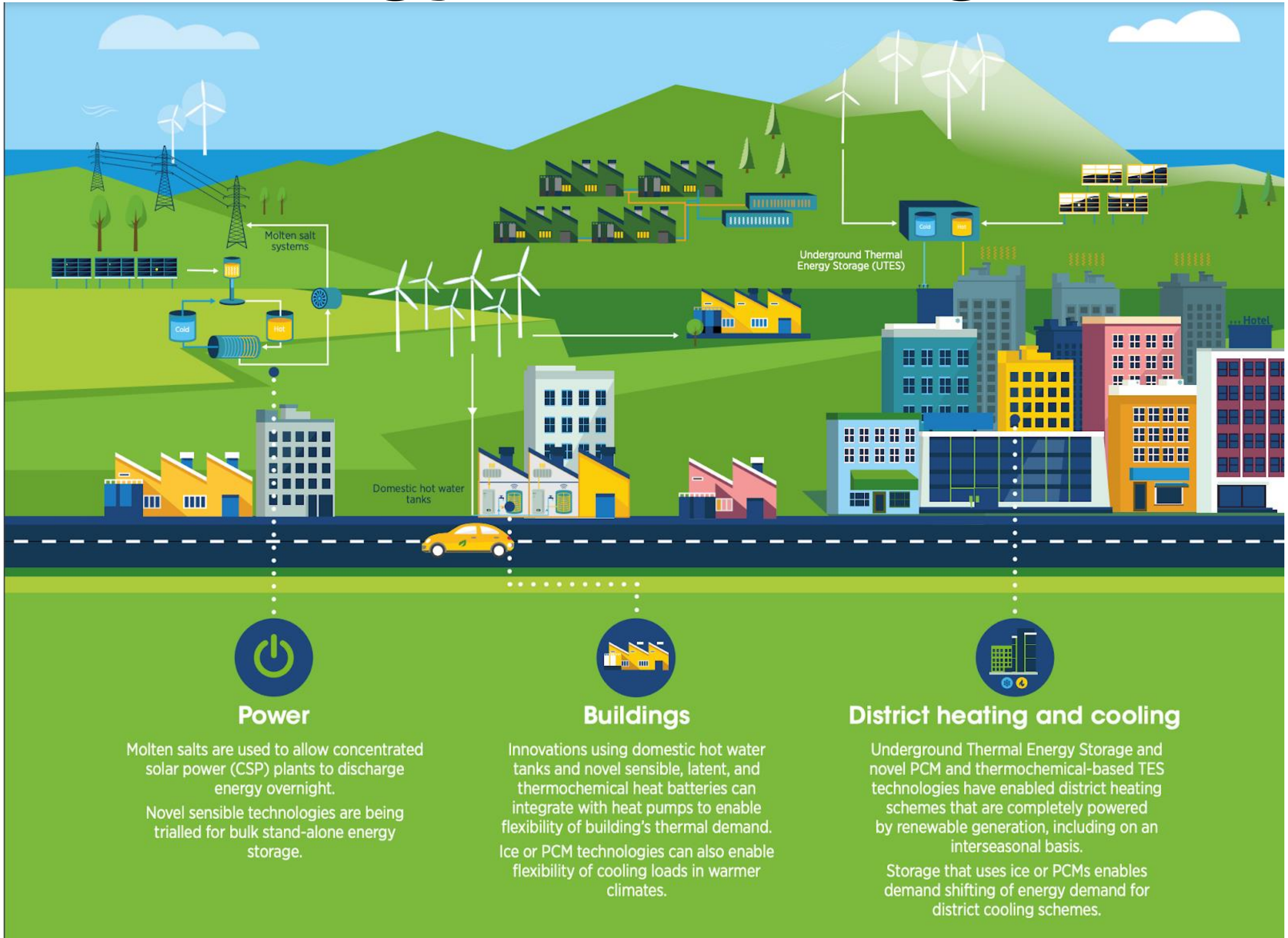


Fig. 2.17 Schematic diagrams of two important classes of cycles. (*a*) Power cycles. (*b*) Refrigeration and heat pump cycles.

Renewable Energy Technologies



Aalto University
School of Engineering

Energy Storage

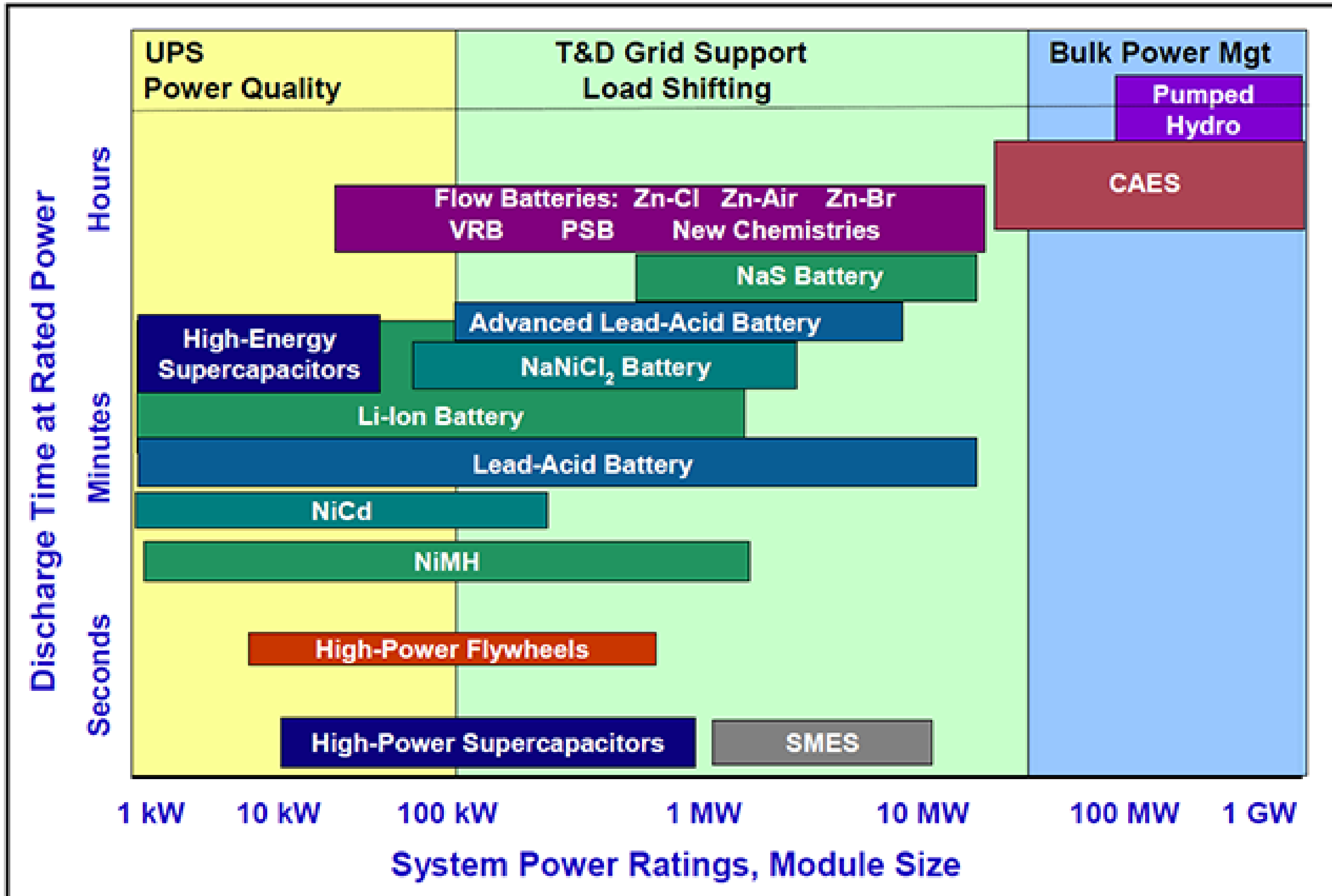
The need is widespread, including use with conventional fossil- and nuclear-fueled power plants, power plants using renewable sources like solar and wind, and countless applications in transportation, industry, business, and the home.

Electricity can be stored as internal energy, kinetic energy, and gravitational potential energy and converted back to electricity when needed.

Owing to thermodynamic limitations associated with such conversions, the effects of friction and electrical resistance for instance, an overall input-to-output loss of electricity is always observed

Among technically feasible storage options, economics usually determines if, when, and how storage is implemented.

Energy Storage



Energy & 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
- The largest source of air pollution is the motor vehicles, and the pollutants released by the vehicles are usually grouped as hydrocarbons (HC), nitrogen oxides (NOx), and carbon monoxide (CO)

Ozone and Smog **Acid Rain** **The Greenhouse Effect: Global Warming and Climate Change**

KEY EQUATIONS

$$\Delta E = \Delta U + \Delta \mathrm{KE} + \Delta \mathrm{PE}$$	Change in total energy of a system.
$$\Delta \mathrm{KE} = \mathrm{KE}_2 - \mathrm{KE}_1 = \frac{1}{2}m(\mathrm{V}_2^2 - \mathrm{V}_1^2)$$	Change in kinetic energy of a mass *m*.
$$\Delta \mathrm{PE} = \mathrm{PE}_2 - \mathrm{PE}_1 = mg(z_2 - z_1)$$	Change in gravitational potential energy of a mass *m* at constant *g*.
$$E_2 - E_1 = Q - W$$	Energy balance for closed systems.
$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$	Energy rate balance for closed systems.
$$W = \int_{s_1}^{s_2} \mathbf{F} \cdot \mathbf{ds}$$	Work due to action of a force **F**.
$$\dot{W} = \mathbf{F} \cdot \mathbf{V}$$	Power due to action of a force **F**.
$$W = \int_{V_1}^{V_2} p\, dV$$	Expansion or compression work related to fluid pressure. See Fig. 2.4.

odynamic Cycles

$$W_{\mathrm{cycle}} = Q_{\mathrm{in}} - Q_{\mathrm{out}}$$	Energy balance for a *power cycle*. As in Fig. 2.17a, all quantities are regarded as positive.
$$\eta = \frac{W_{\mathrm{cycle}}}{Q_{\mathrm{in}}}$$	Thermal efficiency of a power cycle.
$$W_{\mathrm{cycle}} = Q_{\mathrm{out}} - Q_{\mathrm{in}}$$	Energy balance for a *refrigeration* or *heat pump cycle*. As in Fig. 2.17b, all quantities are regarded as positive.
$$\beta = \frac{Q_{\mathrm{in}}}{W_{\mathrm{cycle}}}$$	Coefficient of performance of a refrigeration cycle.
$$\gamma = \frac{Q_{\mathrm{out}}}{W_{\mathrm{cycle}}}$$	Coefficient of performance of a heat pump cycle.