Thermodynamics: An Engineering Approach

8th Edition

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Topic 4

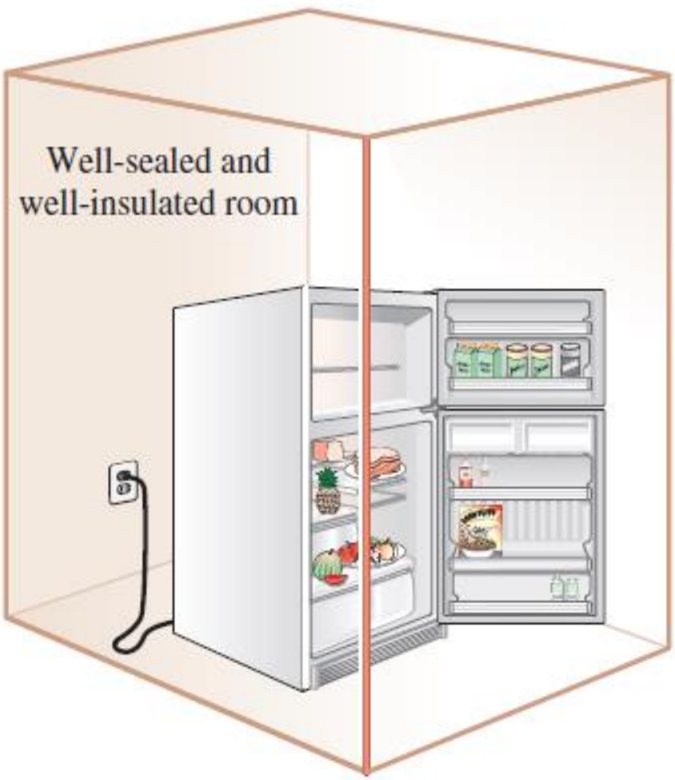
Energy Introduction

Objectives

- Introduce the concept of energy and define its various forms.
- Discuss the nature of internal energy.
- Define specific heat and demonstrate properties for various substances.
- Show relationships between internal energy, enthalpy, and specific heat.

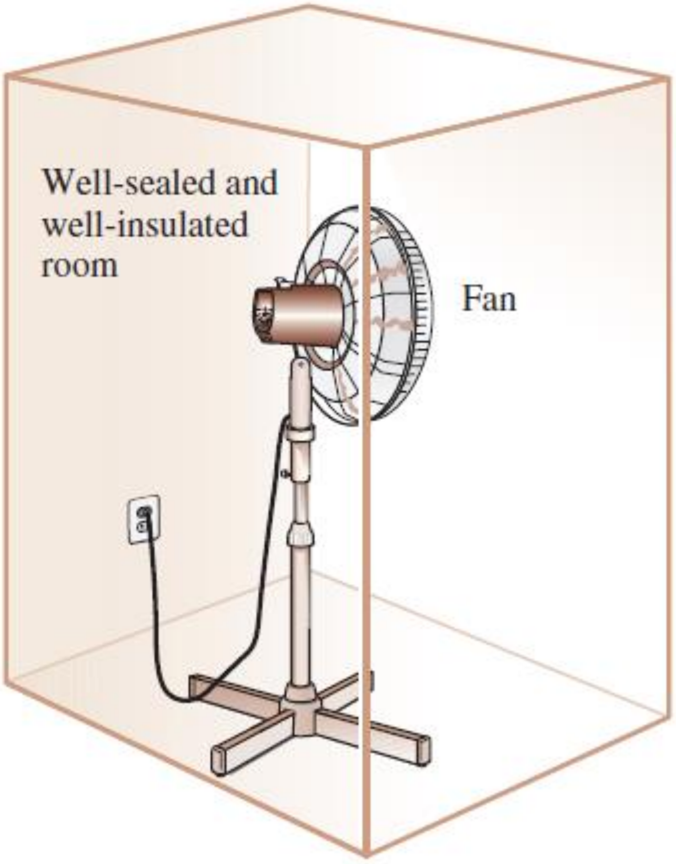
INTRODUCTION

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

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

FIGURE 2–4
The macroscopic energy of an object changes with velocity and elevation.

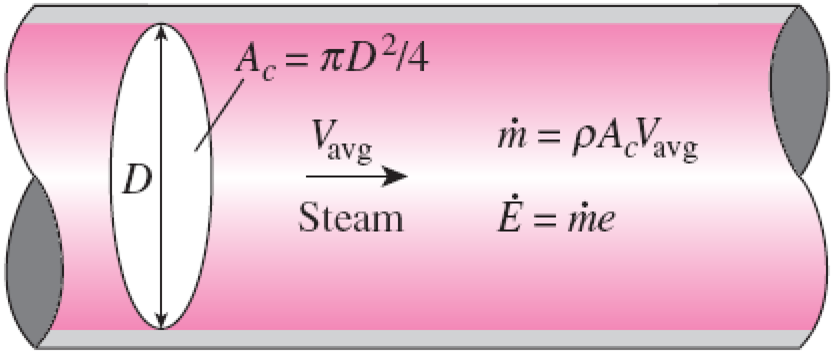
FIGURE 2–3
At least six different forms of energy are encountered in bringing power from a nuclear plant to your home: nuclear, thermal, mechanical, kinetic, magnetic, and electrical.

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

$$\mathrm{ke} = \frac{V^2}{2} \qquad (\mathrm{kJ/kg})$$ Kinetic energy per unit mass

$$\mathrm{PE} = mgz \qquad (\mathrm{kJ})$$ Potential energy

$$\mathrm{pe} = gz \qquad (\mathrm{kJ/kg})$$ Potential energy per unit mass



Mass flow rate

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

Energy flow rate

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

$$E = U + \mathrm{KE} + \mathrm{PE} = U + m\frac{V^2}{2} + mgz \qquad (\mathrm{kJ})$$ Total energy of a system

$$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{V^2}{2} + gz \qquad (\mathrm{kJ/kg})$$ Energy of a system per unit mass

$$e = \frac{E}{m} \qquad (\mathrm{kJ/kg})$$ Total energy per unit mass

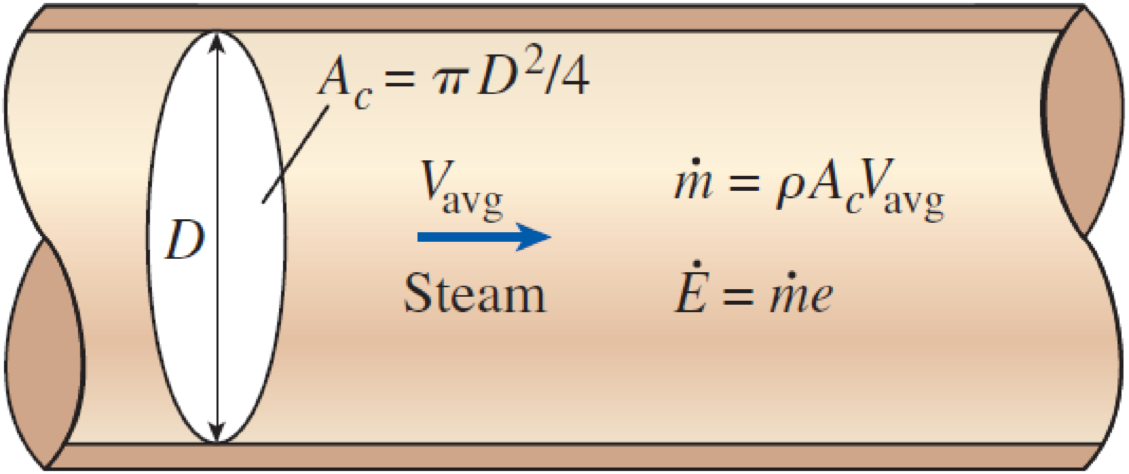


FIGURE 2–5
Mass and energy flow rates associated with the flow of steam in a pipe of inner diameter D with an average velocity of V_{avg}.

Mass flow rate: $$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \quad \text{(kg/s)}$$

Energy flow rate: $$\dot{E} = \dot{m}e \quad \text{(kJ/s or kW)}$$

Example

Isobutane is piped through a piping network with an inside diameter of 2 in. If the volumetric flow rate at a particular point is 225 gallons per minute (gpm), what is the mass flow rate? What is the average velocity of the fluid?

Example 1

Some Physical Insight to Internal Energy

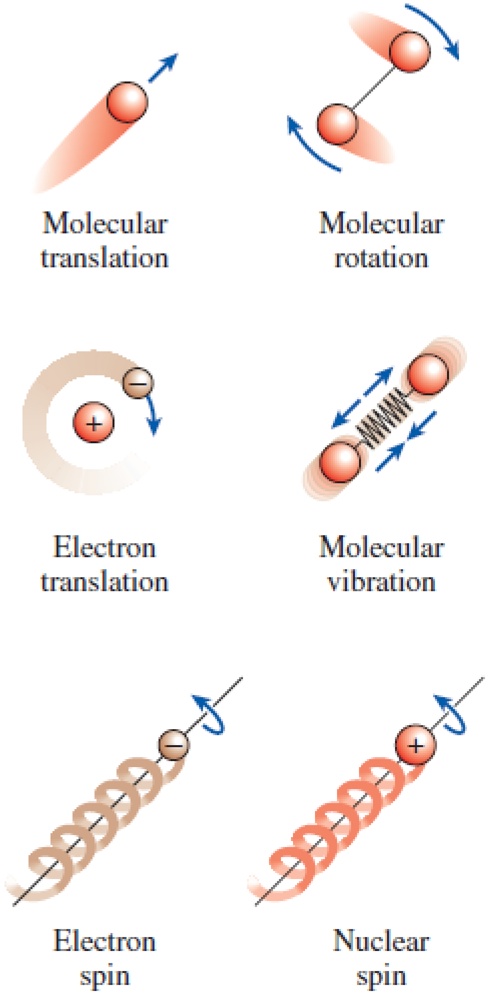


FIGURE 2–6
The various forms of microscopic energies that make up *sensible* energy.

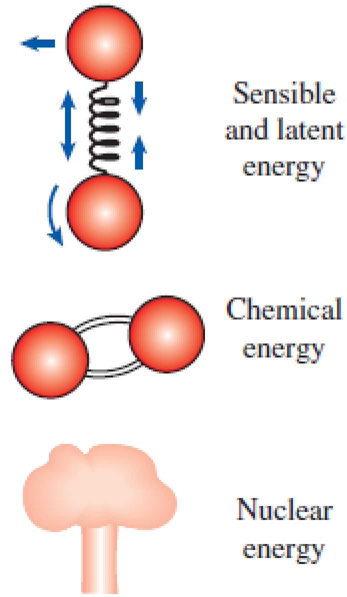


FIGURE 2–7
The internal energy of a system is the sum of all forms of the microscopic energies.

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**.

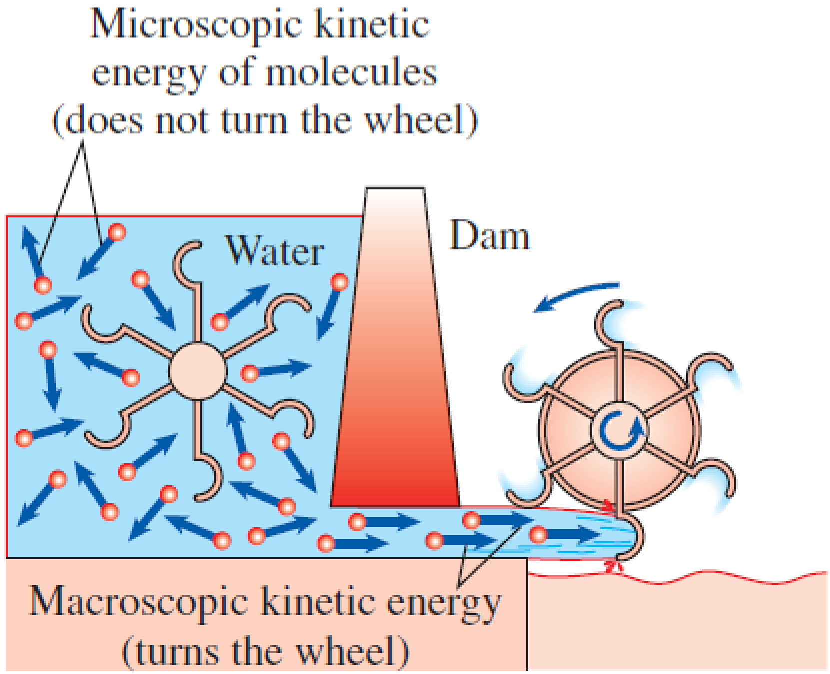


FIGURE 2–8
The *macroscopic* kinetic energy is an organized form of energy and is much more useful than the disorganized *microscopic* kinetic energies of the molecules.

- **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.

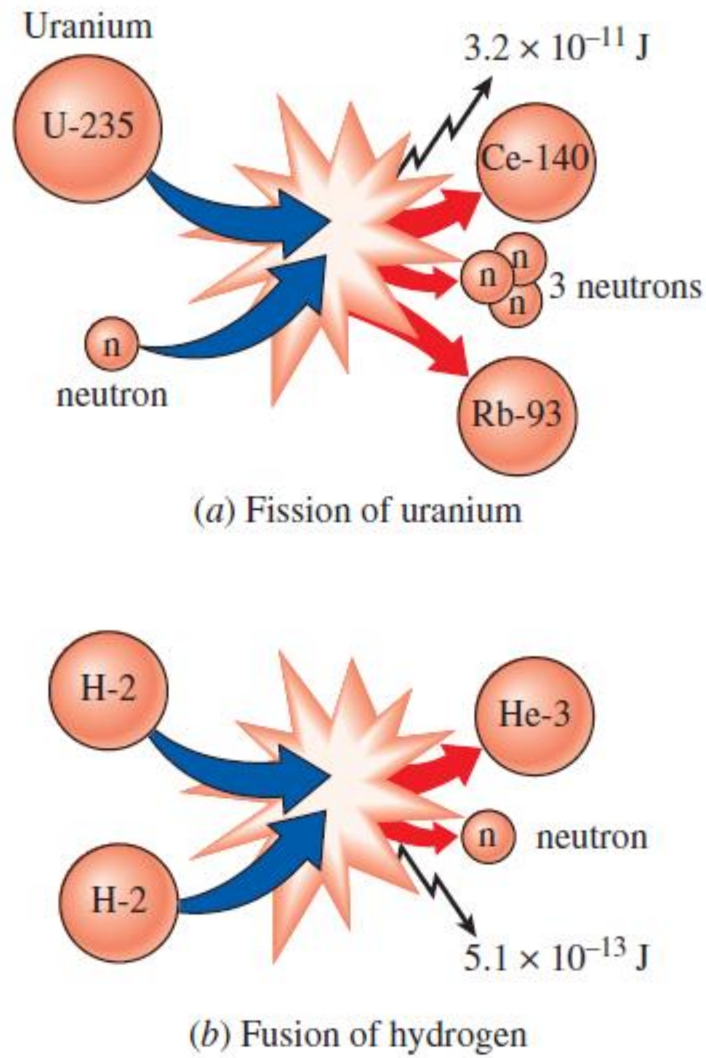


FIGURE 2–9
The fission of uranium and the fusion of hydrogen during nuclear reactions, and the release of nuclear energy.

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.

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

Mechanical energy of a flowing fluid per unit mass

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

Rate of mechanical energy of a flowing fluid

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

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

Rate of mechanical energy change of a fluid during incompressible flow

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

Example

Determine the mechanical work the pump imparts to the water.

Example 2

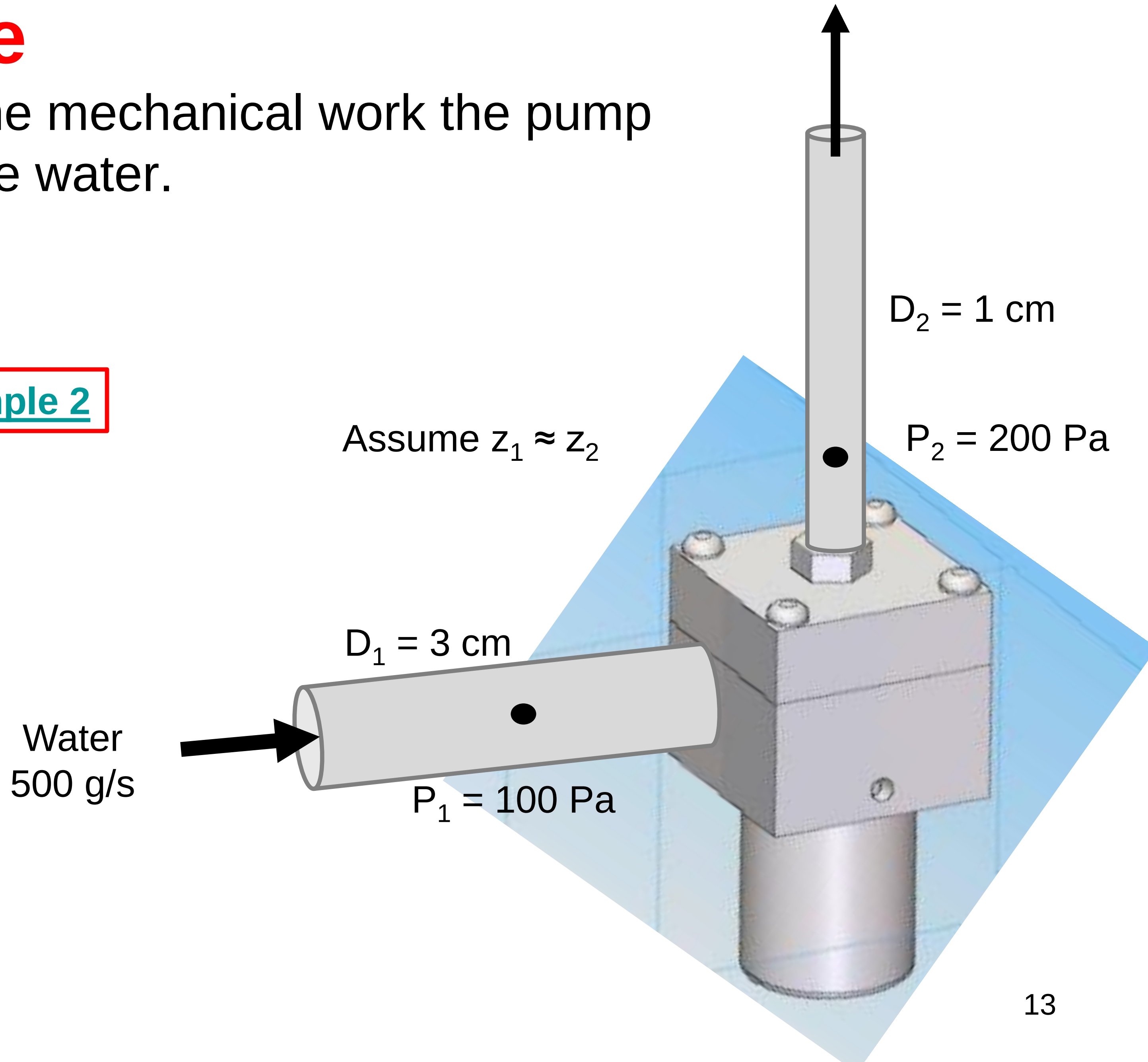
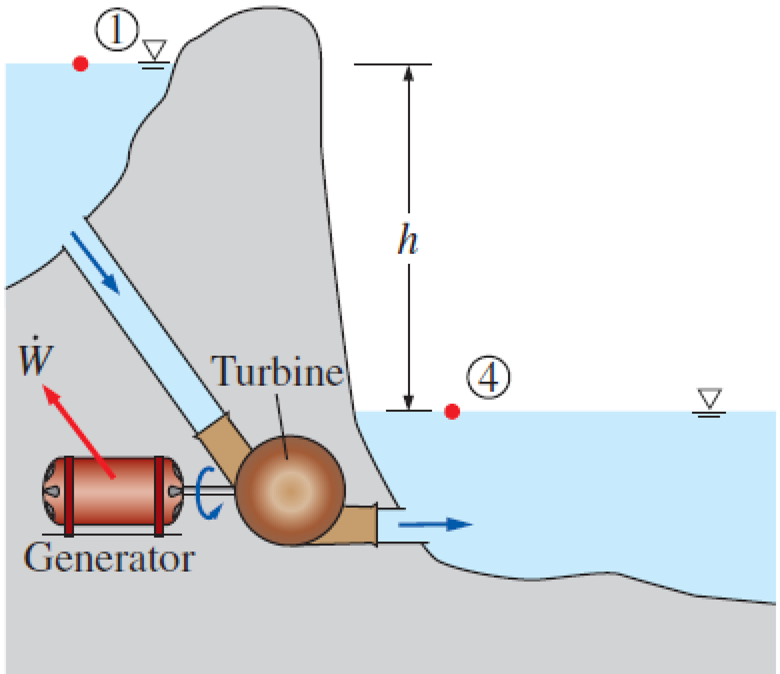


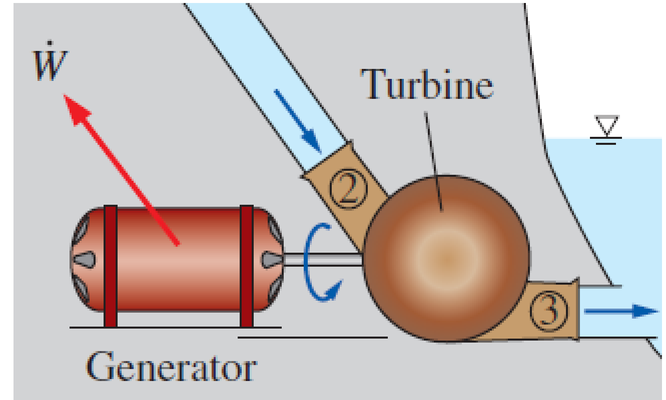
FIGURE 2–11
Mechanical energy is a useful concept for flows that do not involve significant heat transfer or energy conversion, such as the flow of gasoline from an underground tank into a car.



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

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

(*a*)



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

since $V_2 \approx V_3$ and $z_2 = z_3$

(*b*)

FIGURE 2–12

Mechanical energy is illustrated by an ideal hydraulic turbine coupled with an ideal generator. In the absence of irreversible losses, the maximum produced power is proportional to (*a*) the change in water surface elevation from the upstream to the downstream reservoir or (*b*) (close-up view) the drop in water pressure from just upstream to just downstream of the turbine.

SPECIFIC HEATS

Specific heat at constant volume, c_v: The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

Specific heat at constant pressure, c_p: The energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.

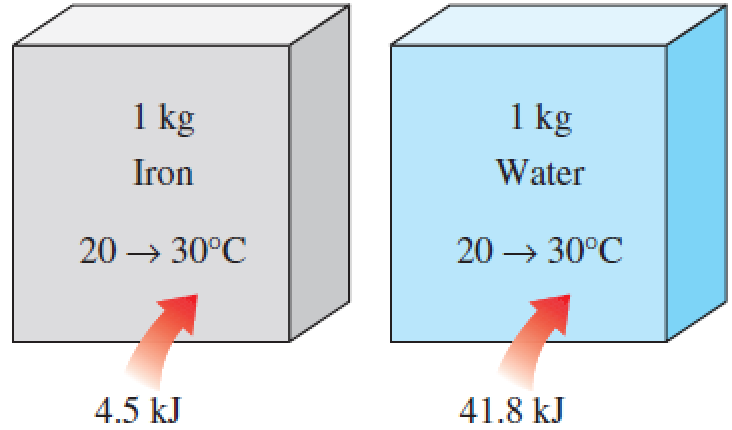


FIGURE 4–17
It takes different amounts of energy to raise the temperature of different substances by the same amount.

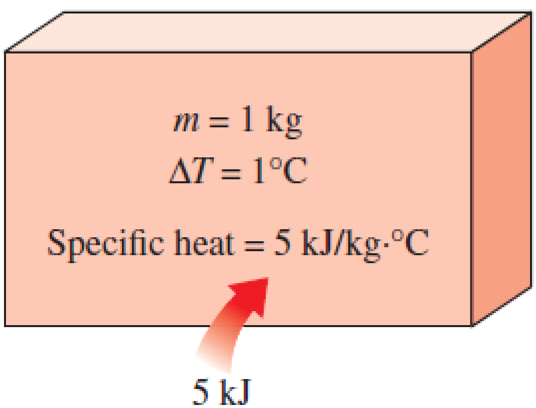
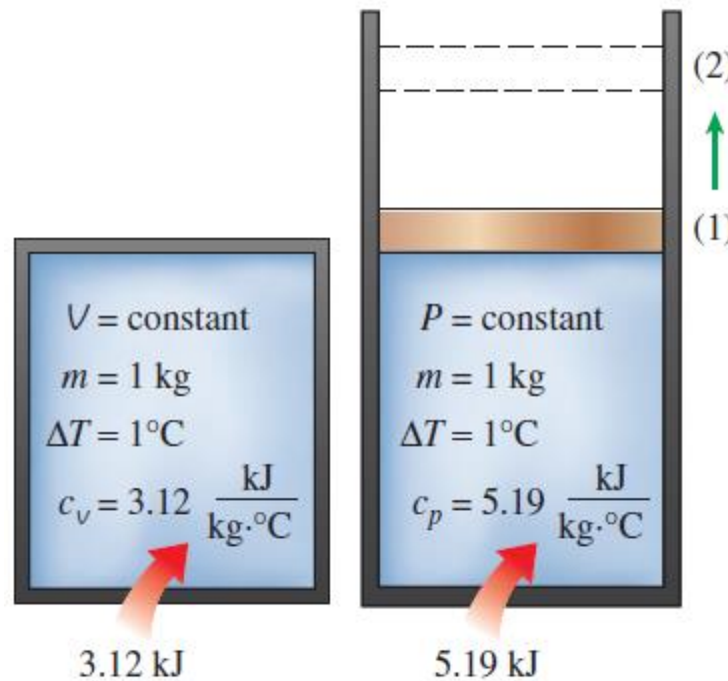


FIGURE 4–18
Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

Constant-volume and constant-pressure specific heats c_v and c_p (values are for helium gas).



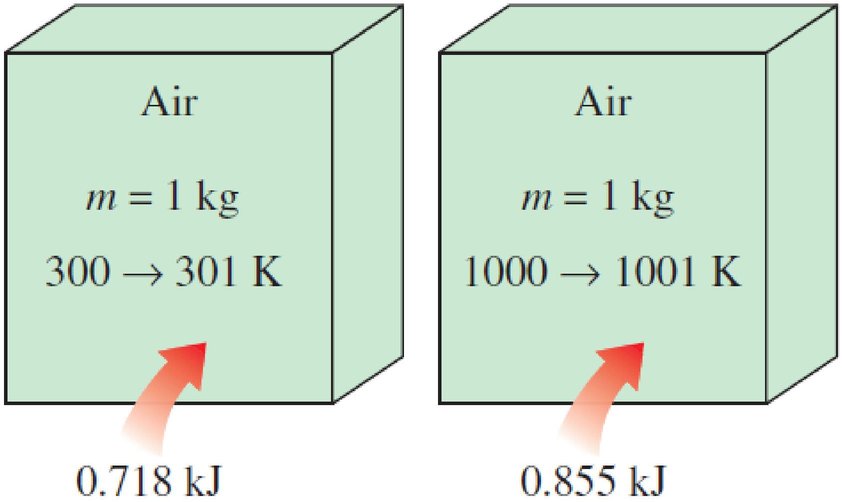


FIGURE 4–21
The specific heat of a substance changes with temperature.

- The equations are valid for *any* substance undergoing *any* process.
- c_v and c_p are properties.
- c_v is related to the changes in *internal energy* and c_p to the changes in *enthalpy*.
- A common unit for specific heats is kJ/kg·°C or kJ/kg·K. **Are these units identical?**

True or False?
c_p is always greater than c_v

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v$$

= the change in internal energy with temperature at constant volume

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

= the change in enthalpy with temperature at constant pressure

Formal definitions of c_v and c_p.

INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF IDEAL GASES

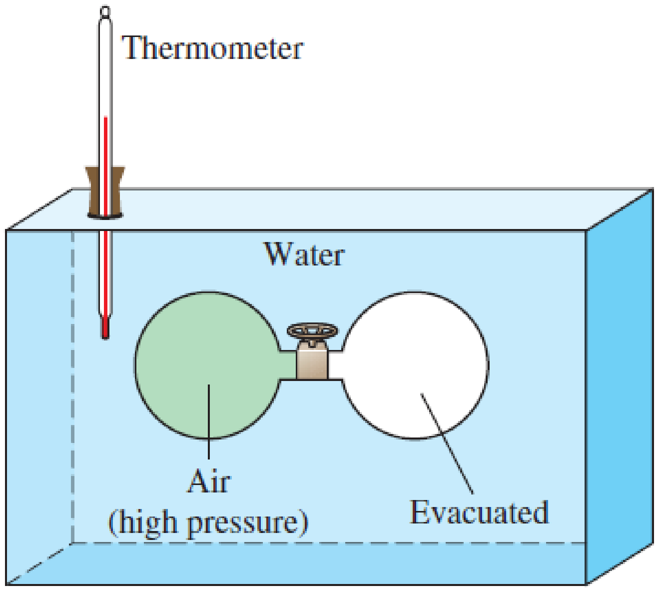


FIGURE 4–22
Schematic of the experimental apparatus used by Joule.

$$\left.\begin{aligned} h &= u + Pv \\ Pv &= RT \end{aligned}\right\} \quad h = u + RT$$

$$u = u(T) \quad h = h(T)$$

$$du = c_v(T)\,dT \quad dh = c_p(T)\,dT$$

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)\,dT$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)\,dT$$

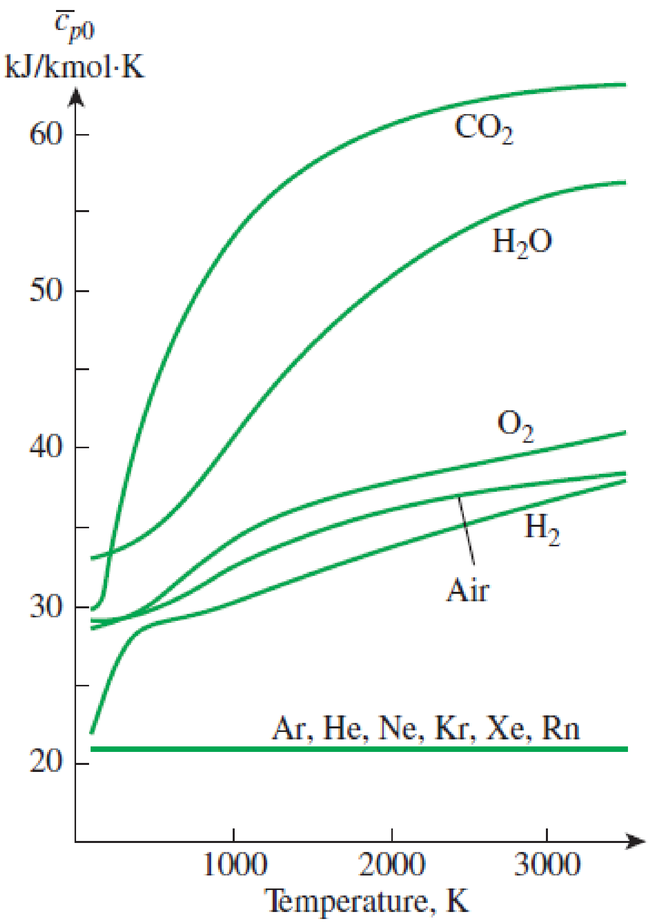
Joule showed using this experimental apparatus that $u=u(T)$

$$\boxed{\begin{aligned} u &= u(T) \\ h &= h(T) \\ c_v &= c_v(T) \\ c_p &= c_p(T) \end{aligned}}$$

For ideal gases, u, h, c_v, and c_p vary with temperature only.

Internal energy and enthalpy change of an ideal gas

- At low pressures, all real gases approach ideal-gas behavior, and therefore their specific heats depend on temperature only.
- The specific heats of real gases at low pressures are called *ideal-gas specific heats*, or *zero-pressure specific heats*, and are often denoted c_{p0} and c_{v0}.



Ideal-gas constant-pressure specific heats for some gases (see Table A–2*c* for c_p equations).

- *u* and *h* data for a number of gases have been tabulated.
- These tables are obtained by choosing an arbitrary reference point and performing the integrations by treating state 1 as the reference state.

Air

T, K	u, kJ/kg	h, kJ/kg
0	0	0
·	·	·
·	·	·
300	214.07	300.19
310	221.25	310.24
·	·	·

In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

Internal energy and enthalpy change when specific heat is taken constant at an average value

$$u_2 - u_1 = c_{v,\text{avg}}(T_2 - T_1)$$
$$h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1) \quad \text{(kJ/kg)}$$

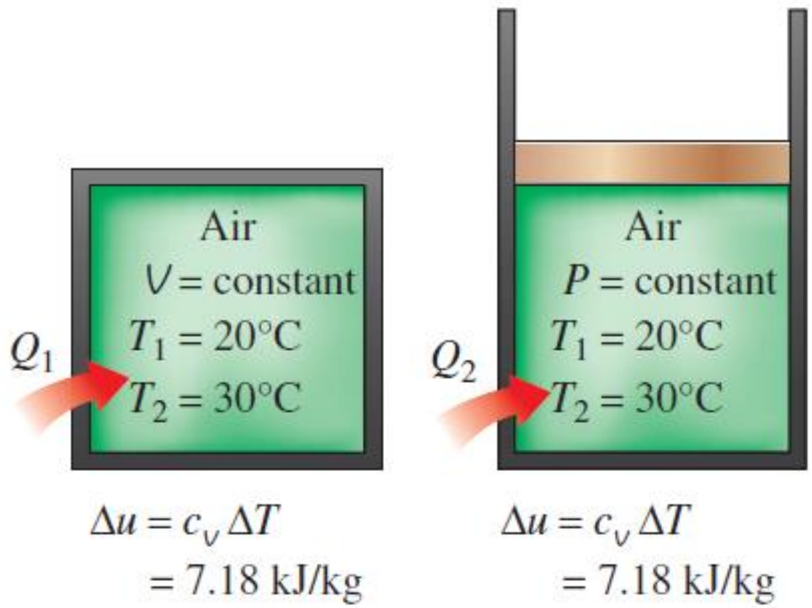


FIGURE 4–27
The relation $\Delta u = c_v \Delta T$ is valid for *any* kind of process, constant-volume or not.

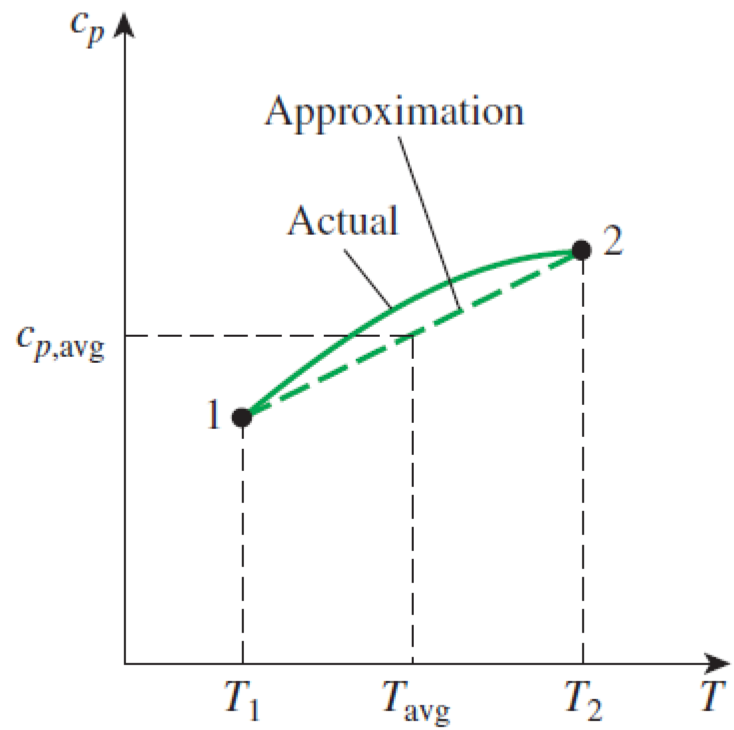


FIGURE 4–26
For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.

Specific Heat Relations of Ideal Gases

$$h = u + RT,$$
$$dh = du + R\,dT$$
$dh = c_p dT$ and $du = c_v dT$

The relationship between c_p, c_v and R

$$c_p = c_v + R \qquad (\text{kJ/kg}\cdot\text{K})$$

On a molar basis

$$\bar{c}_p = \bar{c}_v + R_u \qquad (\text{kJ/kmol}\cdot\text{K})$$

$$k = \frac{c_p}{c_v}$$ Specific heat ratio

Air at 300 K

$$\left.\begin{aligned} c_v &= 0.718 \text{ kJ/kg·K} \\ R &= 0.287 \text{ kJ/kg·K} \end{aligned}\right\} c_p = 1.005 \text{ kJ/kg·K}$$

or

$$\left.\begin{aligned} \bar{c}_v &= 20.80 \text{ kJ/kmol·K} \\ R_u &= 8.314 \text{ kJ/kmol·K} \end{aligned}\right\} \bar{c}_p = 29.114 \text{ kJ/kmol·K}$$

The c_p of an ideal gas can be determined from a knowledge of c_v and R.

- The specific ratio varies with temperature, but this variation is very mild.
- For monatomic gases (helium, argon, etc.), its value is essentially constant at 1.667.
- Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

Three ways of calculating Δu *and* Δh

1. By using the tabulated *u* and *h* data. This is the easiest and **most accurate** way when tables are readily available.
2. By using the c_v or c_p relations (Table A-2c) as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are **very accurate**.
3. By using average specific heats. This is very simple and certainly very convenient when property tables are not available. The results obtained are **reasonably accurate** if the temperature interval is not very large.

$$\Delta u = u_2 - u_1 \text{ (table)}$$

$$\Delta u = \int_1^2 c_v(T)\, dT$$

$$\Delta u \cong c_{v,\text{avg}}\, \Delta T$$

Three ways of calculating Δu.

Evaluation of the Δu of an Ideal Gas

Air at 300 K and 200 kPa is heated at constant pressure to 600 K. Determine the change in internal energy of air per unit mass, using

(a) data from the air table

(b) the functional form of the specific heat

(c) the average specific heat value

Example 3

INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF SOLIDS AND LIQUIDS

Incompressible substance: A substance whose specific volume (or density) is constant. Solids and liquids are incompressible substances.

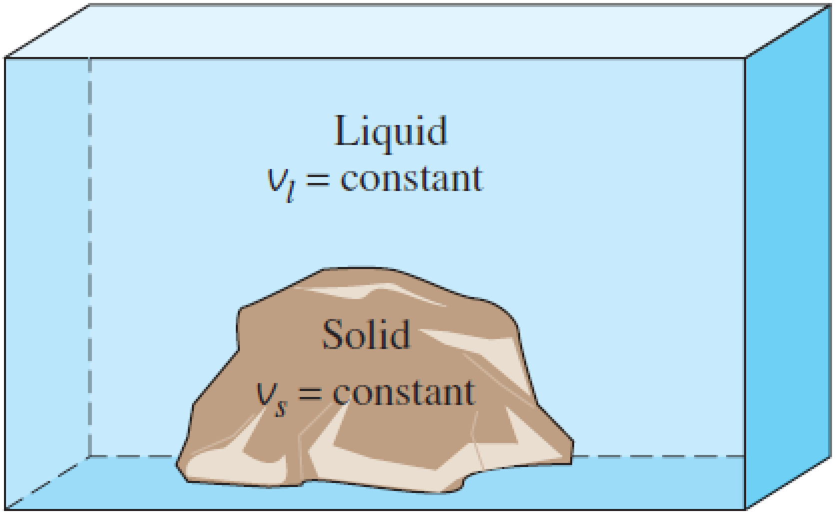


FIGURE 4–33
The specific volumes of incompressible substances remain constant during a process.

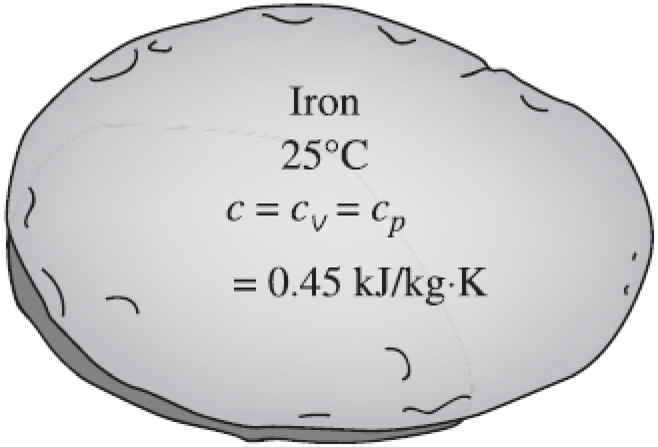


FIGURE 4–34
The c_v and c_p values of incompressible substances are identical and are denoted by c.

Internal Energy Changes

$$du = c_v dT = c(T)dT$$

$$\Delta u = u_2 - u_1 = \int_1^2 c(T)dT$$

For small temperature intervals:

$$\Delta u \cong c_{avg}(T_2 - T_1)$$

Enthalpy Changes

$$dh = du + d(Pv) = du + v\,dP + P\,dv$$

For incompressible substances: dv = 0

$$dh = du + v\,dP$$

$$\Delta h = \Delta u + v\Delta P \cong c_{avg}\Delta T + v\Delta P$$

For solids: $v\,\Delta P \ll c_{avg}\Delta T \quad \rightarrow \Delta h = \Delta u \cong c_{avg}\Delta T$

For liquids:

Constant pressure (e.g. heaters): $\Delta P = 0 \rightarrow \Delta h = \Delta u \cong c_{avg}\Delta T$

Constant temperature (e.g. pumps): $\Delta T = 0 \rightarrow \Delta h = v\Delta P$

Cooling of an Iron Block by Water

A 50-kg iron block at 80^{o}C is dropped into an insulated tank that contains 0.5 m^3 of liquid water at 25^{o}C. Determine the temperature when thermal equilibrium is reached.

Hint: For thermal equilibrium to be reached, the sum of the changes of internal energy of the iron block and water must be equal to zero.

Example 4

Enthalpy of a Compressed Liquid

Determine the enthalpy of liquid water at 100ºC and 15 Mpa.

Normally, we would use the steam stables.

$$P > P_{sat\,@\,100℃} \;\rightarrow\; compressed\ liquid$$

Table A-7

$$@\,15\,MPa \;\;\&\;\; 100℃ \quad h = 430.39\,\frac{kJ}{kg}$$

What if there was no information for this state in the Table A-7?

We approximate use saturated liquid properties in Table A-4

$$h \cong h_{f\,@\,100℃} = 419.17\,\frac{kJ}{kg}$$

Enthalpy of a Compressed Liquid

Determine the enthalpy of liquid water at 100ºC and 15 Mpa.

What if we use the equation for a constant-temperature process?

$$\Delta \boldsymbol{h} = \boldsymbol{v}\,\Delta \boldsymbol{P} \quad \rightarrow \quad \boldsymbol{h_2} = \boldsymbol{h_{f@100℃}} + \boldsymbol{v_{f@100℃}}(\boldsymbol{P_2} - \boldsymbol{P_{sat@100℃}})$$

$$\boldsymbol{h} = \mathbf{419.17}\frac{\boldsymbol{kJ}}{\boldsymbol{kg}} + \left(\mathbf{0.001}\frac{\boldsymbol{m^3}}{\boldsymbol{kg}}\right)(\mathbf{15,000} - \mathbf{101.42})\boldsymbol{kPa}$$

$$= \mathbf{434.07}\frac{\boldsymbol{kJ}}{\boldsymbol{kg}}$$

Comparing our last two values to the exact value in Table A-7:

using saturation liquid approximation – 2.6% error

using equation for constant temp process -- ~1% error

Summary

- Forms of energy
  - Macroscopic = kinetic + potential
  - Microscopic = Internal energy (sensible + latent + chemical + nuclear)
- Specific heats
  - Constant-pressure specific heat, c_p
  - Constant-volume specific heat, c_v
- Internal energy, enthalpy, and specific heats of ideal gases
  - Specific heat relations of ideal gases
- Internal energy, enthalpy, and specific heats of incompressible substances (solids and liquids)