Chapter 14
Heat
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14-1 Heat As Energy Transfer

We often speak of heat as though it were a material that flows from one object to another; it is not. Rather, it is a form of energy.

Unit of heat: calorie (cal)

1 cal is the amount of heat necessary to raise the temperature of 1 g of water by 1 Celsius degree.

Don’t be fooled—the calories on our food labels are really kilocalories (kcal or Calories), the heat necessary to raise 1 kg of water by 1 Celsius degree.

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If heat is a form of energy, it ought to be possible to equate it to other forms. The experiment below found the mechanical equivalent of heat by using the falling weight to heat the water:

\[ 4.186 \text{ J} = 1 \text{ cal} \]
\[ 4.186 \text{ kJ} = 1 \text{ kcal} \]

Definition of heat:
Heat is energy transferred from one object to another because of a difference in temperature.

- Remember that the temperature of a gas is a measure of the kinetic energy of its molecules.
14-2 Internal Energy

The sum total of all the energy of all the molecules in a substance is its internal (or thermal) energy.

Temperature: measures molecules’ average kinetic energy

Internal energy: total energy of all molecules

Heat: transfer of energy due to difference in temperature

Internal energy of an ideal (atomic) gas is equal to the average kinetic energy per molecule multiplied by the number of molecules.

But since we know the average kinetic energy in terms of the temperature, we can write:

\[ U = \frac{3}{2} nRT, \]  

\( \text{internal energy of ideal monatomic gas} \)  

(14-1)
If the gas is molecular rather than atomic, rotational and vibrational kinetic energy needs to be taken into account as well.

14-3 Specific Heat

The amount of heat required to change the temperature of a material is proportional to the mass and to the temperature change:

\[ Q = mc \Delta T, \quad (14-2) \]

The specific heat, \( c \), is characteristic of the material. Some values are listed at left.
Specific Heat: \[ c \] = J/(kg*K)

Molar Heat Capacity: \[ C \] = J/(mol*K)

\[
Q = m c \Delta T
\]

\[
Q = \frac{mC \Delta T}{kg K}
\]

\[
Q = \frac{nMC \Delta T}{mol K}
\]

\[
C = cM
\]

- Molar heat capacity for elemental solids ~ 25 J/(mol*K)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Specific Heat, ( c ) (J/kg · K)</th>
<th>Molar Mass, ( M ) (kg/mol)</th>
<th>Molar Heat Capacity, ( C ) (J/mol · K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>910</td>
<td>0.0270</td>
<td>24.6</td>
</tr>
<tr>
<td>Beryllium</td>
<td>1970</td>
<td>0.00901</td>
<td>17.7</td>
</tr>
<tr>
<td>Copper</td>
<td>390</td>
<td>0.0635</td>
<td>24.8</td>
</tr>
<tr>
<td>Ethanol</td>
<td>2428</td>
<td>0.0461</td>
<td>111.9</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>2386</td>
<td>0.0620</td>
<td>148.0</td>
</tr>
<tr>
<td>Ice (near 0°C)</td>
<td>2100</td>
<td>0.0180</td>
<td>37.8</td>
</tr>
<tr>
<td>Iron</td>
<td>470</td>
<td>0.0559</td>
<td>26.3</td>
</tr>
<tr>
<td>Lead</td>
<td>130</td>
<td>0.207</td>
<td>26.9</td>
</tr>
<tr>
<td>Marble (CaCO3)</td>
<td>879</td>
<td>0.100</td>
<td>87.9</td>
</tr>
<tr>
<td>Mercury</td>
<td>138</td>
<td>0.201</td>
<td>27.7</td>
</tr>
<tr>
<td>Salt (NaCl)</td>
<td>879</td>
<td>0.0585</td>
<td>51.4</td>
</tr>
<tr>
<td>Silver</td>
<td>234</td>
<td>0.108</td>
<td>25.3</td>
</tr>
<tr>
<td>Water (liquid)</td>
<td>4190</td>
<td>0.0180</td>
<td>75.4</td>
</tr>
</tbody>
</table>

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Specific Heat: \([c] = \text{J/(kg*K)}\)
Molar Heat Capacity: \([C] = \text{J/(mol*K)}\)

- Rule of Dulong and Petit
  - The molar heat capacity for elemental solids is approximately constant \(25 \text{ J/(mol*K)}\)
  - number of atoms per mole is \(N_A\), heat needed to raise temperature of one atom same.
  - Atomic mass does not matter, only *how many atoms* matters.
  - Why? 1 molecule’s average KE = \(3/2 \text{kT}\)
  - Total energy per atom = KE + PE = \(3\text{kT}\)
    - SHM, PE like vibrating in 3D, equipartition of energy principle: each velocity component contributes \(1/2\text{kT}\) of energy per molecule

\[
C_V = 3R \approx 24.9 \text{ J/(mol*K)}
\]
(volume constant so that all energy goes internally, not used up to do work of expanding the volume)
14-3 Specific Heat

Heat in = Increase in Internal Energy – Work done on piston

Specific heats of gases are more complicated, and are generally measured at constant pressure ($c_p$) or constant volume ($c_V$).

Solids: usually measure $c_p$ at constant atmospheric pressure
Gas: $c_V$ usually easier to measure

$c_V$ and $c_p$ are different especially for gas

$c_V \leq c_p$
14-3 Specific Heat

Specific heats of gases are more complicated, and are generally measured at constant pressure ($c_p$) or constant volume ($c_V$).

Some sample values:

<table>
<thead>
<tr>
<th>Gas</th>
<th>$c_p$ (constant pressure)</th>
<th>$c_V$ (constant volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam (100°C)</td>
<td>0.482</td>
<td>0.350</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.218</td>
<td>0.155</td>
</tr>
<tr>
<td>Helium</td>
<td>1.15</td>
<td>0.75</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.199</td>
<td>0.153</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.248</td>
<td>0.177</td>
</tr>
</tbody>
</table>

14-4 Calorimetry—Solving Problems

Closed system: no mass enters or leaves, but energy may be exchanged

Open system: mass may transfer as well

Isolated system: closed system where no energy in any form is transferred

For an isolated system,

Energy out of one part = energy into another part

Or: heat lost = heat gained
The instrument to the left is a calorimeter, which makes quantitative measurements of heat exchange. A sample is heated to a well-measured high temperature, plunged into the water, and the equilibrium temperature measured. This gives the specific heat of the sample.

Another type of calorimeter is called a bomb calorimeter; it measures the thermal energy released when a substance burns.

This is the way the caloric content of foods is measured.
Example 5

• 0.150 kg sample of an alloy is heated to 540°C.
• It is then quickly placed in 0.400 kg of water at 10.0°C
  – c_water = 4186 J/(kgK)
• which is contained in an aluminum cup 0.200 kg
  – c_Al = 900 J/(kgK)
• The final temperature of the system is 30.5°C
• What is the specific heat of the alloy?
14-5 Latent Heat

Energy is required for a material to change phase, even though its temperature is not changing.

Test Your Understanding of Section 17.6 You take a block of ice at 0°C and add heat to it at a steady rate. It takes a time \( t \) to completely convert the block of ice to steam at 100°C. What do you have at time \( t/2 \)? (i) all ice at 0°C; (ii) a mixture of ice and water at 0°C; (iii) water at a temperature between 0°C and 100°C; (iv) a mixture of water and steam at 100°C.

Heat of fusion, \( L_F \): heat required to change 1.0 kg of material from solid to liquid

Heat of vaporization, \( L_V \): heat required to change 1.0 kg of material from liquid to vapor

\[ Q = mL \]
Water: fusion 333, vaporization 2260.

Makes sense?
Evaporation as a cooling process?

Example 6

- 1.5 kg water at 20°C
- Turn into ice, -12°C
- Energy needed?
Example 7

- 0.50 kg ice at -10°C
- 3.0 kg tea (water) at 20°C
- a) Will the final mixture be solid or liquid?
- b) What is the final temperature of the mixture?

14-5 Latent Heat

The total heat required for a phase change depends on the total mass and the latent heat:

\[ Q = mL, \quad (14-4) \]

Problem Solving: Calorimetry

1. Is the system isolated? Are all significant sources of energy transfer known or calculable?
2. Apply conservation of energy.
3. If no phase changes occur, the heat transferred will depend on the mass, specific heat, and temperature change.
4. If there are, or may be, phase changes, terms that depend on the mass and the latent heat may also be present. Determine or estimate what phase the final system will be in.

5. Make sure that each term is in the right place and that all the temperature changes are positive.

6. There is only one final temperature when the system reaches equilibrium.

7. Solve.

The latent heat of vaporization is relevant for evaporation as well as boiling. The heat of vaporization of water rises slightly as the temperature decreases.

On a molecular level, the heat added during a change of state does not go to increasing the kinetic energy of individual molecules, but rather to break the close bonds between them so the next phase can occur.
14-6 Heat Transfer: Conduction

Heat conduction can be visualized as occurring through molecular collisions.

The heat flow per unit time is given by:

$$\frac{Q}{t} = kA \frac{T_1 - T_2}{\ell}$$  \hspace{1cm} (14-5)

Protective tile (ceramic) used in space shuttle

- thermal conductivity: low or high?
- heat capacity: low or high?
The constant \( k \) is called the thermal conductivity.

Materials with large \( k \) are called conductors; those with small \( k \) are called insulators.

Air is a good insulator!

Wool sweater, fur
Building materials are measured using \( R \)-values rather than thermal conductivity:

\[
R = \frac{l}{k}
\]

Here, \( l \) is the thickness of the material.

**Example 14-8** Heat loss through windows. A major source of heat loss from a house in cold weather is through the windows. Calculate the rate of heat flow through a glass window 2.0 m \( \times \) 1.5 m in area and 3.2 mm thick, if the temperatures at the inner and outer surfaces are 15.0°C and 14.0°C, respectively (Fig. 14-7).

**Approach** Heat flows by conduction through the 3.2-mm thickness of glass from the higher inside temperature to the lower outside temperature. We use the heat conduction equation, Eq. 14-5.

**Solution** Here \( A = (2.0 \text{ m})(1.5 \text{ m}) = 3.0 \text{ m}^2 \) and \( l = 3.2 \times 10^{-3} \text{ m} \). Using Table 14-4 to get \( k \), we have

\[
Q = kA \frac{T_1 - T_2}{l} = \frac{(0.84 \text{ J/s} \cdot \text{m} \cdot \text{C}^{-1})(3.0 \text{ m}^2)(15.0^\circ \text{C} - 14.0^\circ \text{C})}{(3.2 \times 10^{-3} \text{ m})} = 790 \text{ J/s}.
\]

**Note** This rate of heat flow is equivalent to \( (790 \text{ J/s})/(4.19 \times 10^3 \text{ J/kcal}) = 0.19 \text{ kcal/s} \), or \( (0.19 \text{ kcal/s}) \times (3600 \text{ s/h}) = 680 \text{ kcal/h} \).
Convection occurs when heat flows by the mass movement of molecules from one place to another. It may be natural or forced; both these examples are natural convection.

Many home heating systems are forced hot-air systems; these have a fan that blows the air out of registers, rather than relying completely on natural convection.

Our body temperature is regulated by the blood; it runs close to the surface of the skin and transfers heat. Once it reaches the surface of the skin, the heat is released through convection, evaporation, and radiation.
The most familiar example of radiation is our own Sun, which radiates at a temperature of almost 6000 K.

The energy radiated has been found to be proportional to the fourth power of the temperature:

\[
\frac{Q}{t} = \epsilon \sigma A T^4, \quad (14-6)
\]

The constant \( \sigma \) is called the Stefan-Boltzmann constant:

\[ \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4 \]

The emissivity \( \epsilon \) is a number between zero and one characterizing the surface; black objects have an emissivity near one, while shiny ones have an emissivity near zero.
**Radiation**

- A good absorber is also a good emitter
- blackbody $e = 1$

- A reflector $e = 0$ (shiny, light colored objects)
  - is a bad absorber and bad emitter

**Dewar Flask**

- vacuum – no conduction, convection
- silver – great reflector, no radiation loss
Radiation

**EXAMPLE 14–9 | ESTIMATE | Cooling by radiation.** An athlete is sitting uncloth ed in a locker room whose dark walls are at a temperature of 15°C. Estimate the body’s rate of heat loss by radiation, assuming a skin temperature of 34°C and $\epsilon = 0.70$. Take the surface area of the body not in contact with the chair to be 1.5 m$^2$.

**APPROACH** We use Eq. 14–7, which requires Kelvin temperatures.

**SOLUTION** We have

$$\frac{Q}{t} = \epsilon \sigma A (T_1^4 - T_2^4)$$

$$= (0.70)(5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4)(1.5 \text{ m}^2)[(307 \text{ K})^4 - (288 \text{ K})^4] = 120 \text{ W.}$$

**NOTE** This person’s “output” is a bit more than what a 100-W bulb uses.

**NOTE** Avoid a common error: $(T_1^4 - T_2^4) \neq (T_1 - T_2)^4$.

---

Radiation

- resting person internal metabolism 100W
- Example, 120W loss
- Lose more energy than you make!
- Uncomfortable even if air is 25°C
- radiation ~ 50% heat loss in normal room!
- Comfortable: Floors/walls warmer, even if air is not so warm. Incubators
If you are sitting in a place that is too cold, your body radiates more heat than it can produce. You will start shivering and your metabolic rate will increase unless you put on warmer clothing.

If you are in the sunlight, the Sun’s radiation will warm you. In general, you will not be perfectly perpendicular to the Sun’s rays, and will absorb energy at the rate:

\[
\frac{Q}{t} = (1000 \text{ W/m}^2) \epsilon A \cos \theta, \quad (14-8)
\]
This cos $\theta$ effect is also responsible for the seasons.

Thermography—the detailed measurement of radiation from the body—can be used in medical imaging. Warmer areas may be a sign of tumors or infection; cooler areas on the skin may be a sign of poor circulation.
Summary of Chapter 14

• Internal energy $U$ refers to the total energy of all molecules in an object. For an ideal monatomic gas,

$$U = \frac{3}{2} nRT,$$

$$\text{internal energy of ideal monatomic gas}$$ (14-1)

• Heat is the transfer of energy from one object to another due to a temperature difference. Heat can be measured in joules or in calories.

• Specific heat of a substance is the energy required to change the temperature of a fixed amount of matter by 1° C.

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Summary of Chapter 14

• In an isolated system, heat gained by one part of the system must be lost by another.

• Calorimetry measures heat exchange quantitatively.

• Phase changes require energy even though the temperature does not change.

• Heat of fusion: amount of energy required to melt 1 kg of material.

• Heat of vaporization: amount of energy required to change 1 kg of material from liquid to vapor.

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Summary of Chapter 14

- Heat transfer takes place by conduction, convection, and radiation.
- In conduction, energy is transferred through the collisions of molecules in the substance.
- In convection, bulk quantities of the substance flow to areas of different temperature.
- Radiation is the transfer of energy by electromagnetic waves.