4 Energy

Learning Goals

After studying this chapter, students should be able to:

- distinguish between heat, temperature, and internal energy (p. 69);
- explain the relationship between heat and phase changes (pp. 70–73);
- apply the first law of thermodynamics to the atmosphere (pp. 74–78); and
- explain how energy is transferred as heat and work (pp. 78–84).

Summary

1. The **law of conservation of energy** states that energy can never be created or destroyed but can be transformed from one type to another and transferred from one object to another. Two forms of energy that are important in the atmosphere are **internal energy** and **radiant energy**.
2. Energy can be transferred as heat, work, or both. **Heat** transfers energy as a result of temperature differences. **Work** transfers energy by mechanical means. In the atmosphere, work is usually associated with the expansion or compression of air.
3. **Sensible heat** is associated with temperature changes, while **latent heat** is associated with phase changes. Specific heat is a property of a substance that determines how much its temperature will change in response to sensible heat transfer.
4. The **first law of thermodynamics** is a statement of the conservation of energy. It states that changes in internal energy are equivalent to transfers of energy as heat, work, or both.
5. Two thermodynamic processes that are important in the atmosphere are constant pressure processes and adiabatic processes. An **adiabatic process** is one in which temperature changes without adding or removing heat.
6. Heat is transferred by conduction, convection, and radiation. The transfer of heat by **conduction** is far more important in the ground than it is in the air. **Convection** transfers heat in fluids and is, therefore, an important heat transfer process in the atmosphere. **Radiation** can transfer heat through a vacuum, making it the only method by which heat transfer occurs from the sun to Earth and from Earth to space. Together, convection and radiation transfer heat between Earth's surface and the atmosphere.

Key Terms

Adiabatic process A thermodynamic process in which temperature changes without a transfer of heat (p. 76).

Conduction The transfer of heat between molecules in contact (p. 68).

Conductivity The property of a substance that describes its ability to conduct heat (p. 78).

Convection Vertical motions in a fluid that transfer the properties (e.g., heat) of that fluid (p. 68).

Deposition A phase change from gas to solid (p. 72).

Diabatic process A process in which temperature changes as a result of heat transfer (p. 78).

Electromagnetic waves Waves that are formed and propagated by oscillating electric and magnetic fields (p. 81).

First law of thermodynamics A law that states that a change in the internal energy of a substance is associated with the transfer of energy as heat or by work (p. 74).

Heat Energy in the process of being transferred from a warmer object to a cooler object (p. 68).

Internal energy The total energy contained within the atoms and molecules of a substance (p. 69).

Kinetic energy Energy associated with motion (p. 69).

Laminar boundary layer The layer of air in contact with Earth's surface, through which heat is transferred by conduction (p. 79).

Latent heat Heat associated with a phase change (p. 69).

Latent heat of fusion The amount of heat associated with the phase change of a substance between solid and liquid (p. 72).

Latent heat of vaporization The amount of heat associated with the phase change of a substance between liquid and gas (p.71).

Law of conservation of energy The law that states that energy cannot be created or destroyed but can be transformed from one form to another and transferred as heat or work (p. 68).

Mechanical convection Convection that is driven by mechanical forces (p. 79).

Poisson's equation An equation relating temperature and pressure for an adiabatic process (p. 77).

Potential energy Energy associated with position (p. 69).

Radiation The emission of energy as electromagnetic waves. This term is also used to denote the energy that travels in this way (p. 68).

Sensible heat Heat associated with a temperature change (p. 69).

Specific heat The amount of heat, in joules, required to raise the temperature of 1 kg of a substance by 1 K (p. 69).

Sublimation A phase change from solid to gas (p. 72).

Surface roughness The degree of irregularity of a surface (p. 80).

Thermal convection Convection that is driven by the density differences that result from temperature differences (p. 79).

Thermal energy That part of the internal energy of a substance that is associated with the kinetic energy of the molecules (p. 69).

Turbulence Random, irregular motions in a fluid (p. 79).

Wind shear A change in wind speed and/or direction in any direction across the flow (p. 80).

Key Equations

Heat flow (sensible heat)

$$Q = m\, c\, \Delta T$$

Latent heat of vaporization

$$Q = L_v\, m$$

Latent heat of fusion

$$Q = L_f\, m$$

First law of thermodynamics for constant pressure

$$Q = m\,c_v\,\Delta T + P\,\Delta V = m\,c_p\,\Delta T$$

Adiabatic process

$$c_p\,\Delta T = \frac{\Delta P}{\rho}$$

Poisson's equation

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{R_d}{c_p}}$$

Answers to Selected Review Questions (p. 85)

1. **How are heat, internal energy, and temperature different from one another?**

   Heat is the transfer of energy from warmer to colder objects. Internal energy is the total energy of the molecules in a substance—it includes both kinetic and potential energy. Temperature is a measure of the average kinetic energy of the molecules.

3. **How does a substance's specific heat influence its response to heat transfer?**
   Substances with high specific heats will warm or cool less than substances with low specific heats, given the same input or output of heat.

5. **Why is the heat involved in phase changes called latent, or hidden, heat?**

   It is called latent, or hidden, because there is no temperature change.

7. **In what ways are heat and work the same? In what ways are they different?**

   Heat and work are the same in that they both transfer energy. They are different in that heat transfers energy as a result of temperature difference and work transfers energy by mechanical means.

9. **Given the same input of heat, why will the temperature of an air parcel increase more in a constant volume of process than it will in a constant pressure process? Which process is applicable to the atmosphere? Why?**

   The temperature will increase more in a constant volume process because in a constant pressure process some of the heat is used in expansion of the gas. A constant pressure process is more applicable to the atmosphere because as the air expands, the pressure it exerts on the surrounding air does not change.

11. **How is heat transferred by a) conduction, b) convection, and c) radiation?**

    a) Conduction transfers heat from molecule to molecule through a substance or between substances. b) Convection transfers heat through the motions of liquids and gases. c) Radiation is a form of energy that travels as electromagnetic waves and, in the process, transfers heat.

Answers to Selected Problems (p. 85)

1. **If 10 mL of water condenses on a glass holding 300 mL of a cold drink, how much will the drink warm? Assume that all the latent heat released by condensation warms the drink and that the specific heat of the drink is the same as the specific heat for water (Note that 1 L of water weighs 1 kg.)**

   Step 1: Condense the water vapour.
   $Q = L_v\, m$
   $= (2.26 \times 10^6\ \text{J·kg}^{-1})\ (0.01\ \text{kg})$
   $= 22{,}600\ \text{J}$

   Step 2: Warm the water.
   $$\Delta T = \frac{Q}{m\,c}$$
   $$= \frac{22{,}600\,\text{J}}{(0.3\,\text{kg})(4186\,\text{J kg}^{-1}\,\text{K}^{-1})}$$
   $= 18\ \text{K}$

3. **How much heat does a freezer need to remove for 500 g of water at 20°C to be made into a block of ice at −15°C?**

   Step 1: Cool the water 20 K.
   $Q = m\ c\ \Delta T$
   $= (0.5\ \text{kg})\ (4186\ \text{J·kg}^{-1}\text{·K}^{-1})\ (20\ \text{K})$
   $= 41{,}860\ \text{J}$

   Step 2: Freeze the water.
   $Q = (0.5\ \text{kg})\ (3.34 \times 10^5\ \text{J·kg}^{-1})$
   $= 167{,}000\ \text{J}$

   Step 3: Cool the ice 15 K.
   $Q = (0.5\ \text{kg})\ (2100\ \text{J kg}^{-1}\text{·K}^{-1})\ (15\ \text{K})$
   $= 15{,}750\ \text{J}$

   Step 4: Add together the heat removed at each step:
   $41{,}860\ \text{J} + 167{,}000\ \text{J} + 15{,}750\ \text{J}$
   $= 224{,}610\ \text{J}$

5. **How much heat would be released into the atmosphere if 1 km^3 of ocean water cooled by 1ºC? (This problem shows that water stores a lot of heat!)**

   Mass of water: 1 km^3 = 1×10^{12} kg
   $Q = (1 \times 10^{12} \text{ kg})\ (4186 \text{ J·kg}^{-1}\text{·K}^{-1})\ (1 \text{ K})$
   $= 4.2 \times 10^{15}$ J

Study Questions

For suggested answers, see below.

1. What are the differences between thermal energy and potential energy?
2. Why does water have a high specific heat?
3. How can liquid water change to vapour at temperatures below 100°C?
4. How does a rough surface and a strong wind influence temperature with height?
5. How would temperatures at the surface and in the troposphere be different if radiation was the only heat transfer process?

Additional Problems

For answers, see below.

1. How much heat is needed to raise the temperature of 7 kg of gold by 15°C?
2. If 100,000 J of heat are added to 24 kg of asphalt, how much will the asphalt warm?
3. If 250 mL of water at 6°C is poured into a glass with a temperature of 22°C and a weight of 150 g, what will be the equilibrium temperature?
4. How much latent heat is released when 3 kg of water freezes?
5. How much latent heat is released when 36 kg of water evaporates?
6. How much heat is required to warm 800 g of water from ice at −9°C liquid at 13°C?
7. Calculate the total heat lost in cooling 1.5 kg of vapour at 108°C to an ice cube at −17°C.
8. In a column of air with a height of 3 km, a cross-sectional area of 2 m^2 and a density of 1.1 kg/m^3, how much heat must be added to raise its temperature by 1°C? How much of this heat is used in the expansion of the air?

9. Determine the temperature of an air parcel after it sinks from a height of 3500 m to a height of 1500 m. At 3500 m its temperature was −21°C and its pressure was 65.2 kPa. At 1500 m its pressure was 84.6 kPa.

10. How much latent heat is required for 4 L of water to vaporize? How much does the internal energy of the water molecules increase as a result of this phase change? (Note that 1 L of water weighs 1 kg).

Answers to Study Questions

1. Thermal energy is the part of internal energy of a substance that comes from the kinetic energy of the molecules because of the association between kinetic energy and temperature. Potential energy is associated with position and results from the attractive forces between the molecules (p. 69)

2. When water is heated, most of the increased internal energy is used to weaken the bonds between the molecules. This leaves only a small amount of energy for increasing the kinetic energy of the molecules. (p. 69)

3. Some surface molecules in a liquid have enough energy to become vapour. There is a range in the speed of the molecules; in liquids, the fastest ones will be able to escape from the surface. (p. 71)

4. These can generate vertical motions that mix the air forcing warm air down and cold air up. As a result, temperature is more uniform. (p. 80)

5. Far less heat transfer would occur. As a result, the Earth's surface would be over 60°C hotter on average and the temperature decrease with height in the troposphere would be greater. (p. 83)

Answers to Additional Problems

1. $Q = m\,c\,\Delta T$
   $= (7\text{ kg})\,(130\text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1})\,(15\text{ K})$
   $= 13{,}650\text{ J}$

2. $$\Delta T = \frac{Q}{m\,c}$$
   $$= \frac{100{,}000\,\text{J}}{(24\,\text{kg})\,(920\,\text{J kg}^{-1}\,\text{K}^{-1})}$$
   $= 4.5\text{ K}$

3. Heat lost by glass = heat gained by water
   $(0.15\text{ kg})\,(670\text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1})\,(22°\text{C} - \text{T}) = (0.25\text{ kg})\,(4186\text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1})\,(\text{T} - 6°\text{C})$
   $\text{T} = 7.4\text{ K}$

4. $Q = L_f\,m$
   $= (3.34 \times 10^5\text{ J}\cdot\text{kg}^{-1})\,(3\text{ kg})$
   $= 1{,}002{,}000\text{ J}$

5. $Q = L_v\,m$
   $= (2.26 \times 10^6\text{ J}\cdot\text{kg}^{-1})\,(36\text{ kg})$
   $= 81{,}360{,}000\text{ J}$

6. Step 1: Warm the ice 9 K.

$Q = m\ c\ \Delta T$
$= (0.8\ \text{kg})\ (2100\ \text{J kg}^{-1}\ \text{K}^{-1})\ (9\ \text{K})$
$= 15{,}120\ \text{J}$

Step 2: Melt the ice.

$Q = L_f\ m$
$= (3.34 \times 10^5\ \text{J}\cdot\text{kg}^{-1})\ (0.8\ \text{kg})$
$= 267{,}200\ \text{J}$

Step 3: Warm the water 13 K.

$Q = m\ c\ \Delta T$
$= (0.8\ \text{kg})\ (4186\ \text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1})\ (13\ \text{K})$
$= 43{,}534\ \text{J}$

Step 4: Add together the heat required at each step.

325,854 J

7. Step 1: Cool the vapour 8 K.

$Q = m\ c\ \Delta T$
$= (1.5\ \text{kg})\ (2040\ \text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1})\ (8\ \text{K})$
$= 24{,}480\ \text{J}$

Step 2: Condense the vapour.

$Q = L_v\ m$
$= (2.26 \times 10^6\ \text{J}\cdot\text{kg}^{-1})\ (1.5\ \text{kg})$
$= 3{,}390{,}000\ \text{J}$

Step 3: Cool the water 100 K.

$Q = m\ c\ \Delta T$
$= (1.5\ \text{kg})\ (4186\ \text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1})\ (100\ \text{K})$
$= 627{,}900\ \text{J}$

Step 4: Freeze the water.

$Q = L_f\ m$
$= (3.34 \times 10^5\ \text{J}\cdot\text{kg}^{-1})\ (1.5\ \text{kg})$
$= 501{,}000\ \text{J}$

Step 5: Cool the ice 17 K.

$Q = m\ c\ \Delta T$
$= (1.5\ \text{kg})\ (2100\ \text{J kg}^{-1}\ \text{K}^{-1})\ (17\ \text{K})$
$= 53{,}550\ \text{J}$

Step 6: Add together the heat lost at each step.

$= 4{,}596{,}930\ \text{J}$

8. Mass of the column: $6000\ m^3 \times 1.1\ kg \cdot m^{-3} = 6600\ kg$

Calculate the heat needed in a constant volume process (if the air did not expand).

$$
\begin{aligned}
Q &= m\ c_v\ \Delta T \\
&= (6600\ kg)\ (717\ J \cdot kg^{-1} \cdot K^{-1})\ (1\ K) \\
&= 4{,}732{,}200\ J
\end{aligned}
$$

Calculate the heat needed in a constant pressure process (allowing for the air to expand).

$$
\begin{aligned}
Q &= m\ c_p\ \Delta T \\
&= (6600\ kg)\ (1004\ J \cdot kg^{-1} \cdot K^{-1})\ (1\ K) \\
&= 6{,}626{,}400\ J
\end{aligned}
$$

Calculate how much heat is used in the expansion of the air.

$$
\begin{aligned}
W &= P\ \Delta V = m\ c_p\ \Delta T - m\ c_v\ \Delta T \\
&= 6{,}626{,}400\ J - 4{,}732{,}200\ J \\
&= 1{,}894{,}200\ J
\end{aligned}
$$

9. $$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{R_d}{c_p}}$$

$$
\begin{aligned}
T_2 &= \left(\frac{84.6}{65.2}\right)^{0.286} (252) \\
&= 271.5\ K \\
&= -1.5°C
\end{aligned}
$$

10. $$
\begin{aligned}
Q &= L_v\ m \\
&= (2.26 \times 10^6\ J \cdot kg^{-1})\ (4\ kg) \\
&= 9{,}040{,}000\ J
\end{aligned}
$$

$$
\begin{aligned}
W &= P\ \Delta V \\
&= (1.013 \times 10^5\ Pa)\ (6.684\ m^3 - 0.004\ m^3) \\
&= 676{,}684\ J
\end{aligned}
$$

$$
\begin{aligned}
\Delta U &= Q - W \\
&= 9{,}040{,}000\ J - 676{,}684\ J \\
&= 8{,}363{,}316\ J
\end{aligned}
$$