Course Learning Outcomes for Unit VII

Upon completion of this unit, students should be able to:

7. Describe fundamental thermodynamic concepts.
   7.1 Explain the various heat transfer mechanisms with practical examples.
   7.2 Recognize the ideal gas law and apply it to daily life.
   7.3 Describe the relationship between kinetic energy and the Kelvin temperature.

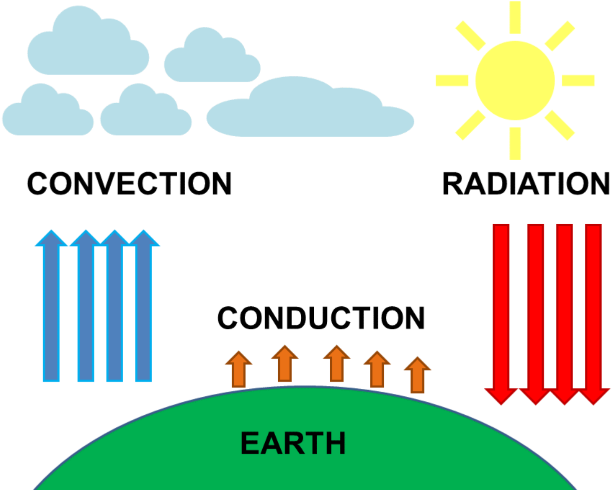
Required Unit Resources

Chapter 13: The Transfer of Heat

Chapter 14: The Ideal Gas Law and Kinetic Theory

Unit Lesson

The Three Methods to Transfer Heat



The above image illustrates the three heat transfer methods. The sun heats the Earth by radiation, the surface of the Earth heats the air by conduction, and the warm air rises by convection.

What is heat? *Heat* is energy that moves from a high-temperature object to a low-temperature object. Its unit is the Joule (J), but sometimes it is measured with the kilocalorie (kcal). The conversion factor between the two units is 1 kcal = 4186 J. The transfer of heat is processed by the following mechanisms.

Conduction is the process in which heat is transferred through a material. The atoms or molecules in a hotter part of the material have greater energy than those in a colder part of the material, and thus the energy is transferred from the hotter place to the colder place. Notice that the bulk motion of the material has nothing to do with this process. You can easily find examples of conduction. A radiator in your house is one of them. If you put an object on the radiator, the object will become warmer. Another example is when you pour the brewed hot coffee into a cold cup; the heat from the hot coffee makes the cup itself hot.

The heat Q conducted during a time t through a bar of length L and cross-sectional area A is expressed as

$Q = kA\,(dT)\,t\,/\,L$. Here, k is thermal conductivity, and it depends on the substance; dT is the temperature difference between the higher temperature and the lower temperature of the bar.

Convection is the process in which heat is transferred by the bulk motion of a fluid. According to the ideal gas law for constant pressure, the volume (V) is proportional to the temperature (T). V increases as T increases, and the density decreases within the constant mass. Warm air rises and cooler air goes down; this circulation makes the energy transported. The generated energy from the center of the sun is transported by convection near the photosphere. Cool gas sinks while bubbles of hot gas rise. There is a patchwork pattern of small (average diameter about 700 km), transient (average lifetime from 5 to 10 minutes) granules. The granulation is the visible consequence of the convection.

Radiation is the process in which heat is transferred by light, electromagnetic waves. An electromagnetic wave consists of an oscillating magnetic and electric field moving at the speed of light, c = 300,000 km/s. This method does not need a material medium, unlike the two other methods. Every object absorbs and emits electromagnetic waves at the same time. When an object absorbs and emits radiation perfectly, it is called a blackbody. The emitted light by a blackbody is called blackbody radiation, and its spectrum is a continuum because interactions between severely packed atoms are so strong that all detailed spectral features do not remain. Also, they are in thermal equilibrium, so blackbody radiation only depends on its absolute temperature, not on the chemical composition of the object.

After John Maxwell's theory of electromagnetism appeared in 1864, many attempts were made to understand blackbody radiation theoretically. None succeeded until in 1900 Max Planck postulated that electromagnetic energy can propagate only in discrete quanta, or photons, each with an energy of $E = h\nu$. This brilliant German physicist then derived the spectral intensity relationship, or Planck radiation law, a log-log plot between intensity and temperature. These masterpieces are a combination of classical works by Wien's law and Rayleigh-Jeans' law (Nave, n.d.). Wien expressed the wavelength λ_{max} at which the maximum intensity of blackbody radiation is emitted by Wien's displacement law: $\lambda_{max} = 2.898 \times 10^{-3} / T\ [m]$. Here, T is the surface temperature. For example, the continuum spectrum from our sun is approximately a blackbody, peaking at $\lambda_{max} \approx 500$ nm; therefore, the surface temperature must be near 5800 K. The emitted maximum flux of a star determines the color with the maximum intensity of blackbody radiation formula. Meanwhile, Rayleigh-Jeans' distribution works at high temperatures and long wavelengths, which have low frequencies (Nave, n.d.). It is useful to obtain the brightness temperature in radio astronomy. For further explanation, please visit the webpage "Blackbody Intensity".

The Sun's Influence on the Earth

The sun's violent activities such as erupting solar flares, coronal mass ejections, and solar winds are greatly influencing the Earth as well as the rest of the solar system. The sun is one of 200 billion stars that exist in the Milky Way galaxy. The size and mass of the sun are enormous. The size is about 1,390,000 km and the mass is 1.989×10^{30} kg. The sun possesses approximately 99.8% mass of the solar system. The surface of the sun is called the photosphere, a visible atmosphere with a depth of about 500 km, and its blackbody temperature is about 5800 K.

There are violent regions that can affect the Earth's environment, such as sunspots (11-year cycle), flares, and the corona. The sunspots look darker because the temperature is relatively lower, about 3800 K. They appear dark only against the bright sun and would still be brighter than the full moon when placed in the night sky! These spots are produced by magnetic field interactions, and the diameter of one is about 50,000 km. The magnetic field in the sunspots is about 1,000 times stronger than average. Hot gas ejected from the sun often follows the magnetic field line and traces out the loop structure of the magnetic field, called prominences. Sometimes we observe a brief eruption of hot, ionized gases from a sunspot group. This phenomenon is known as a *solar flare*. These magnetic storms are closely related to sunspot cycles. In 1 or 2 years after the maximum sunspots, non-repetitive magnetic storms follow, and then a strong aurora can be observed. Meanwhile, just after the minimum of sunspots, repetitive magnetic storms come, and then a weak aurora appears.

The above layer of the photosphere is called a chromosphere and has less dense gas with high temperature. We can detect visible UV and x-ray lines from highly ionized gases. Temperature increases gradually from about 4,500 K to 10,000 K, and then jumps to one million K. One distinctive feature is a spicule, which extends upward from the photosphere into the chromosphere along the boundaries of super granules.

Spicules are filaments of cooler gas from the photosphere that rise up into the chromosphere. Each of them can last about 5 to 15 minutes. The above of chromosphere is called a corona. The corona extends up to a few million kilometers, and the temperature is about several million K with an extremely low density. Coronal gas is heated through motions of magnetic fields anchored in the photosphere below. X-ray images of the sun reveal coronal holes. These arise at the footpoints of the open field lines and are the origin of the solar wind. A coronal mass ejection is a much larger eruption that involves immense amounts of gas from the corona. We can see the corona during a solar eclipse. The sun has a strong magnetic field, and the magnetosphere or heliosphere extends out beyond the orbit of Pluto.

The solar wind, the outflow of low-density charged particles (mostly electrons and protons), moves with a speed of 450 km/sec. An extreme magnetic phenomenon like an aurora on the Earth happens because of high energy particles from the solar wind and the flares. According to the solar wind research space probes such as *Wind*, *ACE*, and *SOHO*, there is a dynamically stable position, about 1.6×10^6 km from the Earth. Moreover, the solar wind affects the tail parts of comets and the orbits of space probes. The output of solar energy is not always constant. There was a minimum period of sunspot activity in the late 17th century, called the Maunder Minimum. This period was strangely consistent with the cold period, or the Little Ice Age in northern Europe. It is estimated that solar energy has been increased by about 40% since the formation of the sun. The age of the sun is about 4.5 billion years old. About half of the hydrogen has been consumed since the birth of the sun, so there are about 5 billion years left until the sun dies.

The solar wind can have a large influence on our planet, particularly in times of the active sun (near sunspot maximum) when the wind is strong and can contain bursts corresponding to flares and coronal mass ejections from the sun. The solar wind has a significant influence on our ionosphere, the Earth's magnetic field, on Earth's auroras, and on telecommunication systems. For example, there are reasons to believe that a burst of particles from a coronal mass ejection detected 5 days earlier by SOHO may have killed the Telstar 401 communication satellite on January 11, 1997 (National Aeronautics and Space Administration, n.d.).

Ideal Gas Law

When a gas has a very low density (where the average distance between molecules of the gas are very large), it is called an ideal gas. The ideal gas law is the relationship between pressure, volume, and temperature. More exactly, the absolute pressure (P) of an ideal gas is proportional to the temperature and is inversely proportional to the volume (V).

$$\boxed{PV = nRT = NkT}$$

Here, R is the universal gas constant, and n is the number of moles. One gram-mole of a substance contains as many particles (atoms or molecules) as there are atoms in 12 grams of the isotope carbon-12. According to experiments, 12 grams of C-12 have 6.022×10^{23} atoms. The number of atoms per mole is called Avogadro's number N_A. The ratio between the universal gas constant R and the number of moles n is defined as Boltzman's constant k. Please note, the product n and N_A is the total number of particles. So, the product of pressure P and volume V is expressed as NkT.

If the temperature is not changing, that is, T = constant, the pressure P is inversely proportional to the volume V of the gas: PV = constant. This is called Boyle's law. See Figure 14.7 in Section 14.2 of Chapter 14 in the eTextbook (Cutnell et al., 2022). The respiration through the lungs/alveoli allows the oxygen into and the carbon dioxide out from our bodies. When the lung volume increases by the contraction of the diaphragm and other respiratory muscles, the pressure of the lung decreases by Boyle's Law (PV = constant), and this leads the inward air movement to the lung.

If the pressure P is constant, the volume V is proportional to the temperature T: V / T = constant. This is called Charles' law.

Kinetic Theory of Gases

The kinetic theory of gases illustrates the microscopic behavior of elementary particles, and it describes the macroscopic picture of the motion. We assume that the number of particles is very large. Also, the separation between particles is large. The motion of particles is assumed to be random with a constant speed. The kinetic theory states that the kinetic energy of the gas particles is proportional to the Kelvin temperature of the system. The Kelvin temperature is also proportional to the product of the mass of the particles and the square of the *rms* speed of the particles. The internal energy of the gas is also related to its Kelvin temperature.

In this unit, we have explored the detailed mechanism of heat transfer methods with the behavior of the ideal gas. In addition, the kinetic theory and ideal gas law explain the various physical phenomena. In the next unit, we will utilize these concepts to understand thermodynamics laws.

References

Cutnell, J. D., Johnson, K. W., Young, D., & Stadler, S. (2022). *Physics* (12th ed.). Wiley.

National Aeronautics and Space Administration. (n.d.). *Telestar 401.* https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1993-077A#:~:text=Telstar%20401%20was%20an%20AT,video%20and%20data%2Dcommunications%20satellites.

Nave, R. (n.d.). *Blackbody intensity as a function of frequency*. HyperPhysics. http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html#c5

Learning Activities (Nongraded)

Nongraded Learning Activities are provided to aid students in their course of study. You do not have to submit them. If you have questions, contact your instructor for further guidance and information.

1. Solve Questions 35–44 under Physics in Biology, Medicine, and Sports in Chapter 13 of your eTextbook.
2. Solve Questions 49–59 under Physics in Biology, Medicine, and Sports in Chapter 14 of your eTextbook.