

Chapter 4: Transfer of Thermal Energy

Goals of Period 4

Section 4.1: To define temperature and thermal energy

Section 4.2: To discuss three methods of thermal energy transfer.

Section 4.3: To describe ways to minimize heat transfer

Section 4.4: To discuss insulation and R-values

4.1 Temperature and Thermal Energy

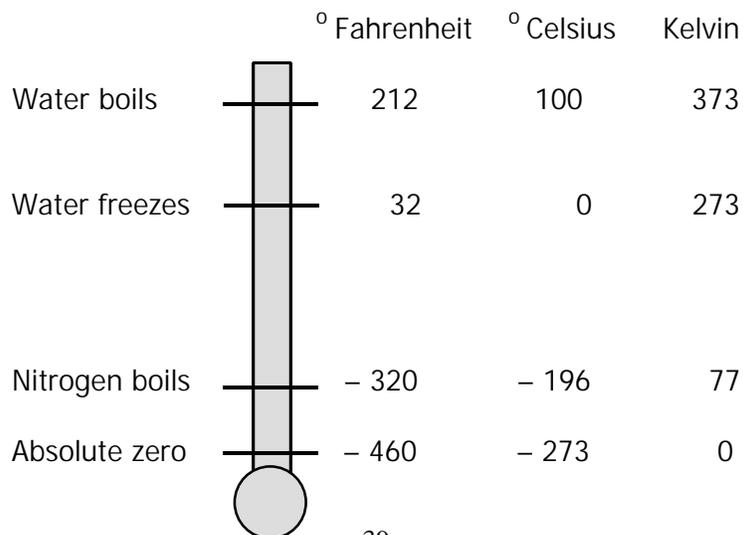
Temperature

Temperature is a measure of how hot or cold an object is. Many properties change as the temperature changes. For example, an object may change in size or a substance may change in **phase**, which means if it is gas, liquid or solid. In order to measure temperature, we use thermometers that make use of properties that change with temperature. Three temperature scales are commonly used for measuring temperature: the Fahrenheit, the Celsius and the Kelvin scales. Most of the world's population uses the Celsius temperature scale.

The Fahrenheit scale was developed in the 18th century by Ole Roemer and modified by Gabriel Fahrenheit. The zero point of the scale corresponds to the freezing point of a mixture of ice, water and salt, which was the lowest temperature that Roemer could obtain in his laboratory. When Fahrenheit began producing thermometers, he chose the normal temperature of the human body as the second reference point, and called it 96 degrees. In this scale, water freezes at 32 degrees and boils at 212 degrees.

In the Celsius scale, the freezing point of water is zero degrees, and the boiling point is 100 degrees. The Celsius scale is called a centigrade scale because there is 100 Celsius degrees between the freezing and boiling points of water. The Kelvin scale is another centigrade scale with zero as the lowest temperature that can be achieved theoretically. For this reason, zero Kelvin is called absolute zero. Zero Kelvin corresponds to -273 degrees Celsius. The degree size of the Kelvin scale is the same as the degree size of the Celsius scale, so that water freezes at 273 K and boils at 373 K.

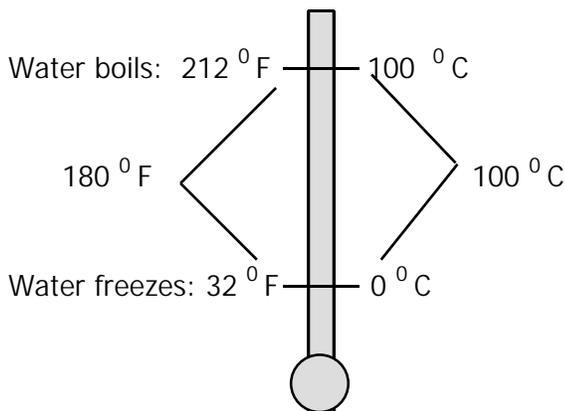
Figure 4.1 A Comparison of Temperature Scales



Microscopically, Kelvin temperature is a measure of the average kinetic energy of the atoms or molecules in a substance. As thermal energy is added to a substance, the motions of the molecules increase, and we say the substance is hotter. The microscopic picture will be examined more closely in the next period.

In the Fahrenheit scale there is a 180 degree difference between the boiling point and freezing point of water, as illustrated in Figure 4.2. In the Celsius scale there is a 100 degree difference between the boiling point and freezing point of water. Therefore, 180 Fahrenheit degrees correspond to 100 Celsius degrees. Using ratio reasoning, we find that there are 9 Fahrenheit degrees per every 5 Celsius degrees.

Figure 4.2 Fahrenheit and Celsius



$$\frac{180^{\circ}\text{F}}{100^{\circ}\text{C}} = \frac{9^{\circ}\text{F}}{5^{\circ}\text{C}}$$

We can use this relationship to convert from Fahrenheit to Celsius as shown in Equation 4.1. Since the freezing point of water is 32 degrees higher in the Fahrenheit scale than the Celsius scale, we add 32 degrees to the ratio to form an equation for converting Celsius temperatures to Fahrenheit.

$$T_F = 9/5 T_C + 32 \quad \text{(Equation 4.1)}$$

where

- T_F = temperature in degrees Fahrenheit
- T_C = temperature in degrees Celsius

Concept Check 4.1

- a) How many Celsius degrees correspond to 50 Fahrenheit degrees? _____
- b) What Fahrenheit temperature corresponds to 32 °C?

In class, we will use ratio reasoning to find that Equation 4.2 represents the conversion of degrees Fahrenheit to degrees Celsius.

$$T_C = 5/9 (T_F - 32) \quad \text{(Equation 4.2)}$$

Concept Check 4.2

- a) In the Celsius scale, water at sea level boils at 100 °C and freezes at 0 °C at sea level. What is the Celsius difference in temperature between boiling and freezing water? _____
- b) In the Kelvin scale, water boils at 373 Kelvin and freezes at 273 Kelvin. What is the Kelvin difference in temperature between boiling and freezing water? _____
- c) Using ratio reasoning, find how many Celsius degrees correspond to one Kelvin. _____
- d) Write an equation for the conversion of degrees Celsius to Kelvin.

$$T_K = \underline{\hspace{2cm}}$$

Thermal Energy

Thermal energy is the total internal energy of the atoms or molecules of a substance. Heat is thermal energy that is being transferred between two places and is measured in the same units as energy. However, there are units that are commonly used for thermal energy. In the British system of units, thermal energy is normally measured in British Thermal Units (BTU). In scientific work, the usual unit of thermal energy is the calorie (c) or the kilocalorie (C), which is 1000 calories. When describing the energy content of food, the "calories" listed are actually kilocalories. For example, a 240 "calorie" bag of chips contains 240 kilocalories or 240,000 calories (and 140,000 calories from fat).

(Example 4.1)

One calorie of energy equals 4.19 joules of energy. How many joules of energy does a 350 "calorie" doughnut contain?

The 350 "calories" are actually 350 kilocalories = 350,000 calories.

$$350,000 \text{ calories} \times \frac{4.19 \text{ joules}}{\text{calorie}} = 1,466,500 \text{ joules}$$

(Example 4.2)

Thermal energy is also measured in British Thermal Units (BTU). One BTU equals 253 calories. How many joules of energy equal one BTU? (Hint: one calorie equals 4.19 joules.)

Use ratio reasoning to convert units.

$$\frac{4.19 \text{ joules}}{1 \text{ calorie}} \times \frac{253 \text{ calorie}}{1 \text{ BTU}} = \frac{1,060 \text{ joules}}{\text{BTU}}$$

It is important to note that temperature and thermal energy are not the same thing. For example, you could have a cup of water and a bathtub of water at the same temperature, but there would be more thermal energy associated with the bathtub of water. When using thermal energy to get work done, the efficiency is calculated by finding the differences in the high and low temperatures divided by the low temperature. The Kelvin scale is used because the total energy of a substance is proportional to the temperature in Kelvin. Thus, the Kelvin scale is used when determining the efficiency of physical systems, such as a heat engine. A gasoline engine is one example that will be discussed in a future period.

Concept Check 4.3

You drop one piece of hot steel into a container of cold water at 2 °C. Then you drop two identical pieces of hot steel at the same temperature into a second container of cold water at 2 °C. After 15 minutes have passed, how will the temperatures of the water in the two containers compare?

4.2 Transfer of Thermal Energy as Heat

The transfer of energy as heat can take place via three processes: conduction, convection, and radiation. In conduction and radiation, energy transfers occurs without the transfer of mass. You will see several examples of all three of these processes throughout this period.

Conduction is the transport of thermal energy through an object by a series of collisions between adjacent atoms, molecules, or electrons. If one end of a metal spoon is held in a pan on a stove, the other end soon becomes hot. The energy from the stove causes the molecules in the end of the spoon that is in the pan to move faster, increasing the rate and size of their vibrations. These molecules transfer some of their extra kinetic energy to neighboring molecules and these, in turn, affect their neighbors. Therefore, the temperature of the entire spoon increases. If the pan is kept at a constant temperature, after some time the pan and the spoon will have the same temperature. No smart person would pick up this spoon without a potholder. The potholder is a poor conductor of heat and a good thermal insulator.

How rapidly an object transports thermal energy by conduction depends, in part, on what material the object is made of. This property is known as **thermal conductivity**. Table 4.1 on the next page lists the thermal conductivity of some common materials.

Convection is the transfer of thermal energy due to the motion of the substance that contains the thermal energy. Although the conduction process can occur in liquids and gases as well as solids, convection may have a much larger effect in liquids and gases where the molecules are free to migrate.

Table 4.1 Thermal Conductivity of Common Materials

Metals	Thermal Conductivity (J/s m °C)	Non-metals	Thermal Conductivity (J/s m °C)
Silver	420	Brick	0.84
Copper	380	Glass	0.84
Aluminum	237	Water	0.56
Brass	120	Cork	0.042
Iron	80	Wood	0.04
Nickel	<80	Air	0.023

A hot cup of coffee transfers thermal energy as heat to the surrounding air by convection. The heated air over the coffee expands and rises. The rising heated air is replaced by cooler, denser air, which, in turn, expands and rises. This circulation of air is an example of convection. Convection occurs because as the temperature is increased, most materials expand. This means that they become less dense. Thus, the warmer air near the hot coffee is buoyed up to the ceiling just as a piece of cork, which is less dense than water, rises to the surface of the water. When home furnaces were first introduced, most home heating systems relied on convection to circulate the warmer air. Now, the natural process of convection has been replaced by ducts and fans, which transfer the warm air.

Radiation, which is short for electromagnetic radiation, was discussed in chapters 2 and 3. We found that energy can be transferred by radiation from one location to another. No medium, such as air or water, is needed for the radiation to travel and transfer energy. It can pass through a perfect vacuum, as energy from the sun does in reaching earth. If you stand near an open fire such as a campfire, you notice that the side of you facing the fire becomes much warmer than the other side even if no wind is blowing. The explanation is that energy is transferred from the burning material to you via electromagnetic radiation. Of course, a small amount of energy is also transferred as heat via conduction and convection. For a campfire most of the radiant energy is infrared radiation.

It is important to realize that for heat to be transported between two points, a temperature difference between those two points must exist. That is, one point must be hotter than the other. Of its own accord, heat flows from regions of higher temperature to regions of lower temperature. To transfer thermal energy as heat from a cooler to a warmer region, work is required, just as work is required to lift a weight against gravity.

Concept Check 4.4

- a) A 10 lb block of lead at a temperature of 300 K sits on another 10 lb block of lead at 200 K. Both blocks fill a very well insulated box. What happens to the temperature of the 300 K block after 5 minutes have passed? _____

What happens to the temperature of the 200 K block after the same length of time has passed? _____

- b) Now each lead block is heated to the same temperature, 350 K, and placed one on top of the other in the well insulated box. How do the temperatures of the blocks compare after 5 minutes? _____

4.3 Minimizing Heat Transfer (Heat Flow)

In many cases, we wish to prevent heat transfer. For example, the less heat that leaves our home in the winter, the less energy (and money) we need to keep it comfortable. In cases where we are trying to minimize transfer of thermal energy, we must take all three kinds of heat transfer into account.

To understand how to limit heat transfer by conduction, let us consider a physical model for the process, such as heat flow through a wall. We have already discussed one factor that we would expect to make a difference, and that is the material of which the wall is made. The higher the thermal conductivity of the material, the faster heat would be transferred. However, thermal conductivity is a property of the material, and we also expect the shape and amount of the material to have an effect on heat transfer.

It is reasonable to expect that heat flow through a wall would increase as the area of the wall is increased and would decrease as the thickness of the wall is increased. It is also reasonable that the difference in temperature between the sides of the wall should make a difference: the greater the temperature difference, the faster we would expect heat to flow. These expectations can be written in equation form, as shown in Equation 4.3.

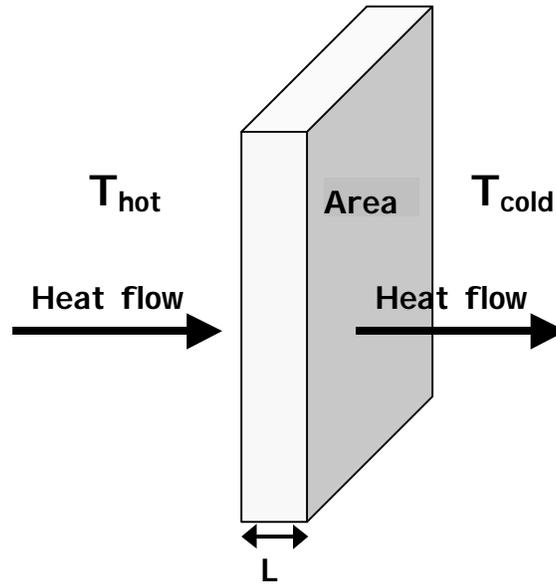
(Equation 4.3)

$$\text{Heat flow} = \frac{\text{energy transferred}}{\text{time}} = \frac{K A (T_{\text{hot}} - T_{\text{cold}})}{L}$$

where

- K** = the thermal conductivity (J/s m °C or BTU inch/hour foot² °F)
- A** = the cross sectional area (meters² or feet²)
- T** = temperature (°C or °F)
- L** = thickness (meters or inches)

Figure 4.3 Heat Flow through a Wall



(Example 4.3)

The heat flow through a 6 meter by 4 meter brick wall is 996 joules per second. The temperature on one side of the wall is 25 °C and the temperature on the other side is 5 °C. The thermal conductivity of brick is 0.83J/s m °C. What is the thickness of the wall?

Solve equation 4.3 for L :

$$L = \frac{K A (T_{hot} - T_{cold})}{E / t} = \frac{(0.83 \text{ J/s m } ^\circ\text{C}) \times (6 \text{ m} \times 4 \text{ m}) \times (25 \text{ } ^\circ\text{C} - 5 \text{ } ^\circ\text{C})}{996 \text{ J/s}} =$$

$$\frac{(0.83 \text{ J/s m } ^\circ\text{C}) \times (24 \text{ m}^2) \times (20 \text{ } ^\circ\text{C})}{996 \text{ J/s}} = 0.4 \text{ meters}$$

Concept Check 4.5

How much heat flows per second through a brick wall that is 3 meters by 3 meters in size and 10 cm in thickness. The temperature is 30 °C on one side of the wall and 10 °C on the other side. The thermal conductivity of brick is 0.83J/s m °C.

In building a wall that would limit the transfer of thermal energy by conduction, we typically would have the most control over the building material and the wall thickness.

Therefore, we would want to choose a material with a low thermal conductivity, and make it as thick as is possible.

Losses from convection can be reduced by obvious measures, such as plugging drafts and closing windows. Trapping pockets of air also prevents heat loss due to convection. Materials such as Styrofoam, fiberglass, wool, and down trap pockets of air and reduce thermal energy transfer by convection. A way to limit heat transfer by radiation is to reflect as much of the radiation as possible. This is why, for example, many thermos bottles are silvered on the inside.

4.4 Reducing Heat Transfer with Insulation

We often wish to minimize the amount of heat transferred between the inside and outside walls of homes and buildings. If we assume that we cannot change the outside temperature and we are not willing to reduce the wall area, we must make the wall of a very poor heat conductor and make it as thick as we can. The building industry has devised a ranking, or R-value, of the insulating properties of various materials based on their thickness and their thermal conductivity. The **R-value** of insulation is the ratio of the thickness of the wall to the thermal conductivity **K** of the material, as shown in Equation 4.4. The larger the R-value, the better the insulating property of the building material.

(Equation 4.4)

$$R = \frac{L}{K}$$

where

$$R = \text{the R-value of the material} \left(\frac{\text{m}^2 \text{ } ^\circ\text{C}}{\text{J/s}} \text{ or } \frac{\text{ft}^2 \text{ } ^\circ\text{F}}{\text{BTU/hr}} \right)$$

L = thickness (meters or inches)

K = the thermal conductivity (J/s m °C or BTU inch/hour ft² °F)

Table 4.2 R-Values of Common Materials

Material	R-Value (BTU/inch)	Material	R-Value (BTU/inch)
Glass	7.2	Vermiculite	2.20
Cellulose (blown)	3.67	Fiberglass (blown)	2.20
Rock wool (batting)	3.38	Air	1.44
Fiberglass (batting)	3.16	Wood (avg pine)	1.28
Rock wool (blown)	2.75	Wallboard	1.0
Perlite	2.75	Brick	0.11

Equation 4.3 can be used to calculate the heat flow using the thermal conductivity K and the wall thickness L .

(Equation 4.3)

$$\text{Heat flow} = \frac{\text{energy transferred}}{\text{time}} = \frac{K A (T_{\text{hot}} - T_{\text{cold}})}{L}$$

By substituting $R = L/K$, we can rewrite this equation, as shown in Equation 4.5.

(Equation 4.5)

$$\text{Heat flow} = \frac{\text{energy transferred}}{\text{time}} = \frac{A (T_{\text{hot}} - T_{\text{cold}})}{R}$$

where

A = the cross sectional area (meters² or feet²)

T = temperature (°C or °F)

R = the R-value of the material $\left(\frac{\text{m}^2 \text{ } ^\circ\text{C}}{\text{J/s}} \text{ or } \frac{\text{ft}^2 \text{ } ^\circ\text{F}}{\text{BTU/hr}} \right)$

(Example 4.4)

The heat flow through a 3 foot by 4 foot piece of plywood wall is 667 BTU per hour. The temperature on one side of the wall is 65 °F and the temperature on the other side is 30 °F. The plywood is 0.5 inches thick. What is the R-value of the plywood?

Solve equation 4.5 for R :

$$R = \frac{A (T_{\text{hot}} - T_{\text{cold}})}{\text{BTU/hr}} = \frac{(3 \text{ ft} \times 4 \text{ ft}) \times (65 \text{ } ^\circ\text{F} - 30 \text{ } ^\circ\text{F})}{667 \text{ BTU/hr}} =$$

$$\frac{(12 \text{ ft}^2) \times (35 \text{ } ^\circ\text{F})}{667 \text{ BTU/hr}} = \frac{0.62 \text{ ft}^2 \text{ } ^\circ\text{F}}{\text{BTU/hr}}$$

Period 4 Summary

4.1: Temperature is not the same as heat. Heat is energy in transfer.

Thermal energy is the total internal energy of the molecules and atoms of a substance.

Temperature is measured using the Celsius, Fahrenheit, and Kelvin scales.

Temperature in Kelvin is proportional to the average kinetic energy of the molecules and atoms.

4.2: The transfer of thermal energy as heat requires a difference in temperature between the two points of transfer.

Heat may be transferred by means of conduction, convection, or radiation.

Conduction is the transfer of thermal energy (heat in transfer) due to collisions between the molecules in the object. Collisions between adjacent atoms and molecules transfer kinetic energy from the warmer to the cooler object.

The objects must be in physical contact.

Convection is thermal energy transferred by the flow of matter.

Radiation is the transfer of energy by electromagnetic radiation. Radiation can travel in a vacuum.

4.3: Thermal conductivity **K** is a constant indicating how easily heat is transferred through a substance.

Heat transfer through a surface, such as a wall, can be minimized by reducing the area or the thermal conductivity of the wall or by increasing the thickness of the wall.

$$\text{Heat flow} = \frac{\text{energy transferred}}{\text{time}} = \frac{K A (T_{\text{hot}} - T_{\text{cold}})}{L}$$

4.4: The R-value of insulation is the ratio of the insulation thickness to the thermal conductivity: **R = L/K**

The heat flow equation can be written in terms of **R**:

$$\text{Heat flow} = \frac{\text{energy transferred}}{\text{time}} = \frac{A (T_{\text{hot}} - T_{\text{cold}})}{R}$$

Period 4 Exercises

- E.1 A practical handle for a hot pan can be made from each of the following EXCEPT
- a) a poor conductor of heat.
 - b) a thermal insulator.
 - c) plastic.
 - d) wood.
 - e) silver.
- E.2 In order for thermal energy to be transferred between two blocks of iron, the iron blocks
- a) must be in contact with each other.
 - b) must have different sizes.
 - c) must have different temperatures.
 - d) cannot be located in a vacuum.
 - e) must have different specific heats.
- E.3 Radiant energy is best absorbed by surfaces that are
- a) shiny.
 - b) black.
 - c) white.
 - d) smooth.
 - e) silvered.
- E.4 Warm air rises because
- a) it is more dense than the surrounding cooler air.
 - b) it is less dense than the surrounding cooler air.
 - c) it is just as dense as the surrounding cooler air but has a larger thermal, which forces it up.
 - d) hot objects always rise.
 - e) NONE of the answers is correct.
- E.5 If you stand next to a bonfire that is burning in the center of an open area on a calm day, most of the energy transferred to you as heat is transferred via
- a) conduction through open air.
 - b) convection through open air.
 - c) radiation.
 - d) sublimation.
 - e) diffusion.

- E.6 The heat flow through a 6 foot by 10 foot brick wall is 4,500 BTU per hour. The temperature on one side of the wall is 75 °F and the temperature on the other side is 50 °F. The brick is 3 inches thick. What is the R-value of the brick?
- a) 0.11 BTU/inch
 - b) 0.25 BTU/inch
 - c) 0.33 BTU/inch
 - d) 0.85 BTU/inch
 - e) 1.36 BTU/inch

Period 4 Review Questions

- R.1 What is temperature? What is heat? What is thermal energy?
- R.2 How is heat transferred to your hand if you touch a hot light bulb? If you place your hand beside (but not touching) a light bulb? If you place your hand above the light bulb?
- R.3 Why does an unheated waterbed feel colder than air at the same temperature?
- R.4 In class you touch pieces of glass, cork, and aluminum. Which felt the warmest? Why?
- R.5 Hot water or steam radiators warm a room primarily via radiation and by which other methods of heat transfer?