7.4.2 HEAT AND TEMPERATURE[M8]

Suppose we fill a large beaker and a small beaker with boiling water. The water in the two beakers is at the same temperature, but the water in the large beaker can give off more heat. It could, for example, melt more ice than could the water in the small beaker.

It is possible, therefore, for a body to be at a high temperature and give off little heat; to be at a high temperature and give off a large quantity of heat; to be at a low temperature and give off little heat; or to be at a low temperature and give off a large quantity of heat.

Heat is thermal energy that is absorbed, given up, or transferred from one body to another. The temperature of a body is a measure of its ability to give up heat to or absorb heat from another body. Thus, heat is a form of energy and the temperature of a body determines whether or not heat will be transferred to or from any nearby body.

When a material is hot, it has more thermal energy than when it is cold. Thermal energy is the total potential and kinetic energy associated with the random motion and arrangements of the particles of a material.

Temperature is the "hotness" or "coldness" of a material. The quantity of thermal energy in a body affects its temperature. The same quantity of thermal energy present in different bodies, however, does not give each the same temperature. The ratio between temperature and thermal energy is different for different materials.

The experiments of Count Rumford and James Prescott Joule show that mechanical energy and heat are equivalent and that heat must thus be a form of energy. Since thermal energy is also defined as a form of energy, you may wonder why two different terms-- thermal energy and heat-- are used.

An example will illustrate the difference. The temperature of the air in a bicycle tyre will rise when the tyre is being pumped up. It will also rise when the tyre is out in the sun. In both cases the thermal energy and the temperature of the air are increased. In the first case the work done in pumping was converted to thermal energy. In the second case the rise in temperature was due to energy transferred from the sun to the tyre. The term heat is used when the transfer of thermal energy from one body to another body at a different temperature is involved.

Temperature is defined in terms of measurements made with thermometers that will be described later. But the following qualitative definition gives the relationship between temperature and energy. Temperature is a physical quantity that is proportional to the average kinetic energy of translation of particles in matter.

7.4.2.1 Heat

The total heat energy of a substance is the total potential and kinetic energy of its particles:

In a gas the particles move freely. The hotter it becomes the more rapidly the particles move.

In a liquid the particles move less freely than in a gas. The motion of the particles increases with temperature.

In a solid the particles are free to vibrate, but do not move around. The particles vibrate more vigorously when a solid is heated.

7.4.2.1.1 Latent Heat

When a solid melts or a liquid boils, heat is needed to overcome the cohesive forces between the particles. In such state changes, a substance does not change temperature—the increased energy is stored in the form of potential energy.

The heat taken in or given out during a change of state is called **latent heat**. The heat energy required to change a substance from solid to liquid or liquid to gas, without change of temperature, is called **latent heat of fusion** or **latent heat of vaporisation** respectively.

7.4.2.1.2 Heat Capacity and Specific Heat

The heat content of a substance depends upon the kind and amount of matter in the substance. The **heat capacity** of a body is the quantity of heat needed to raise its temperature by 1 °C. A body with a high heat capacity warms more slowly because it must absorb a greater quantity of heat; it also cools more slowly because it must give off more heat. Water, for example, has a greater capacity for heat than any other common substance.

The **specific heat** of a body is the ratio of its heat capacity to its mass.

7.4.2.1.3 Heat Transfer

Thermal energy, or heat, always moves from hotter to colder regions, and there are three main ways in which this transfer can occur:

Conduction A mechanism whereby heat can be transferred through solids without the individual particles of the solid themselves moving or changing their positions.

The free electrons in metals make them the best conductors of both electricity and heat. As with electricity, most of the heat conducted through a metal is transmitted by its electrons.

Very poor conductors of heat are called **heat insulators**.

Convection A mechanism, typically found in liquids and gases, whereby heat is transferred via circulating currents of hot matter. These currents are established naturally whenever a temperature gradient exists in a fluid material, since warmer, less dense matter tends to rise while cooler, more dense matter tends to sink.

Radiation Hot objects emit energy in the form of electromagnetic radiation—both visible light, which we can *see*, and infrared rays, which we cannot see but which we can *feel*. When this radiation strikes an object it is absorbed, leading to excitation of the particles of the object and thus imparting heat energy.

This represents a way in which heat energy can, in effect, be rapidly transferred through a vacuum as well as through gases. Remember, however, that electromagnetic radiation is itself not heat, which is something that only a material object can possess.

7.4.2.1.4 Heat Absorption & Radiation

Dull, black objects absorb radiated heat more readily than bright, shiny objects, which tend to reflect it. While not quite as obvious, dull, black objects are also better radiators of heat than bright, shiny ones.

A process that gives off heat is known as an exothermic process—it will *feel* hot, since it generates heat. A process that absorbs heat as it progresses is known as an endothermic process—it will *feel* cold, since it absorbs heat from its environment.

In a closed system, the heat given off by hot materials is always equal to the heat received by cold materials.

7.4.2.1.5 Thermal Expansion

Solids, liquids and gases all expand when heated because their particles move more and thus take up more space.

The change in unit length of a solid when its temperature is changed by 1 °C is known as its **coefficient of linear expansion**. Different materials, however, expand at different rates when heated. This fact is exploited in the use of bi-metal strips—strips of two different metals, bonded together—in temperature switches (*e.g.* in a refrigerator).

The expansion of most liquids is also proportional to their increase in temperature. The behaviour of water, however, is exceptional in this regard—it reaches its maximum density at 4 °C, with the result that ice floats to the top of any body of water.

Suppose an expansion bulb is filled with pure water at 0 °C. As the bulb and water are warmed, the water gradually contracts until a temperature of 4 °C is reached. As the temperature of the water is raised above 4 °C, the water expands. Because the volume of water decreases as the temperature is raised from 0 °C to 4 °C, the mass density of the water increases. (The mass of the water is constant.) Above 4 °C the volume of water increases as the temperature is raised, and the mass density decreases. Therefore, water has its maximum mass density, 1.0000 g/cm^3, at 4 °C. Never Forget this!

This unusual variation of the density of water with the temperature can be explained as follows. When ice melts to water at 0 °C, the water still contains groups of molecules bonded in the open crystal structure of ice. As the temperature of water is raised from 0 °C to 4 °C, these open crystal fragments begin to collapse and the molecules move closer together. The speed of individual molecules also increases during the 0 °C to 4 °C interval, but the effect of the collapsing crystal structure predominates and the density increases. Above 4 °C the effect of increasing molecular speed exceeds the effect of collapsing crystal structure and the volume increases.

If water did not expand slightly as it is cooled below 4 °C, and expand much more as it freezes, the ice that forms on the surface of a lake would sink to the bottom. During the cold winter months, ice would continue to form until the lake was frozen solid. In the summer months only a few meters of ice at the top of the lake would melt.

However, because of the unusual properties of ice and water, no ice forms at the surface of a pond until all the water in it is cooled to 4 °C. As the surface water cools below 4 °C, it expands slightly and floats on the 4 °C water. Upon freezing at 0 °C, further expansion takes place and the ice floats on the 0 °C water.

7.4.2.1.6 Measuring Heat

There is no instrument that directly measures the amount of thermal energy that a body gives off or absorbs. Quantities of heat must be measured by the effects they produce. For example, the amount of heat given off when a fuel burns can be measured by measuring the temperature change in a known quantity of water that the burning produces. If one sample of coal warms 1.0 kg of water 1.0 °C, and another sample warms 1.0 kg of water 2.0 °C, then the second sample gives off twice as much heat.

A calorie is defined as the quantity of heat needed to raise the temperature of 1 g of water by 1 °C. The SI unit for heat, however, is the **joule**, the same as that for energy. The relationship between calories and joules is:

1 calorie = 4.1868 joules

7.4.2.1.7 Heat Appliances

An electric radiator warms a room by convection and radiation.

A vacuum flask cuts down heat transfer due to:

- Conduction, as it made of glass;
- Convection, since air is removed from between its walls;
- Radiation, because its walls are silvered.

The operation of the traditional Coolgardie Safe, or any evaporative cooler, depends on the fact that evaporating water absorbs heat—its latent heat of vaporisation—and thus cools its immediate environment. A refrigerator also makes use of the fact that latent heat is absorbed when a substance—the refrigerant—changes state from liquid to gas.

The refrigerator is an example a heat appliance that illustrates most of the aspects of heat and temperature we have discussed.

The illustration provides a schematic representation of the operational components of a refrigerator—it is essentially just a long pipe, joined to a compressor, forming a closed loop. The pipe has two distinct sections separated from each other by a fine jet. One consists of a coil *inside* the cabinet, the other a coil *outside*.

A refrigerator makes use of the fact that some gases can readily be changed to the liquid state by means of moderate pressure. A gas of this type (called the *refrigerant*) is present in the inside coil.

After the gas flows into the compressor, which is outside the cabinet, it is compressed. The gas particles are pushed together until they are close enough to be held by their own attractive forces, whereupon the gas becomes a liquid.

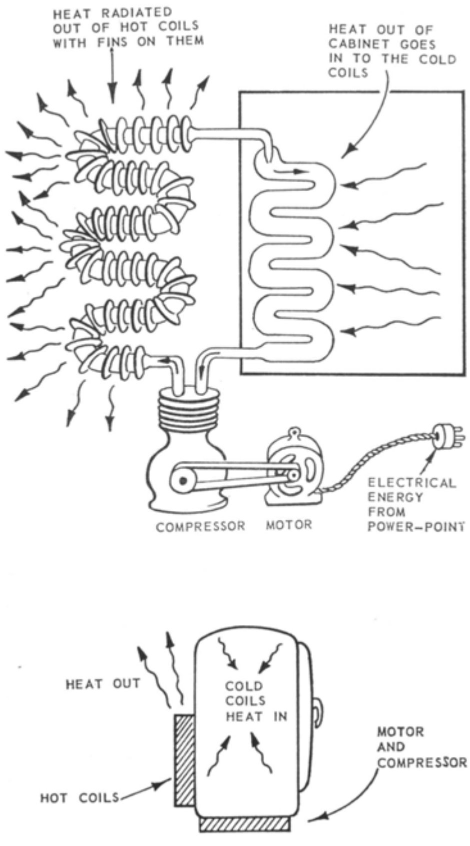

Figure 8.13 Schematic illustration of the main working units of a refrigerator

This change of state from gas to liquid is accompanied by the liberation of *latent heat*, so that the liquid that is sent from the compressor to the outer coil is quite warm. The function of the outer coil is to cool the liquid down to room temperature before it passes back into the cabinet interior. Therefore the outer coil is designed to lose heat as rapidly as possible, both by *radiation* and *convection*. To increase the rate of heat loss by radiation, the outer coil is painted black and is fitted with fins that increase its surface area. To ensure that a convection current will be maintained the outer coil is usually surrounded by a metal box, open at both the top and bottom. As warm air leaves the top of the box, cooler air enters from the bottom to take its place.

The outer coil is made of such a length that by the time the liquid s passing into the cabinet it has cooled down to room temperature, although it is still under pressure. It is then forced through the jet, into the low pressure section of the circuit, inside the cabinet. The reduction of pressure as the liquid passes through the jet results in its changing back to a gas. To do this, it must absorb heat—the *latent heat* of vaporisation—leaving the newly formed gas extremely cold. Heat then passes form the air in the cabinet into the refrigerant gas.

The cooling coil is located [inside and] at the top of the cabinet to ensure that *convection* currents are set up in the air inside the cabinet. As the air cools, it falls over the food on the shelves below. Warmer air rises to take its place and is in turn cooled.

The outside size of a refrigerator is so much larger than the inside because the thick walls are packed with insulation to minimise heat transfer [from outside to the inside] via *conduction*.

The natural way for heat to move is from hot objects to cold objects. It travels down a temperature gradient, like water travels downhill. A refrigerator makes heat travel in the opposite direction—from the cold air inside the cabinet to the warmer air outside. In this sense, a refrigerator acts as a heat pump. It pumps heat uphill, so to speak, against a temperature gradient just as a water pump makes water flow uphill against gravity.

7.4.2.2 Temperature

Temperature is a measure of the average kinetic energy of the particles in a substance. It is not the same as heat, although it is a measure of the degree of hotness of the substance, and has nothing to do with the total amount of matter. Temperature is a measure of how hot an object is.

7.4.2.2.1 Temperature Scales

Temperature is measured in degrees. The Celsius and Kelvin temperature scales are based on the triple point of water, which is the temperature at which the solid, liquid, and vapour phases of water can coexist.

The triple point of water is the SI standard for temperature. Its assigned value is 273.16 K (Kelvin). Originally, two fixed points were used to define standard temperature interval. They were the steam (the boiling point of water at standard atmospheric pressure) and the ice point (the melting point of ice when equilibrium with water saturated with air at standard atmospheric pressure).

The Celsius (or Centigrade) scale, devised by the Swedish astronomer Anders Celsius (1701 – 1744), is the most commonly used temperature scale. It is based on the freezing and boiling points of water at sea level, arbitrarily assigned the values of 0 °C and 100 °C respectively. One degree Centigrade (1 °C) is then defined as 1/100 of this temperature range.

The Fahrenheit scale, named after the German physicist Gabriel Fahrenheit (1686 – 1736) and originally used by most western countries, was abandoned as these countries adopted the Metric System, although it is still used in the USA for weather measurements. In this scale, the freezing point of water is assigned the value of 32 °F, its boiling point 212 °F and the range in between divided into 180 equal parts to define 1 °F.

The Kelvin scale is based on the definition of absolute zero, the temperature at which the kinetic energy of the molecules of all matter is at its minimum. Absolute zero is defined as 0 K (-273.16 °C) and 1 K = 1 C°.

The Rankine scale, named after the Scottish engineer and physicist William John Macquom Rankine, was an earlier absolute temperature scale (0 °R = 0 K) based on the Farenheit degree (*i.e.* 1 R° = 1 F°)

7.4.2.2.2 Thermometers

The most commonly used thermometers contain either mercury or alcohol (usually coloured red or blue). In both cases, the liquid volume increases rather uniformly with temperature over the useful range of the instruments. Thus, as the temperature of the thermometer bulb increases, the contents expand and rise up the thermometer tube in proportion to the increase in temperature.

Temperature sensors, used to measure temperature in many industrial and laboratory applications, depend on an electrical phenomenon known as the thermoelectric effect.

Note that thermometers measure temperature, not heat.