From " PHYSICS for Scientists & Engineers
SERWAY

HEAT TRANSFER

In practice, it is important to understand the rate at which heat is transferred between a system and its surroundings and the mechanisms responsible for the heat transfer. You may have used a Thermos bottle or some other thermally insulated vessel to store hot coffee (or ice water) for a length of time. The vessel reduces heat transfer between the outside air and the hot coffee. Ultimately, of course, the liquid will reach air temperature since the vessel is not a perfect insulator. There will be not heat transfer between system and its surroundings when they are at the same temperature.

HEAT CONDUCTION

The easiest heat transfer process to describe quantitatively is called heat conduction. In this process, the heat transfer can be viewed on an atomic scale as an exchange of kinetic energy between molecules, where the less energetic particles gain energy by colliding with the more energetic particles. For example, if you insert a metallic bar into a flame while holding one end, you will find that the temperature of the metal in your hand increases. The heat reaches your hand through conduction. The manner in which heat is transferred from the flame, through the bar, and to your hand can be understood by examining what happening to the atoms and electrons are vibrating about their equilibrium positions. As the flame heats the rod, those metal atoms and electrons near the flame begin to vibrate with larger and larger amplitudes. These, in turn, collide with their neighbors and transfer some of their energy in the collisions. Slowly, metal atoms and electrons farther down the rod increase their amplitude of vibration, until the large-amplitude vibration is an increase in temperature of the metal, and possibly a burned hand.

Although the transfer of the heat through a metal, can be partially explained by atomic vibrations and electron motions, the rate of heat conduction also depends on the properties of the substance being heated. For example, it is possible to hold a piece of asbestos in a flame indefinitely. This implies that very little heat is being conducted through the asbestos. In general, metals are good conductors of heat, and materials such as asbestos, cork, paper, and fiberglass are poor conductors. Gases also are poor conductors because of their dilute nature. Metal are good conductors of heat because they contain large numbers of electrons that are relatively free to move through the metal and can transport energy from one region to another. Thus, in a good conductor, such as copper, heat conduction takes place via the vibration of atoms and via the motion of free electrons.

The conduction of heat occurs only if there is a difference in temperature between two parts of the conducting medium. Consider a slab of material of thickness Δx and cross-sectional area A with its opposite faces at different temperatures T_1 and T_2, where $T_2 > T_1$. One finds from experiment that the heat ΔQ transferred in a time Δt flows from the hotter end to the colder end. The rate at which heat flows, $\Delta Q / \Delta t$, is found to be proportional to the cross-sectional area, the temperature difference, and inversely proportional to the thickness. That is $\Delta Q/\Delta t \sim A\, \Delta T/\Delta x$

It is convenient to use the symbol H to represent the heat transfer rate. That is, we take $H = \Delta Q/\Delta t$. For a slab of infinitesimal thickness dx and temperature difference dT, we can write the law of heat conduction

$H = - kA\, dT/dx$ (1)

where the proportionality constant k is called the thermal conductivity of the material, and dT/dx is the temperature gradient (the variation of temperature with position). The minus sign in equation (1) denotes the fact that heat flows in the direction of decreasing temperature.

Suppose a substance is in the shape of a long uniform rod of length L and is insulated so that no heat can escape from its surface except at the ends, which are in thermal contact with heat reservoirs having temperatures T_1 and T_2. When a steady state has been reached, the temperature at each point along the rod is constant in time. In this case, the temperature gradient is the same everywhere along the rod and is given by $dT/dx = (T_1 - T_2)/L$. thus the heat transfer rate is $H = kA\,(T_2 - T_1)/L$.

Substances that are good heat conductors have large thermal conductivity values, whereas good thermal insulators have low thermal conductivity values.

CONVECTION

At one time or another you probably have warmed your hands by holding them over an open flame. In this situation, the air directly above the flame is heated and expands. As a result, the density of the air decreases and the air rises. This warmed mass of air heats your hands as it flows by. Heat transferred by the movement of a heated substance is said to have been transfer by convection. When the movement results from differences in density, as in the example of air around the fire, it is referred to as natural convection. When the heated substance is forced to move by a fan or pump, as in some hot-air and hot-water heating systems, the process is called forced convection.

The circulating pattern of air flow at a beach is an example of convection. Likewise, the mixing that occurs as water is cooled and eventually freezes at its surface is an example of convection in nature. Recall that the mixing by convection currents ceases when the water temperature reaches 4 °C. since the water in the lake cannot be cooled by convection below 4 °C, and because water is a relatively poor conductor of heat, the water near the bottom remains near 4 °C for a long time. As a result, fish have a comfortable temperature in which to live even in periods of prolonged cold weather.

If it were not for convection currents, it would be very difficult to boil water. As water is heated in a teakettle, the lower layers are warmed first. These heated regions expand and rise to the top because their density is lowered. At the same time, the denser cool water replaces the warm water at the bottom of the kettle so that it can be heated.

The same process occurs when a room is heated by a radiator. The hot radiator warms the air in the lower region of the room. The warm air expands and rises to the ceiling because of its lower density. The denser regions of cooler air from above replace the warm air, setting up the continuous air current pattern.

RADIATION

The third way of transferring heat is through radiation. All object radiate energy continuously in the form of electromagnetic waves. The type of radiation associated with the transfer of heat energy from one location to another is referred to as infrared radiation.

Through electromagnetic radiation, approximately 1340 J of heat energy from the sun strikes 1 m^2 of the top of the earth 's atmosphere every second. Some of this energy is reflected back into space and some is absorbed by the atmosphere, but enough arrives at the surface of the earth each day to supply all of our energy needs on this planet hundreds of times over (if it could be captured and used efficiently). The growth in the number of solar houses in this country is one example of an attempt to make use of this free energy.

Radiant energy from the sun affects our day-to-day existence in a number of ways. It influences the earth 's average temperature, ocean currents, agriculture, rain patterns, and so on. For example, consider what happens to the atmospheric temperature at night. If there is a cloud cover above the earth, the water vapor in the clouds reflects back a part of the infrared radiation emitted by the earth and consequently the temperature remains at moderate levels. In the absence of this cloud cover, however, there is nothing to prevent this radiation from escaping into space, and thus the temperature drops more on a clear night than when it is cloudy.

The rate at which an object emits radiant energy is proportional to the forth power of its absolute temperature. This is known as Stefan 's law,and is expressed in equation form as $P = \sigma A e T^4$ (2)

e is a constant called the emissivity. The value of e can vary between zero and unity, depending on the properties of the surface.

An object radiate at the rate given by equation (2). At the same time, the object also absorbs electromagnetic radiation. If the latter process did not occur, an object would eventually radiate all of its energy and its temperature would reach absolute zero. The energy that a body absorbs comes from its surroundings, which consists of other objects which radiate energy. If an object is at a temperature T and its surroundings are at a temperature T_0, the net energy gained or lost each second by the object as a result of radiation is given by

$P_{net} = \sigma A e(T^4 - T_0^4)$.

When an object is in equilibrium with its surroundings, it radiates and absorbs energy at the same rate, and so its temperature remains constant. When an object is hotter than its surroundings, it radiates more energy than it absorbs and so it cools. An ideal absorber is defined as an object that absorbs all of the energy incident on it. The emissivity of an ideal absorber is equal to unity. Such an object is often referred to as a black body. An ideal absorber is also an ideal radiator of energy. In contrast, an object with an emissivity equal to zero absorbs none of energy incident on it. Such an object reflects all the incident energy and so is an ideal reflector.