THERMAL PROPERTIES OF MATTER

HEAT TRANSFER

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We have previously discussed conductors and insulators, materials that facilitate or impede heat transfer between objects. Now, let's delve into the intricacies of energy transfer rates. Consider the kitchen, where you may utilize a metal or glass pot to ensure efficient heat transfer from the stove to your cooking. On the other hand, your refrigerator is equipped with insulation material that hinders heat flow into the food stored inside. How can we articulate the distinction between these two types of materials?

The three primary mechanisms of heat transfer are conduction, convection, and radiation. Conduction takes place within a body or between two bodies in direct contact. Convection relies on the movement of mass from one region of space to another. Radiation involves heat transfer through electromagnetic radiation, such as sunlight, without the necessity for matter to be present in the space between the bodies.

Conduction

Imagine you're holding one end of a copper rod and exposing the other end to a flame. Surprisingly, the end you're holding starts getting hotter, even though it's not directly in contact with the flame. This phenomenon occurs because heat travels to the cooler end through conduction within the material.

On the atomic level, the atoms in the hotter regions possess, on average, more kinetic energy than their cooler counterparts. They transfer their energy to neighboring atoms, warming them in the process. These warmed atoms, in turn, pass on their energy to their neighbors, creating a chain reaction that extends throughout the material. It's crucial to note that, although the atoms themselves remain stationary within their respective regions of the material, the energy they carry manages to propagate across the material through this process.

Most metals utilize a highly efficient mechanism for heat conduction. Within the metal, certain electrons can disassociate from their parent atoms and move freely throughout the crystal lattice. These liberated or "free" electrons play a crucial role in swiftly transporting energy from hotter to cooler regions within the metal. As a result, metals generally exhibit excellent heat conductivity.

It's important to note that heat transfer exclusively takes place between regions with differing temperatures, and the direction of heat flow is always from higher to lower temperature. In Figure (a) depicted below, there is a rod composed of conducting material with a cross-sectional area denoted as A and a length denoted as L. The left end of the rod is maintained at a temperature T, while the right end is at a lower temperature, T_2, causing heat to flow from the left to the right. The rod's sides are enveloped by an insulating material, ensuring that no heat transfer occurs laterally.

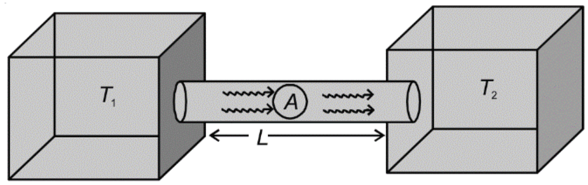

Fig.: (a) Steady state heat flow due to conduction in a uniform rod

When a quantity of heat, denoted as dQ, is transferred through the rod within a time interval dt, the rate at which heat flows is represented as $\frac{dQ}{dt}$. This rate is commonly referred to as the heat current and is denoted by H. Mathematically $H = \frac{dQ}{dt}$.

Experimental observations indicate that the heat current is directly proportional to the cross-sectional area A of the rod, as illustrated in Fig. (b). additionally, it is directly proportional to the temperature difference (T_1 - T_2) and inversely proportional to the length of the rod, L, as depicted in Fig. (c).

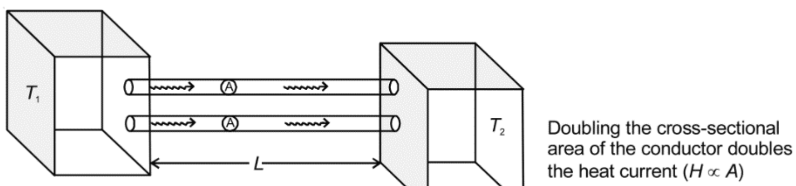

Fig.: (b)

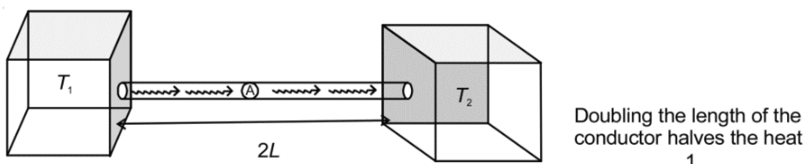

Fig.: (c)

Introducing a proportionality constant denoted as K, referred to as the thermal conductivity of the material, the relationship governing the heat current can be expressed as follows:

$$H = \frac{dQ}{dt} = \frac{KA}{L}\,(T_1 - T_2) \qquad \text{..... (i)}$$

Here, (T_1 - T_2) is the temperature difference per unit length, often termed as the magnitude of the temperature gradient. The constant K, known as the thermal conductivity, is specific to the material of the rod. Materials characterized by a large K are considered good conductors of heat, while those with a small K are deemed poor conductors or insulators. Equation (1) also describes the heat current through a slab or any homogeneous body with a uniform cross-section A perpendicular to the direction of flow, where L represents the length of the heat-flow path.

The unit of heat current, denoted as H or power, is essentially the unit of energy per unit time. In the International System of Units (SI), the unit for heat current is the watt, where 1 watt is equivalent to 1 joule per second (1 W = 1 J/s). The unit of thermal conductivity, denoted as K, can be determined using Equation (i), and it is expressed in SI units as watts per meter-kelvin (W/mK).

The thermal conductivity of stagnant (non-moving) air is notably small. Materials like a wool sweater provide insulation by trapping air between the fibers, and many insulating materials such as Styrofoam and fiberglass primarily consist of stagnant air.

In scenarios where the temperature varies no uniformly along the length of a conductor rod, a coordinate x is introduced to represent the length, and the temperature gradient is generalized as (-dT/dx). The corresponding generalization of Equation (i) is expressed as:

$$H = \frac{dQ}{dt} = -kA\frac{dT}{dx} \qquad \text{..... (ii)}$$

The negative sign signifies that heat always flows in the direction of decreasing temperature.