CHAPTER XII.

CONDUCTION OF HEAT.

164. Conduction.—When heat is applied to one end of a bar of metal it is propagated through the substance of the bar, producing a rise of temperature which is first perceptible at near and afterwards at remote portions. This transmission of heat is called *conduction.* The best conductors are metals, but all bodies conduct heat more or less.

165. Variable and Permanent Stages.—Whenever heat is applied steadily to one end of a bar for a sufficient length of time, we may distinguish two stages in the experiment: 1st, the variable stage, during which all portions of the bar are rising in temperature; and, 2nd, the permanent state, which may subsist for any length of time without alteration. In the former stage the bar is gaining heat; that is, it is receiving more heat from the source than it gives out to surrounding bodies. In the latter stage the receipts and expenditure of heat are equal, and are equal not only for the bar as a whole, but for every small portion of which it is composed.

In this permanent state no further accumulation of heat takes place. All the heat which reaches an internal particle is transmitted by conduction, and the heat which reaches a superficial particle is given off partly by radiation and air-contact, and partly by conduction to colder neighbouring particles. In the earlier stage, on the contrary, only a portion of the heat received by a particle is thus disposed of, the remainder being accumulated in the particle, and serving to raise its temperature. Hence in this earlier stage the transmission of heat from the hot to the cold portions of the bar is checked by the absorption which goes on in the intervening parts. The amount of this absorption which occurs before the final condition is attained will depend upon the capacity of the substance for heat.

166. Conductivity and Diffusivity.—We may thus distinguish between two modes of estimating conducting power. What is especially understood as "conductivity" is independent of absorption, and therefore of thermal capacity. In order to obtain direct measures of it we must observe the flow of heat when the temperatures have become permanent. On the other hand "diffusivity" (to use the name introduced by Lord Kelvin) measures the *tendency to equalization of temperature,* which varies directly as conductivity, and inversely as the thermal capacity of unit volume of the body.

If we compare the times occupied by two equal and similar bodies in passing from the same initial distribution of temperature to the same final distribution, these times will be in the inverse ratio of the diffusivities. If the diffusivities are equal, the times will be the same, and in this case the quantities of heat gained or lost by corresponding portions of the two bodies are directly as the thermal capacities of equal volumes.[1]

167. Definition of Conductivity.—In order to give an accurate definition of conductivity, we must suppose a plate having one face at a uniform temperature v_1, and the other at a higher uniform temperature v_2, and we must suppose all parts of the plate to have attained their permanent temperatures. Then if x denote the thickness of the plate, and k the conductivity of the substance of which it is composed, the quantity, Q, of heat that flows through an area, A, of the plate in the time t will be

$$Q = kA\frac{v_2 - v_1}{x}t; \tag{1}$$

whence we have

$$k = \frac{Qx}{A(v_2 - v_1)t}; \tag{2}$$

and the conductivity may be defined as the quantity of heat that flows in unit time through unit area of a plate of unit thickness, with 1° of difference between the temperatures of its faces.

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[1] The name *diffusivity* is employed by Lord Kelvin in the article "Heat" in the new edition of the *Encyclopædia Britannica.* The name *thermometric conductivity* had previously been used in the same sense by Professor Clerk Maxwell, ordinary conductivity being called *thermal conductivity* for distinction. There is a close analogy between the conduction of heat and the diffusion of liquids; and the coefficient which expresses the facility with which one liquid diffuses into another is precisely analogous to "thermometric conductivity." Hence the name "diffusivity."

When the unit of heat employed in the reckoning is that which raises the temperature of unit volume of water by 1° (a unit which is practically the same as the gramme-degree), the conductivity k may be defined as the *thickness of a stratum of water* which would be raised 1° in temperature by the heat conducted in unit time through a plate of the substance of unit thickness having 1° of difference between its faces.

If for the words *thickness of a stratum of water* we substitute *thickness of a stratum of the substance*, we have the definition of *diffusivity*.

The thicknesses of the two strata will evidently be inversely as the thermal capacities of equal volumes. But the thermal capacity of unit volume of water is unity. Hence the "diffusivity" is equal to the "conductivity" divided by the thermal capacity of unit volume of the substance. If this thermal capacity be denoted by c, we have $c=sd$, where s denotes the specific heat (or thermal capacity of unit mass) and d the density (or mass of unit volume), and the diffusivity κ is

$$\kappa=\frac{k}{c}=\frac{k}{sd}. \qquad (3)$$

Strictly speaking, k in equations (1), (2) is the *mean conductivity* between the two temperatures v_1, v_2, and the conductivity *at* any temperature v will be what k becomes when v_1 and v_2 are very nearly equal to each other and to v. The fact that conductivity varies with temperature was discovered by Forbes. He found that a specimen of iron which had a conductivity ·207 at 0° C. had only a conductivity ·124 at 275° C.

168. **Effect of Change of Units.**—In the C.G.S. (Centimetre-Gramme-Second) system, which we have explained in Part I., A is expressed in square centimetres, x in centimetres, and Q in gramme-degrees. It is immaterial whether the degree be Centigrade or Fahrenheit; for a change in the length of the degree will affect the numerical values of Q and of v_2-v_1 alike, and will leave the numerical value of $\frac{Q}{v_2-v_1}$, and hence of $\frac{Qx}{A(v_2-v_1)t}$, or k unaltered.

To find the effect of changes in the units of length and time, we must note that if the unit of length be x centimetres, the unit of area will be x^2 square centimetres, and the unit of mass, being the mass of unit volume of cold water, will be x^3 grammes. The new unit of heat will therefore be x^3 gramme-degrees.

The new unit of conductivity will be the conductivity of a substance such that x^3 gramme-degrees of heat flow in the new unit of time—which we will call t seconds—through x^2 sq. cm. of a plate x cm. thick, with a difference of 1° between its faces. The conductivity of such a plate, when expressed in C.G.S. units, would be found by putting

$$Q=x^3,\ A=x^2,\ v_2-v_1=1$$

in the formula

$$\frac{Qx}{A(v_2-v_1)t}$$

and would be $\frac{x^4}{x^2t}$ or $\frac{x^2}{t}$.

Hence to reduce conductivities from the new scale to the C.G.S. scale we must multiply them by $\frac{x^2}{t}$; and the same rule will apply to diffusivities, since the quantity c in equation (3) being the ratio of the thermal capacity of the substance to that of water, bulk for bulk, is independent of units.

169. **Illustrations of Conduction.**—The following experiments are often adduced in illustration of the different conducting and diffusing powers of different metals.

Two bars of the same size, but of different metals (Fig. 104), are placed end to end, and small wooden balls are attached by wax to their under surfaces at equal distances. The bars are then heated at their contiguous ends, and, as the heat extends along them, the balls successively drop off. If the conditions are in other respects equal, the balls will begin to drop off first from that which has the greater diffusivity, and the greatest number of balls will ultimately drop off from that which has the greater conductivity.

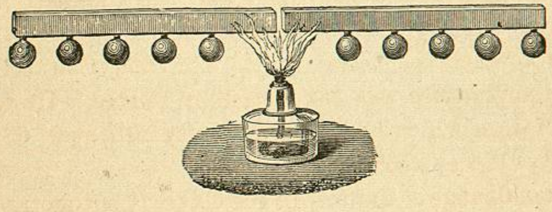

Fig. 104.—Balls Melted off.

The well-known experiment of Ingenhousz (Fig. 105) is of the same kind. The apparatus consists of a box, with a row of holes in one of its sides, in which rods of different metals can be fixed. The rods having previously been coated with wax, the box is filled with boiling water or boiling oil, which comes into contact with the inner ends of the rods. The wax gradually melts as the heat travels along the rods. The order in which the melting begins is the order of the diffusivities of the metals employed, and when it has reached its limit (if the temperature of the liquid be maintained constant) the order of the lengths melted is the order of their conductivities.

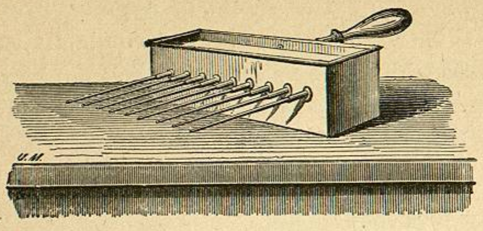

Fig. 105.—Ingenhousz's Apparatus.

170. Metals the Best Conductors.—Metals, though differing considerably one from another, are as a class greatly superior both in conductivity and diffusivity to other substances, such as wood, marble, brick. This explains several familiar phenomena. If the hand be placed upon a metal plate at the temperature of 10° C., or plunged into mercury at this temperature, a very marked sensation of cold is experienced. This sensation is less intense with a plate of marble at the same temperature, and still less with a piece of wood. The reason is that the hand, which is at a higher temperature than the substance to which it is applied, gives up a portion of its heat, which is conducted away by the substance, and consequently a larger portion of heat is parted with, and a more marked sensation of cold experienced, in the case of the body of greater conducting power.

171. Davy Lamp.—The conducting power of metals explains the curious property possessed by wire-gauze of cutting off a flame. If, for example, a piece of wire-gauze be placed above a jet of gas, the flame is prevented from rising above the gauze. If the gas be first allowed to pass through the gauze, and then lighted above, the flame is cut off from the burner, and is unable to extend itself to the under surface of the gauze. These facts depend upon the conducting power of metallic gauze, in virtue of which the heat of the flame is rapidly dissipated at the points of contact, the result being a diminution of temperature sufficient to prevent ignition.

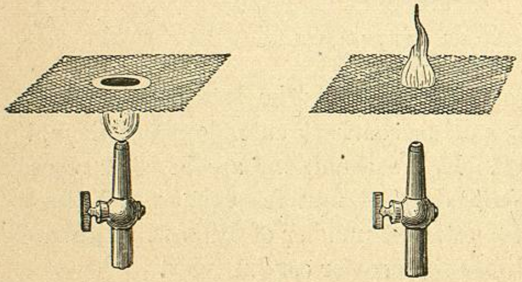

Fig. 106.—Action of Wire-gauze on Flame.

This property of metallic gauze has been turned to account for various purposes, but its most useful application is in the safety-lamp of Sir Humphry Davy.

It is well known that a gas called *fire-damp* is often given off in coal-mines. It is a compound of carbon and hydrogen, and is a large ingredient in ordinary coal-gas.

This fire-damp, when mixed with eight or ten times its volume of air, explodes with great violence on coming in contact with a lighted body. To obviate this danger, Davy invented the safety-lamp, which is an ordinary lamp with the flame inclosed by wire-gauze. The explosive gases pass through the gauze, and burn inside the lamp, in such a manner as to warn the miner of their presence; but the flame is unable to pass through the gauze.

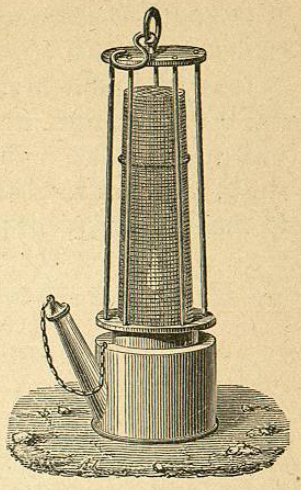

Fig. 107.—Davy Lamp.

172. Walls of Houses.—The knowledge of the relative conducting powers of different bodies has several important practical applications.

In cold countries, where the heat produced in the interior of a house should be as far as possible prevented from escaping, the walls should be of brick or wood, which have feeble conducting powers. If they are of stone, which is a better conductor, a greater thickness is required. Thick walls are also useful in hot countries in resisting the power of the solar rays during the heat of the day.

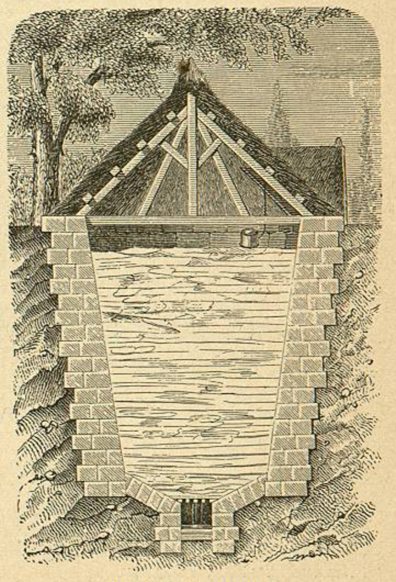

Fig. 108.—Ice-house.

We have already alluded (§ 56) to the advantage of employing fire-brick, which is a bad conductor, as a lining for stoves.

The feeble conducting power of brick has led to its employment in the construction of ice-houses. These are round pits (Fig. 108), generally from 6 to 8 yards in diameter at top, and somewhat narrower at the bottom, where there is a grating to allow the escape of water. The inside is lined with brick, and the top is covered with straw, which, as we shall shortly see, is a bad conductor. In order to diminish as much as possible the extent of surface exposed to the action of the air, the separate pieces are dipped in water before depositing them in the ice-house, and, by their subsequent freezing together, a solid mass is produced, capable of remaining unmelted for a very long time.

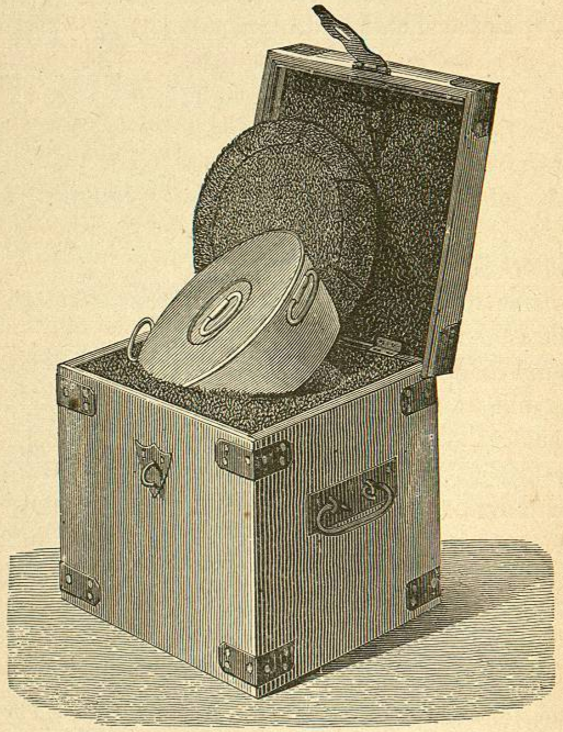

Fig. 109.—Norwegian Cooking-box.

173. Norwegian Cooking-box.—A curious application of the bad conducting power of felt is occasionally to be seen in the north of Europe in a kind of self-acting cooking-box. This is a box lined

inside with a thick layer of felt, into which fits a metallic dish with a cover. The dish is then covered with a cushion of felt, so as to be completely surrounded by a substance of very feeble conducting power. The method of employing the apparatus is as follows:—The meat which it is desired to cook is placed along with some water in the dish, the whole is boiled for a short time, and then transferred from the fire to the box, where the cooking is completed *without any further application of heat*. The resistance of the stuffing of the box to the escape of heat is exceedingly great; in fact, it may be shown that at the end of three hours the temperature of the water has fallen by only about 10° or 15° C. It has accordingly remained during all that time sufficiently high to conduct the operation of cooking.

174. Experimental Determination of Conductivity.—Several experimenters have investigated the conductivity of metals, by keeping one end of a metallic bar at a high temperature, and, after a sufficient lapse of time, observing the permanent temperatures assumed by different points in its length.

If the bar is so long that its further end is not sensibly warmer than the surrounding air, and if, moreover, Newton's law of cooling (§ 186) be assumed true for all parts of the surface, and all parts of a cross section be assumed to have the same temperature, the conductivity being also assumed to be independent of the temperature, it is easily shown that the temperatures of the bar at equidistant points in its length, beginning from the heated end, must exceed the atmospheric temperature by amounts forming a decreasing geometric series. Wiedemann and Franz, by the aid of the formula to which these assumptions lead,[1] computed the relative conducting powers of several of the metals, from experiments on thin bars, which were steadily heated at one end, the temperatures at various points in the length being determined by means of a thermo-electric junction clamped to the bar. The following were the results thus obtained:—

Relative Conducting Powers.

Silver,	100	Steel,	12
Copper,	77·6	Iron,	11·9
Gold,	53·2	Lead,	8·5
Brass,	33	Platinum,	8·2
Zinc,	19·9	Palladium,	6·3
Tin,	14·5	Bismuth,	1·9

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[1] See note B at the end of this chapter.