Heat Transmission and Wall Insulation.

By Dr. Ezer Griffiths.

THE practical man's insistence on simple "overall" coefficients has led to the accumulation of lengthy tables of empirical data for use in calculating the heat transmitted through such structures as cold stores, etc., but little attention has been devoted to a scientific study of the basic facts concerning the heat transfer. Consequently, the interesting phenomena presented by even the most elementary case—that of a heated surface placed vertically—have passed unnoticed until recently.

Here it is scarcely necessary to emphasise the fact that no simple coefficient will, under all conditions, permit of the calculation of the heat transmitted from the air inside to the air outside through a wall. The problem naturally resolves itself into a determination of the true thermal conductivity of the material and of the laws governing the transfer of heat from a surface to the surrounding air.

Conduction of Heat through the Wall Material.

In the case of a cold stores, the walls of which are made of considerable thicknesses of highly insulating material, it is the pure thermal conduction through the wall material which is the important factor to be considered. Under the auspices of the Food Investigation Board a wide range of materials has been studied in recent years at the National Physical Laboratory, Teddington. Special apparatus has to be devised for making tests on these materials of low conductivity.

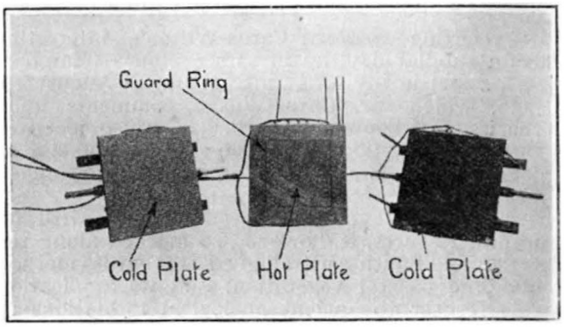


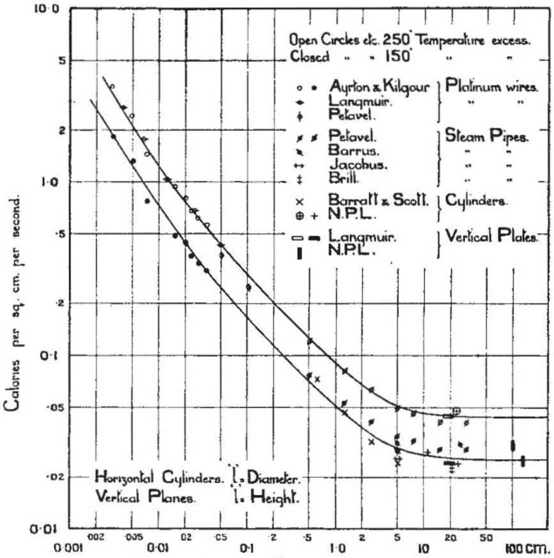
Fig. 1.

Of the many forms of apparatus devised for this work, that shown in the photograph (Fig. 1) has been found to be particularly convenient for carrying out the tests. Essentially it is a hot plate with "guard ring" around, which is inserted between two cold plates, with the material under test sandwiched in between. The resistor elements are made of nichrome strip threaded through suitably spaced holes in a sheet of micanite. Both hot plate element and "guard ring" element are carried on the one sheet of micanite.

The metal plates are of flat aluminium, the central area being entirely separated from the guard ring by a narrow gap. Insulation from the winding is effected by sheets of micanite. A series of copper constantan thermoelements are attached to the inner surfaces of the metal plates by rivets, and the couple wires are carried out in grooves milled in the plates. Thus the faces of the hot face and guard ring are free from protuberances.

The cold faces are made up of two surface plates of standard type. Each cold surface is maintained at a constant temperature by water circulation, and the surface plates are converted into hollow boxes by closing the back of each by a water-tight cover. Cuts are made in the webs of the surface plates, so as to permit of water or cold brine circulation. A series of small holes, into which thermocouples are inserted, are drilled in the plates parallel to the surfaces to various depths.

When the apparatus is used for powders and granulated material, the plates are kept apart by distant pieces, while solid test samples in the form of slabs are pressed in between the hot and cold plates. In the latter case, in order to eliminate the effect of contact resistance at the boundary between the surfaces of the metal and those of the test specimen, a set of disc thermocouples are placed on the faces of the samples. These couples are electrically insulated from the metal plates by the interposition of a single layer of blotting-paper on each face.



EFFECT OF SIZE AND CURVATURE ON HEAT LOSS BY CONVECTION.

Fig. 2.

The thermocouples then give the actual temperatures of the hot and cold faces of the specimens, and the couples permanently fixed in the apparatus are used merely for adjusting the temperature of the "guard ring" to exact equality with that of the hot plate.[1]

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[1] Data for various insulating and building materials have been published in the following reports and papers:—Special Report No. 5 of the Food Investigation Board on "Heat Insulators." Special Report No. 7 of the Building Research Board on "Heat Transmission through Walls, Concretes and Plasters." Trans. of the Faraday Society, vol. xviii., part 2, Dec. 1922, "Some Materials of Low Thermal Conductivity."

Transmission of Heat from the Wall Surface to Air.

The magnitude of the heat interchange between a hot surface and the medium in which it is situated is determined by the shape and orientation of the surface and the physical properties of the surrounding medium, such as its viscosity, density, specific heat, etc. The problem of calculating the actual quantity of heat emitted per unit area in any particular case is extremely complex, involving a combination of the Fourier equations of heat conduction with those of hydrodynamics. Even in the case of a plane surface, set vertically, the simplifying assumptions which have to be adopted to obtain a mathematical solution seriously restrict the usefulness of the results. Hence it has generally been found necessary to resort to an experimental investigation.

Taking for simplicity the case of a heated surface in air at ordinary temperatures and pressures, experiments were made to determine the variation of natural convection with (1) the temperature excess, (2) the dimensions of the hot object in the case of a horizontal cylinder the length of which is large compared with its diameter, and (3) the height in the case of a vertical surface.

The object of these experiments was the elucidation of the laws governing convection, and not the study of the specific case of the walls of a cold stores.

Horizontal Cylinders of Various Diameters.—It is found that the rate of heat loss per unit area depends upon the diameter for cylinders of diameters less than 20 cm. In Fig. 2 experimental results have been collected from various sources, corrected in a uniform manner for radiation and reduced to a standard temperature.[2] They refer to diameters varying from a few mils up to 30 cm. Owing to the wide range of diameters covered (10,000-fold), it is necessary to employ a logarithmic scale.

Effect of Temperature.—The law connecting the rate of heat loss by convection and the temperature was determined by experiments made with a polished aluminium surface 50 in. × 50 in., made up of two plates with a resistance grid clamped between them. It was found that the rate of heat loss varied approximately as the 5/4th power of the temperature excess of the surface above that of the surroundings. As will be shown later, the rate of heat loss is a function of both temperature and dimensions of the hot object.

Influence of the Height of the Wall on the Convection.

Vertical Surfaces.—Experiments have been made on vertical surfaces of various dimensions. It would be expected from general considerations that with any given vertical surface at a uniform temperature the heat loss by convection from the upper portion would be reduced, since the upper portions would be swept, not by cold air as in the lower portion, but by air already warmed.

For similar reasons it might be anticipated that the average heat loss per unit area from vertical surfaces would be relatively less for those of greater height. Lorenz, in working out the mathematical theory, deduced that the average heat loss per unit area for the entire surface would vary inversely as the fourth root of the height.

The experiments to be described demonstrate the fact that the phenomenon was not so simple as that postulated by Lorenz, and that the height effect cannot be represented by the simple $h^{-\frac{1}{4}}$ law.

The experiments took two forms: in one series a study was made of the heat loss from various elements of a vertical surface built up of separate adjacent units, and in the other the average heat loss per unit area was deduced from a study of the over-all effects determined by experiments on vertical surfaces of different heights.

(a) *Experiments on Wall constituted of Separate Elements.*—Each of the 25 elements constituting a 9 ft. high wall was separately heated and the energy supply controlled so that all the sections were at practically the same temperature. The form of the curve connecting heat loss per unit area and height is shown graphically in Fig. 3. It will be observed that the heat loss decreases with increasing height up to a certain point where it is a minimum, and then increases again and ultimately reaches an approximately steady value. The only plausible explanation of this minimum is that the stream line motion of the air persists up to a certain point only, beyond which turbulence sets in.

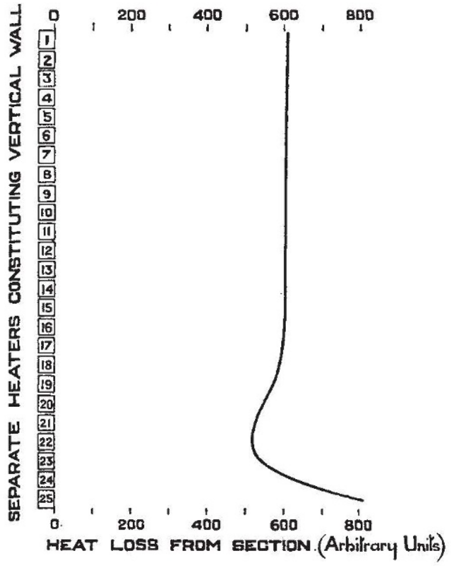

Fig. 3.

Confirmation of this theory was obtained by exploring the distribution of velocity and temperature in the convection stream past the plate by the aid of a linear type hot wire anemometer and resistance thermometer. It was found that above a certain height the strata nearest the plate did not increase appreciably either in temperature or in velocity. Consequently, they are not themselves carrying away the heat from the upper heaters, but are merely transmitting this heat to the outer layers, which by their increase in temperature and velocity carry it away. In this case the method of heat transmission through the close-lying strata can scarcely be pure conduction through stream-line layers, for the heat transfer is greater than gaseous conduction

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[2] Some data for various vertical plane surfaces are also added.

could ordinarily effect. Thus probably the motion of the air is turbulent, resembling rolling, any particle in effect alternately proceeding to the hot plate and then to outer cooler air in its progress upwards, thus actually carrying away the heat at a rate greater than could be the case if this turbulence were absent.

(b) *Variation with Total Height and with Temperature Excess.*—To investigate the matter further, a long electrically-heated cylinder was set up vertically and the heat loss was measured for various steady temperatures. The experiment was repeated with cylinders of different lengths obtained by cutting down the original cylinder, thus reducing the height, but leaving other details unchanged.

On plotting on logarithmetic paper the experimental data obtained with these cylinders, it was found that for each cylinder the results gave approximately a straight line; that is, a relation of the form $H \propto \theta^n$, where H is the heat loss by convection per unit area for a temperature excess θ° C.

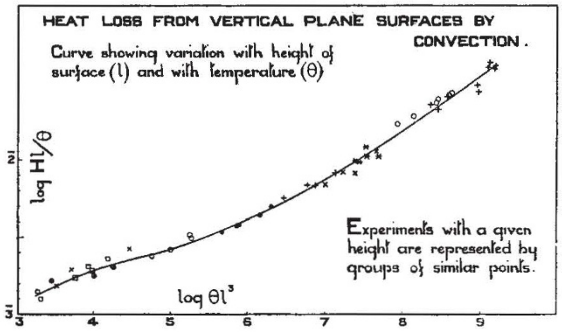

FIG. 4.

A study of the values obtained for *n* showed that the relation between convective heat loss and temperature excess depends upon the height of the wall, and, conversely, it may be shown that the effect of the height depends upon the temperature excess. This pointed to the important conclusion that the equation of heat loss cannot be expressed in such a form that the height and temperature excess are separate factors, but that these variables must be suitably grouped together.

Now the appropriate grouping of the variables may be deduced from the Principle of Similitude, following the general lines of Rayleigh's treatment for convection in a stream of fluid (NATURE, vol. 95, p. 66, 1915). Solving the "dimensional" equations, we find, when only the temperature and size of the hot body are variable, that

$$H = (\theta/l)\, F(\theta l^3)$$

where H is the heat loss per unit area per unit time;
θ = temperature excess of body;
l = linear dimensions of the body;
F denotes an unknown function of (θl^3).

The above formula is applicable only to bodies of similar shape, that is to say, the length, width, and depth of which are always in the same proportion. But with sufficiently wide vertical planes obviously the width will not appreciably affect the heat loss H per unit area, and it may, therefore, be assumed that the formula will also apply to these cases if it is taken to represent the height of the vertical surface. If the above grouping of variables is correct, it follows that points plotted for vertical surfaces with Hl/θ as ordinate and θl^3 as abscissa will all lie on one line, in spite of the fact that different heights (l) and different temperature excess θ are used. In Fig. 4, to cover the wide range, logarithmic values have been plotted, and it shows how well the points lie on a smooth curve.

The point of inflexion implies that there is a certain height for which the heat loss per unit area is a maximum or a minimum. The experiments on the wall composed of separate elements show that the minimum can be observed by direct experiment.

Another feature of the curve is that at its upper extremity it approximates to the form:

$$Hl/\theta = (\theta l^3)^{\frac{1}{3}},$$

i.e. $H \propto \theta^{\frac{1}{3}}$, and so is independent of the height and varies with the temperature according to a $\theta^{\frac{1}{3}}$ law. This is also confirmed by direct experiment. Hence there is strong support for the theory employed in correlating the rate of heat loss with the temperature excess and height.

The detailed account of these experiments will be found in Special Report No. 9 of the Food Investigation Board, entitled "The Transmission of Heat by Radiation and Convection," by E. Griffiths and A. H. Davis.

Local Immunity in Infectious Diseases.

THE usually accepted view that protection against pathogenic bacteria is due to the development of specific antibodies in the blood is disputed by Prof. Besredka of the Pasteur Institute. It is true that after recovery from any infection, or after inoculation with a vaccine consisting of the killed bacteria which cause this infection, the blood acquires properties which it did not possess before; for example, the power of clumping the bacteria or even killing or dissolving them. It was very natural to suppose that the development of these bodies in the blood is directly responsible for recovery from any infection or the failure of the particular organism to gain a footing in successfully vaccinated individuals. Prof. Besredka realised, however, that in certain cases a definite protection exists without the occurrence of such bodies in the blood, and he was led to the belief that their appearance is a secondary and not a necessary sequel to a protection acquired by the special cells which the particular organism preferred.

In the case of anthrax, to which the guinea-pig is very susceptible indeed, Prof. Besredka has proved by ingenious experiments that inoculation of the killed *Bacillus anthracis* into the peritoneal cavity or tissues other than the skin, is not followed by the development of antibodies in the blood, and that no protection against subsequent inoculation of the skin with living organisms is obtained. If, however, the killed organisms are applied to the skin, or, in other words, if the skin is vaccinated, a definite immunity is acquired and the guinea-pigs, which previously would have contracted a virulent infection by the inoculation