Chapter 3 Thermal Transmittance

Thermal Properties

of

Buildings

By

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13.2 THE DEVELOPMENT OF THERMAL TRANSMITTANCE

By the time Péclet wrote his *Traité de Chaleur*, the physical principles were better understood, mainly owing to the work of French physicists, including Péclet himself. Péclet(46) was well aware that the solid parts of the wall as well as the glass transmit heat from the inside to the outside of a building, although according to him "most designers size their equipment on the basis of the volume to be heated – an obvious error" (this in spite of Tredgold's treatise). He realised that the inside surface receives heat by convection from the air and by radiation from the surrounding surfaces; and that the loss from the outside surface occurs by the same processes. The laws of heat conduction between the two surfaces were known, and Péclet applied them to this problem.

The radiation loss from a surface was initially thought to follow Dulong and Petit's law, which they deduced in 1817. Their somewhat complex formula is now known to hold only approximately over the range of temperature covered by Dulong and Petit's experiments. The dependence of the radiation emitted upon the nature of the surface was studied by Leslie in his pioneer work on the absorption and emission of radiation. The relative radiating powers given by him are little different from present-day data. Leslie's results show clearly that the radiation is independent of colour as such. He was able to show that for radiation for these same wavelengths, the absorptive power was equal to the emissive power.

Sir Humphry Davy (*ca.* 1834) showed that the absorptive powers of different colours was different when the surfaces were exposed to sunlight. He found the order of decreasing absorption to be: black, blue, green, red, yellow, white. Hood was aware of Leslie's work, and dimly appreciated the dependence of the absorption on the kind of radiation received by a surface. He did not, however, apply it to considerations of the heat loss from buildings. Powell thought that sunshine contained no "simple heat" (i.e. low temperature radiation). "It was also established by the experiments of Melloni and Nobili that the radiating powers of surfaces, for simple heat, are in the inverse order of their conducting powers." This almost led Hood to conclude that poorly conducting materials should be used for heating surfaces; but he escaped this error by good fortune and a curious argument.

The convection loss was also investigated by Dulong and Petit, who found that this loss was independent of the nature of the surface, but did depend on its size and geometry.

Péclet carried out an extremely careful determination of radiation and convection losses, by observing the cooling of cylinders. He verified Dulong and Petit's laws of cooling (whose form he accepted without question). The cylinders were provided with a variety of surfaces (metal, textile, paper, paint). He also gave approximate expressions for the convection coefficient for surfaces of different shapes and dimensions.

Using his data, Péclet gave the total surface conductance of a masonry wall as 5.6 $kcal/m^2hC$, a value which he assumed to hold for both inside and outside surfaces, and for the interior of a cavity. He was aware that the surface coefficient should depend on the surface temperatures of the walls to which the surface could radiate: if these were the same as that of the surface being considered (as in a room with all surfaces equally exposed) then the radiation transfer is zero. The surface conductance is that due to convection alone. He thus demonstrated that for a room constructed entirely of glass the transmittance would be 1.45-1.65 kcal/m^2hC, whereas for a room with only one glass wall exposed to outside, the transmittance would be 2.48-2.65 kcal/m^2hC.

Although Box[12] repeated this calculation and Carpenter was also aware of it, the conclusion was ignored until Dufton (*ca.* 1935) revived it by proposing the use of equivalent temperature to estimate heat loss. Even then, no practical application was made until the 1970 issue of the IHVE Guide.

Picard[47] used Péclet's data, modified in respect of the convection coefficient. He chose values $h_c = 4$ for inside surfaces, and $h_c = 5$ for outside surfaces. The surface conductance was also studied by Rietschel and by Grashof. Rietschel quotes the formulae:

$$h_o = h_c + h_r + (0.0075\ h_c + 0.0056\ h_r)\ (t_{so} - t_o)^*$$

$$h_i = h_c + h_r + 0.0075\ (t_i - t_{si})$$

but he noted also that the terms with the multiplier involving temperature difference could usually be ignored. He used Péclet's value of $h_r = 2.91$ kcal/m^2hC. The values of h_c determined by Grashof were:

air at very low speeds (inside surface)	3.94 kcal/m^2hC
air at low speeds	4.90
air moving at moderate speed (outside surface)	5.91

These values seem probably to be the basis for Picard's and Rietschel's choice of convection coefficients.

The experiments of Griffiths and Davis in 1922 have provided the most accurate data for the loss of heat by convection and radiation. The existence of a power law for convection transfer was shown theoretically by Nusselt, who proved that the index should be 1.25 instead of the 1.233 given by Dulong and Petit. Griffiths and Davies[27] were able to show that theory and experiment agreed in this respect.

It is now known that the outer surface coefficient for heat transfer is by no means a constant, and can take zero or even negative values under certain conditions. The conditions under which low values may occur are those in which the surface is able to radiate to the night sky, and its temperature may fall below the outdoor air temperature. This difficulty is circumvented, at least to some extent, if sol-air temperature (which includes radiation effects) is employed instead of air temperature, analogously to the use of equivalent temperature instead of the indoor air temperature.

The thermal conductivity of materials was but imperfectly known. Péclet was once again the forerunner in the determination of this property.

Apart from the value for cork, his figures are of the same order as more recent determinations. Péclet's conductivity data were used by Carpenter (1910) and by Barker, and were quoted even as late as 1928 in Poynting and Thomson's *Textbook of*

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*t_o, t_i are outdoor and indoor air temperatures;
t_{so}, t_{si} are corresponding surface temperatures.

Physics,[48] though with the comment that "they probably need revision".

Péclet calculated the total heat loss through a wall by equating the surface transfers to the conduction through the solid. Thus he did not make use of the idea of resistance, although it is implicit in his final formula, which was identical with modern practice. Box[12] gave the symbol U to the quantity we now call thermal transmittance: this appears to be the first (and for many years, the only) use of this letter in this connection.

This method of computing heat losses seems to have been adopted in France and Germany (cf. Picard 1897 and Rietschel 1893-1911), though not in Britain or America, in spite of Box's famous *Treatise* which drew heavily on Péclet's work. Picard, for instance, gives a short table of transmittance, which he says was used in the European countries:[47]

25-cm brick wall, rendered	1.58 kcal/m^{2}hC
Single glass	3.66
Double glass	1.76
Roof	0.65
Wood floor	0.60
Metal roof	2.12

Rietschel's table was much more comprehensive.

We see that, by this time, the need to consider losses through the floor had been appreciated, though of course, in Picard's wood floor, the underside was not in contact with the ground, but the outdoor air.

Péclet had assumed that the floor and roof losses were negligible. He knew that the earth temperature at a depth of 8 m was constant throughout the year, at the mean annual temperature of the locality. Box goes on to state that beneath a building, the ground, being protected from the diurnal variations of atmospheric temperature, will take up the (constant) earth temperature. In Britain (and France), this is "pretty nearly the average temperature of our dwellings in the cold season" and the heat loss to the ground will be nothing.[12]

Rietschel made special additions to the computed or tabulated values of U to allow for variations in orientation or exposure to sun and wind. Debesson,[18] too, used thermal transmittance, and an addition of 2 or 3°C to the usual temperature difference for north-facing walls, and even up to 20-50° in very exposed cases.

The small attention paid to Box's book or to Péclet and Rietschel may be seen from Dye's *Plumbing and Sanitation* of 1897. He discussed a number of empirical rules for estimating heat losses and heating surface. Carpenter[14] suggested, for low-pressure hot water heating:

$$\text{Heating surface} = 0.4\ (\text{glass} + \tfrac{1}{4}\ \text{wall} + 2/55\ \text{volume}).$$

Lawler (USA) went so far as to say that it was "next to impossible to figure out the precise surface required". Dye himself proposed one ft^2 of surface for every 3 ft^2 of glass and 6 ft^2 per 1000 ft^3 of volume. He added that the wall area and the cubic capacity never both enter into the calculations; and of the two, the cubic capacity is the more reliable. It was also said that when low pressure steam was used, the heating surface was to be between 5/8 and $\frac{3}{4}$ of that for hot water (because of the higher temperature). For gravity warm-air systems, no data were available to compute the effectiveness of the furnace surface. It was customary to allow 10 ft^2 of heating surface to each 1000 ft^3 of room volume, or for each 4000 ft^3/h of ventilating air.

In 1904, Jones made a rather detailed comparison of the various proposed (empirical) methods of evaluating heat loss and radiator surface.(33) He found very large discrepancies between them. He admits that to ignore glass area, and to base heat requirements on room volume alone must be wrong; but nevertheless he gives a table based on volume only.

Jones goes on to give a later rule based on glass and wall areas, and on the volume of the room, similar in form to Carpenter's proposal:

$$\text{Radiating surface} = \left(\frac{\text{glass area}}{6} + \frac{\text{wall area}}{12} + \frac{\text{volume}}{120}\right) \quad \text{ft}^2$$

This applied to a hot water system with a mean water temperature of 170°F, designed to give an indoor temperature of 60°F when it is 30° outside. Two air changes per hour is allowed for ventilation. This formula appears to give an excessively large radiator surface, but Jones says that the formulae of Baldwin, Carpenter, Dye, etc. give much less, and claims that tests (which are not described) verified his rule.

The confusion which reigned at that time is well exemplified by Thomas, who, in 1906, wrote:(61)

> "There are quite enough books which give all the formulae for calculating the heating surface required as well as other figures and equations. The unfortunate part of these formulae and calculations is that they are absolutely beyond the brain power of the average hot-water engineer, while the difference between theory and practice makes it unwise to rely on such calculations."

By 1910, however, the present method was coming into use in the English speaking countries which were thus falling into line with continental Europe. Carpenter quotes some test data obtained by Wolff for the German Government, which are probably the first experimental determinations of thermal transmittance:

	U
Single window	1.09 Btu/ft^{2}h^{o}F
Single skylight	1.118
Double window	0.518
4 in brick	0.68
8 in brick	0.46
12 in brick	0.32

Eventually Carpenter, after reviewing all these data, concluded that for all practical purposes, the loss through a window should be taken as 1 Btu/ft^{2}hF and that through a wall, one quarter of this. Ceilings with attics over were to be treated as walls of one-third the area. Floors were ignored. This was, in fact a reversion to earlier practice in America.

Carpenter undertook two full-scale trials, and the results are of some interest:

	Trial A	Trial B
Area of glass, ft^2	96	9281
Area of wall, ft^2	246	31644
Temperature difference, ^{o}F	27-28	31
Measured loss, Btu/h	4247-4240	547200
Calculated loss, Btu/h	4253-4410	532952

These results were held by Carpenter to "indicate the substantial accuracy of the rule just quoted".[14] This must have been fortuitous, for Carpenter does not appear to have measured the ventilation loss. Neither did he compute the heat loss by the more correct method of which he was aware. Nevertheless, he apparently believed that "in a few years, the rule of thumb at present in use will drop out of use entirely and be replaced by rational scientific method."

By 1912, the design of US Federal buildings was based on *U*-values, with allowances for exposure and orientation.[62] The *U*-values were to be chosen according to the number of exposed walls (cf. Box). However, a rule-of-thumb method, like Carpenter's, could be used where windows were weatherstripped.

Barker, in 1912, also used the transmittance, and showed how it might be computed, drawing heavily on Rietschel's text. He writes of a material offering a "resistance to the flow of heat".[7] This seems to be the first use of the concept of thermal resistance, although it is not defined as such. Terminology was still confused; and Barker used the symbol *K* to denote almost every kind of heat transfer coefficient.

Barker also noted the influence of weather upon heat loss, and felt that the heating engineer needed exposure factors and weather factors for use with heat loss coefficients. He was less sanguine than Carpenter about full-scale trials, for he wrote:

> "Because of variations of outdoor temperature, it is and always must be difficult, if not impossible, to obtain a thoroughly satisfactory experimental verification on a large practical scale of the theory on which the calculations (of heat loss) are founded".

The more accurate, if more laborious, method of computing heat losses proposed by Péclet, and urged by Barker and Carpenter, was still not universally adopted. Dye, writing in 1917, gives it cautious approval:

> "Until recent years, it was practice to... allow a certain quantity of radiating surface per 1000 cubic feet of space... . The simple rule can seldom work out correctly. The coefficient method is now almost universally employed, and while this aims at meeting all varying conditions, there is a feeling that some improvement on this will presently be possible. For those who have not a suitable office staff, the method is distinctly tiresome, if not impossible in some cases... . While there is a feeling that the coefficients for heat losses from walls, roofs, glass, etc., are now fairly accurate, there always remains an uncertainty as to the changes of air."[23]

Raynes (1921) suffered from some confusion between the two quantities now termed transmittance and conductance.[51] He used Box's symbol *U* to denote the total hourly heat loss from a building. This was to be further modified by factors to take account of the height, aspect, exposure and intermittent heating.

Between 1910 and 1925, Barker in the UK and Harding and Willard in America made attempts to determine the thermal transmittance of a wall experimentally, using a hot-box method. Barker's values were:

	U
9-in London stock brick, unplastered	0.43 Btu/ft^2h^oF.
4½-in London stock brick, unplastered	0.57
12-in Cavity brick wall, unventilated, unplastered	0.33
12-in Cavity brick wall, ventilated, unplastered	0.42
4½-in Ballast concrete	0.61
6-in Ballast concrete	0.57

His results were adopted as standard by the IHVE in Britain.

In 1917, the German central heating industry published the first edition of its *Rules for Calculating Heat Losses*, and this was probably the first attempt to ensure uniformity of practice. The first DIN Rules, which superseded it, were published in 1929. The first ASHVE Guide appeared in 1922, while that of the IHVE was published in 1935. The first (1929) edition of the DIN Rules resulted in oversized plant; the 1944 version divided Germany into several "climate zones"; the 1959 edition used small "Zuschlage" to cater for a variety of circumstances, such as corner rooms.

In carrying out the calculation of hourly heat loss rate, it was usual to use the air temperature difference between indoors and out. It was assumed that the air temperature was that corresponding to comfort, and since it was known that lower air temperature could be used with radiant heating, an arbitrary reduction in the calculated heat loss was applied for this mode of warming. Around 1931, Dufton had suggested that the indoor equivalent temperature would be a sounder basis, and would eliminate the need for empirical corrections, either for cold walls or for different modes of heating. Although this was never embodied in the Guides, some designers used it in practice. The 1965 IHVE Guide, for example, referred to room temperature, and not air temperature, as a quasi-official recognition of the idea.

Between 1965 and 1970, workers at Building Research Station (England) turned again to Box, under the stimulus of preparing a code for the calculation of thermal transmittance, and introduced "environmental" temperature. With this index, U is a true constant property, and no corrections for number of exposed walls or mode of heating are necessary. (Exposure still remains, since it affects the outside surface resistance.) Dufton's proposal was seen to be valid on theoretical grounds, and has been incorporated in the latest IHVE (now CIBS) Guide.

Thermal transmittance of walls

We have seen that we can calculate the heat transmission through a material from a knowledge of the conductance and the surface temperatures. It has also been remarked that normally we do not know the temperatures of the surfaces, but only that of the air. We shall see that by making use of the surface resistances, we may proceed without a knowledge of the surface temperatures.

Suppose we have a wall, of thermal resistance R, whose surface temperatures are θ_{s_1} and θ_{s_2} (Figure 1.6). The air on one side has the temperature θ_i, and on the other θ_o. The flow of heat from the air to the surface, through the wall, and from the cold surface of the wall to the outside air must all be equal, for there can be no storage of heat or change of temperature in the steady state. We have therefore,

$$\frac{\theta_i-\theta_{s_1}}{R_{s_i}}=\frac{\theta_{s_1}-\theta_{s_2}}{R}=\frac{\theta_{s_2}-\theta_o}{R_{s_0}}=\frac{\theta_i-\theta_o}{R_{s_i}+R+R_{s_0}}=\frac{\theta_i-\theta_o}{R_t} \quad (1.16)$$

The reciprocal of the total thermal resistance R_t is termed the thermal transmittance, U, B.Th.U./ft.^{2} hr. °F. This is the quantity which is of the greatest practical importance in

Extract from BILLINGTON 1952

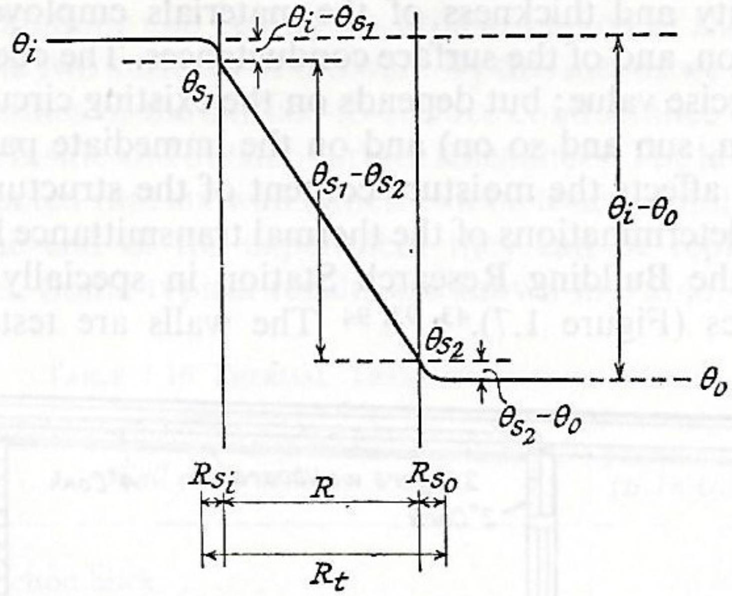

Fig. 1.6 Surface resistances and temperatures

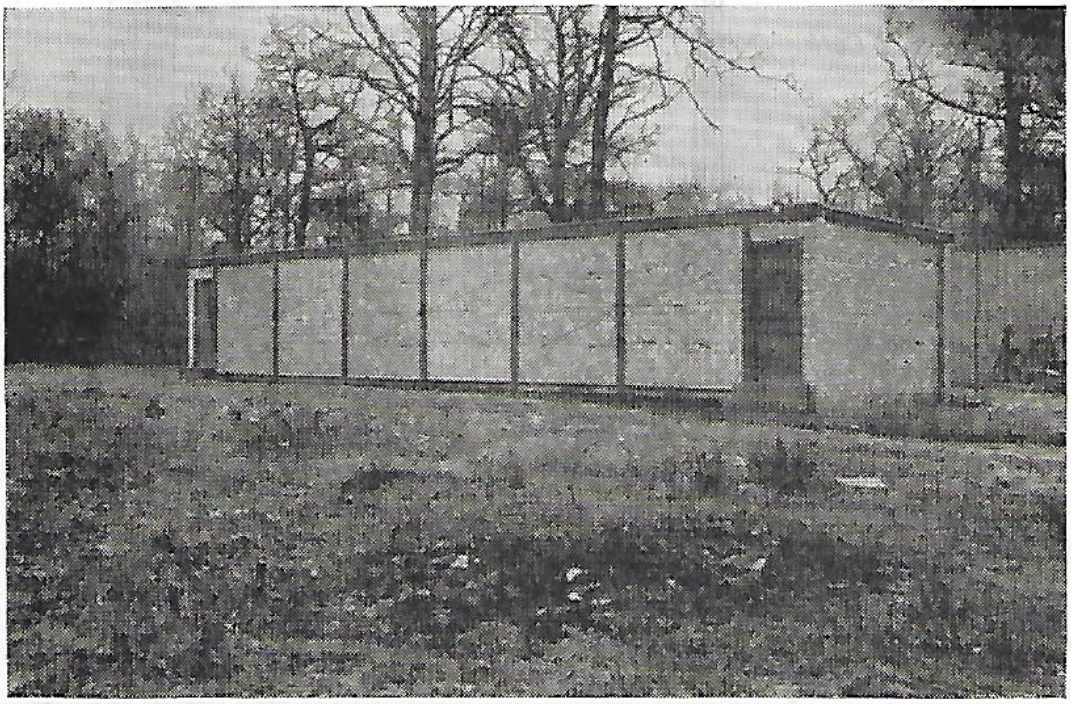

Fig. 1.7 Heat-transmission laboratory

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considering the heat loss from a warmed building. The numerical value indicates the rate of heat loss when conditions inside and outside the building are both steady. The lower the numerical value, the smaller is the heat loss through that part of the structure. The transmittance is a function of the thermal conductivity and thickness of the materials employed in the construction, and of the surface conductances. The coefficient U has no precise value; but depends on the existing circumstances (wind, rain, sun and so on) and on the immediate past history (since this affects the moisture content of the structure).

Direct determinations of the thermal transmittance have been made at the Building Research Station in specially designed laboratories (Figure 1.7).[43, 93, 94] The walls are tested in the

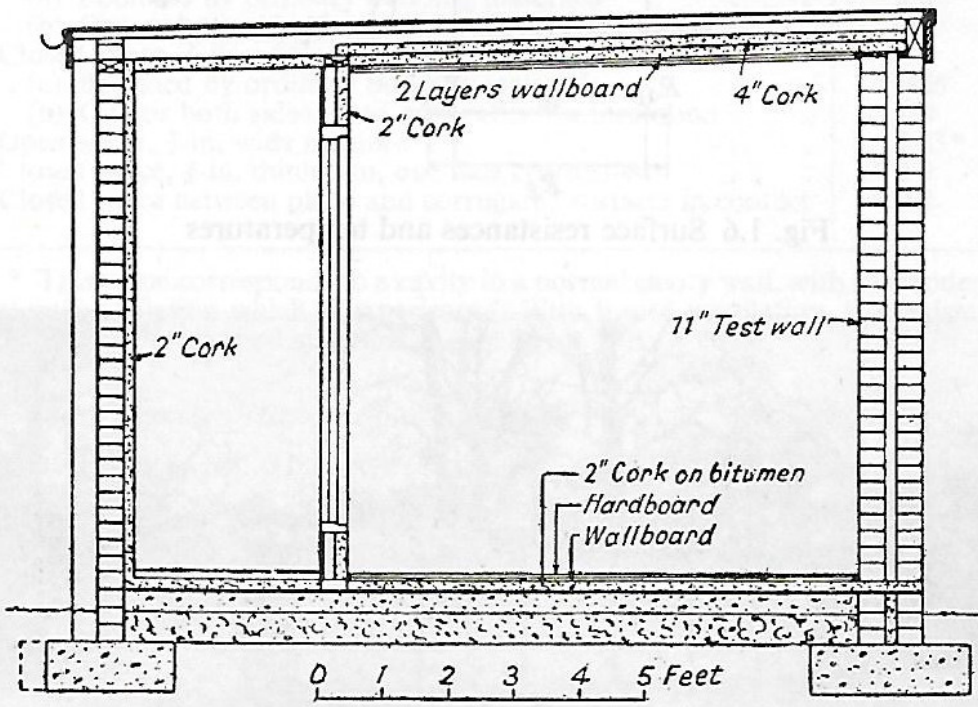

Fig. 1.8 Section through laboratory

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form of panels 8 ft. square, which form one wall of a cubical room (Figure 1.8). The test wall faces north, and is "normally" exposed to wind. The remaining walls, floor and ceiling of the room are heavily insulated to minimise the heat loss through them. The room is heated electrically to a constant temperature of 65° F., and the electrical energy supplied is metered. Practically the whole of the heat supplied escapes to outdoors through the test wall, a small correction being made for the losses through the other surfaces. The energy requirement can be correlated with meteorological data, and the thermal transmittance evaluated. Besides measuring the energy input, and the small losses