THE WARMTH OF FLOORS—A PHYSICAL STUDY*

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(With 9 Figures in the Text)

INTRODUCTION

It is commonly believed that a concrete floor feels cold, whereas a wood floor feels warm. It is not clear however, under what conditions this statement is supposed to be valid, if, in fact, it is true at all. Nevertheless, one supposes that it applies certainly to walking barefoot across the floor; and it is believed by many to apply also when shoes are worn. In common usage, however, no attempt is made to eliminate the factor of surface temperature.

In considering the problem, therefore, we must distinguish a number of factors. Firstly, the foot may be bare or shod. Secondly, the person may be walking (giving rise to momentary contact between the foot and the floor), or he may be standing or sitting (in which case the foot is in contact with the floor for several minutes at a time). Thirdly, the surface temperature of the floor may have some effect on the feeling of warmth or coldness. And finally, we must note the effect of the sub-floor on the feelings produced by a given floor finish.

It is well known that in the steady state the surface temperature of a floor depends solely on the thermal transmittance of the floor and the inside air and ground temperatures. Thus a floor with a high thermal transmittance will present a cooler surface to the room than will a well-insulated floor. A solid concrete floor laid on the ground (for which U is normally taken as 0·20 B.TH.U./ft.^{2}/hr./° F. difference between inside and outside air temperatures) would have a higher surface temperature than a ventilated wood joist floor, for which $U = 0{\cdot}25$ to $0{\cdot}40$. The steady state is, however, rarely attained in practice; and Mackey (1944) has shown that in the non-steady state, the instantaneous floor surface temperature will depend on the conductivity and volumetric specific heat of the materials, as well as on the transmittance. A floor finish for which the product (conductivity × volumetric specific heat) is small has a surface temperature which follows closely the air temperature in the room; and thus the amplitude of the temperature variations on such a floor is larger than in the case of a highly conducting dense floor finish, even though the mean temperatures may be the same in the two cases. Mackey's work, while not directly applicable to the immediate problem, does throw some light on the various factors involved.

EARLY WORK

Some early researches by German workers (Eichbauer, 1912; Reiher & Hoffman, 1930) are worthy of note. Their experiments were generally carried out in the laboratory, so that there was normally no temperature gradient through the sample. Eichbauer (1912) also did some measurements on actual floors. The effect of varying the surface temperature was not studied in any detail. These workers all made use of an artificial 'foot', consisting of a copper block, well insulated at the top and sides. The block was electrically heated, the input being adjusted so that when the block was suspended in air at 19° C. (66° F.), the temperature of the block was 38° C. (100° F.), or 40° C. (104° F.). The temperature of the block was measured by means of copper-constantan thermocouples embedded in it. Cooling curves were plotted from the time the block was placed on the specimen. It is worth noting that during this time heating was continued at the same rate as previously; and that temperature measurements were made at intervals of 1 or 2 min. for periods of up to an hour or more. Some of the results are shown in Figs. 1 and 2.

All the workers reported smooth cooling curves, of which the initial slope and final temperature depended on the nature of the floor finish.

Eichbauer found that for homogeneous floors of highly conducting material, the temperature of the block fell quickly and soon reached its steady state. For insulating materials such as cork, the initial temperature fall was slow, and the total cooling less. With wood floors, he found a rapid initial cooling, but this quickly levelled out to a slow fall in temperature. A similar effect was observed with multilayer floors where the finish was laid on some insulating material. Eichbauer also studied the effect of surface roughness: the rougher the floor, the slower was the cooling; but he found this not to be important save in the case of highly conducting finishes.

Reiher & Hoffman (1930) confirmed Eichbauer's results, and noted further that the initial cooling was dependent solely on the surface layer. This was true for periods up to about half a minute, after which the influence of the sub-floor could be detected.

THE PRESENT EXPERIMENTS

(*a*) *Apparatus*

The present experiments, made with a different form of apparatus, confirm and extend the findings of the German workers. The apparatus used is illustrated in Fig. 3. It consists of a metal canister, fitted with a thick, flat copper base. The canister is insulated on top and at the sides. The temperature of the under surface of the 'foot' is measured by copper-constantan thermocouple wires attached to the base of the canister, and connected to a sensitive galvanometer.

150 cm.^{3} of water, at about 120° F., are placed in the canister, and stirred continuously. The canister is allowed to cool on a slab of cork, a cooling curve being plotted. When the water temperature has fallen to 100° F., the canister is quickly transferred to the specimen, and readings of the base temperature are taken at 10 sec. intervals for 2 min., and thereafter less frequently. The duration of the experiment may be from 5 to 15 min. When the

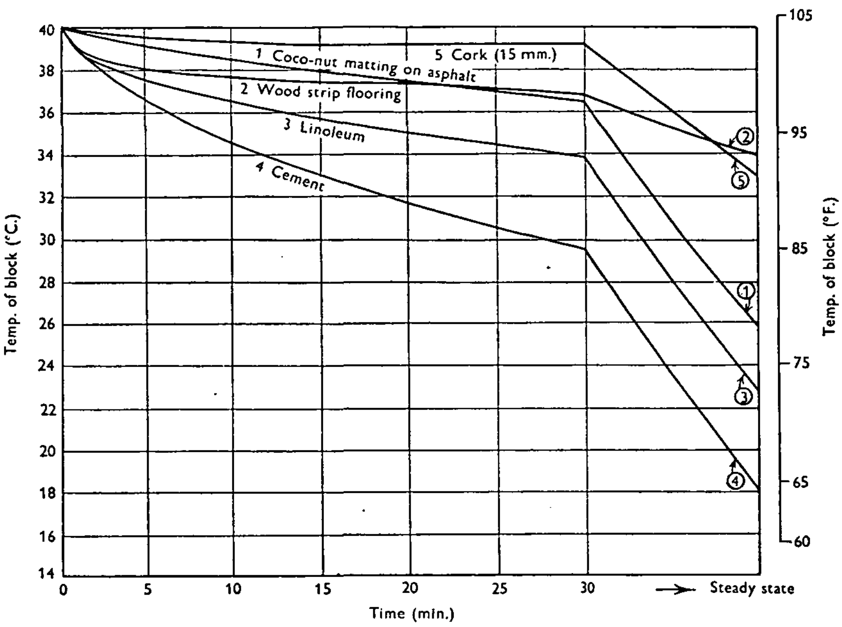

Fig. 1. Typical results on the warmth of floor finishes, after Eichbauer (1912).

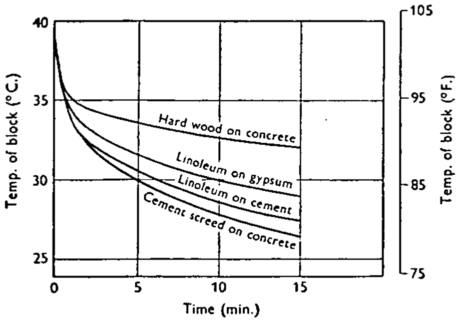

Fig. 2. Typical results obtained by Reiher and Hoffman (1930).

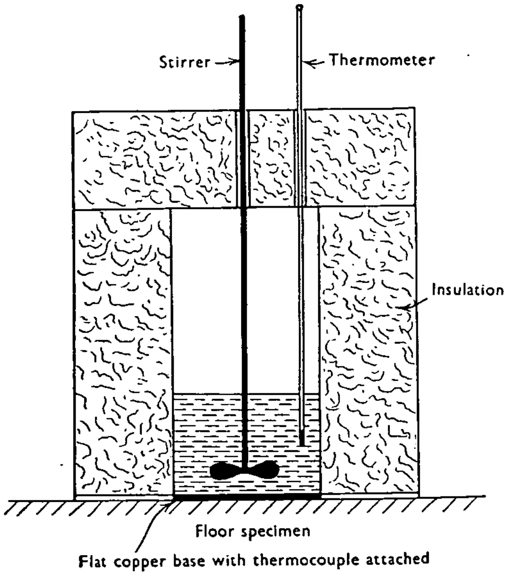

Fig. 3. The artificial foot used in the present experiments.

temperature of the water is 100° F., the base temperature is about 97·5° F.

The heat loss from the sides and top of the can may be allowed for by subtracting from the observed cooling rate (on the specimen) the cooling experienced while the vessel is standing on the cork slab. Thus, if the cooling rate when standing on the cork is 0·35° F./min., the subsequent temperatures are corrected by the addition of 0·35 t °F., where t is the elapsed time in minutes from the commencement of the test. This correction also enables the effect of variations in laboratory air temperature to be eliminated.

The 'foot' used in the present work has about the same thermal capacity as that employed by the German workers. A larger thermal capacity is unsuitable, as the observed cooling rate is then too slow. An important difference between the present apparatus and the form previously employed is the fact that whereas Eichbauer and Reiher & Hoffmann measured the temperature at the centre of the block of copper, it is now measured at the surface of contact between the canister and the floor specimen. By doing this, it was hoped to exaggerate the differences between the various floor finishes in the present experiments, and so to make comparison easier, as well as perhaps to get a closer approximation to the practical case.

In a second series of tests, the base of the canister was covered with the sole of a shoe. This covering was about ¼ in. thick. The base temperature recorded still refers to the underside of the copper base, and not to the surface of the 'shoe'.

(b) *Results with laboratory specimens*

Measurements have been made in the laboratory on specimens of a number of floor finishes, and further measurements have been made on some existing floors. The results obtained with the bare canister on laboratory specimens are shown in Figs. 4–6 and in Table 1. The figures given are means of a number of observations at each temperature. Individual observations could not be reproduced with great accuracy, and this was attributed in part to imperfections in the surfaces being studied. Further, except where readings were taken with the specimen at laboratory temperatures, it was not possible to ensure that the specimen did not exchange some heat with its surroundings. There existed, therefore, the probability that temperature gradients, both vertical and horizontal, were set up in the specimen. Nevertheless, the results were sufficiently concordant to enable some general conclusions to be drawn.

It is seen from Table 1 that, in respect of the instantaneous temperature drop, the materials can be arranged in an order which corresponds closely to the order of the products (conductivity × volumetric specific heat). This applies only to the initial stages: after 1 or 2 min., the influence of the sub-floor becomes apparent.

We note also that the time-temperature curves are not smooth and regular. The base temperature of the canister falls quickly to a more or less steady value in the first few seconds, and then begins to drop in a normal manner. (The fact that the initial drop in temperature does not appear instantaneous is probably due in part to the period of the galvanometer employed—7 sec.—and in part to imperfect contact between the base and the floor.)

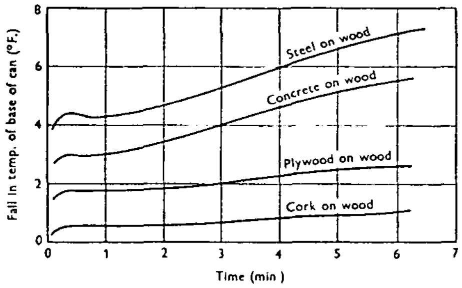

Fig. 4. Rate of cooling of bare foot on surfaces at about 67° F.

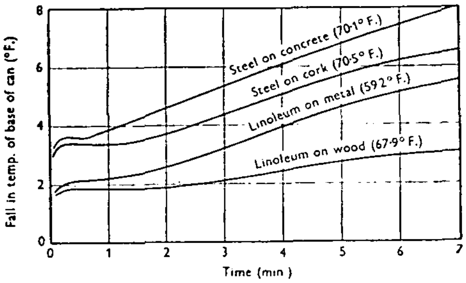

Fig. 5. Effect of sub-floor on rate of cooling.

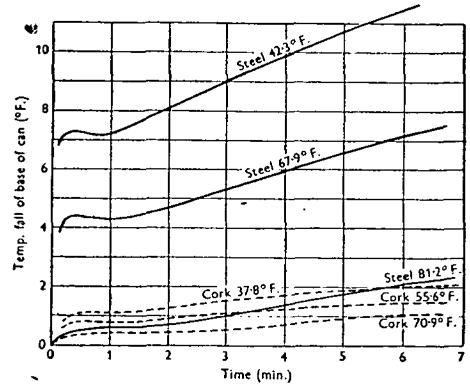

Fig. 6. Effect of surface temperature on rate of cooling.

This phenomenon seems to have been overlooked by Eichbauer (1912) and by Reiher & Hoffman

(1930), who took observations each minute; but van der Held draws attention to its possible occurrence in two more recent papers (1939; 1942). It is known that if two bodies at different temperatures θ_1 and θ_2 are placed in intimate contact, the interface immediately takes up a temperature θ_s, intermediate between θ_1 and θ_2, given by the expression

$$\theta_s = \frac{b_1\theta_1 + b_2\theta_2}{b_1 + b_2}, \qquad (1)$$

where $b = \sqrt{(k\rho c)}$, k = conductivity, ρ = density and c = specific heat of the materials.

Table 1. *Temperature fall of base of artificial 'foot'*

Materials		Surface temperature (° F.)	Instantaneous temperature drop (° F.)	Temperature drop after 6 min. (° F.)
Floor finish	Sub-floor			
$\frac{1}{16}$ in. steel	½ in. timber	81·2	0·6	2·1
	,,	67·9	4·3	7·2
	2 in. concrete	70·1	3·6	7·3
	1 in. cork	70·5	3·4	6·2
	None—standing on tray of ice	42·3	7·2	11·5
		45·1	7·1	11·3
2 in. concrete	Wood	73·4	2·4	3·7
	,,	66·5	3·0	5·5
	,,	65·4	3·0	5·5
	,,	53·8	3·5	6·6
	,,	44·7	4·3	8·1
¼ in. plywood	½ in. timber	68·5	1·8	2·6
	,,	53·8	2·0	2·8
	,,	42·6	2·4	3·5
	¼ in. iron	58·3	1·9	4·2
1 in. cork	Wood	70·9	0·4	1·0
	,,	67·4	0·6	1·1
	,,	55·2	0·8	1·5
	,,	37·8	1·1	2·0
⅛ in. linoleum	¼ in. iron	59·2	2·2	5·1
	2 in. concrete	55·1	2·9	6·8
	½ in. timber	67·9	1·85	2·9
		70·0	1·5	2·9

Table 2. *Computed and observed values of the instantaneous temperature of a surface of contact*

Material	Conductivity (B.TH.U./ft./hr./°F.)	Density (lb./ft.^{3})	Specific heat (B.TH.U./lb./°F.)	$b = \sqrt{(k\rho c)}$	Initial temp. (θ_2) (°F.)	Instantaneous surface temp. (θ_s)	
						Calc. (°F.)	Obs. (°F.)
Copper	220	555	0·09	106	($\theta_1 = 97·5$)	—	—
Steel	26	487	0·11	37·3	70·1	90·3	93·9
					45·1	83·7	90·4
Concrete	1	150	0·24	6	73·4	96·3	95·1
					65·4	95·8	94·5
					44·7	94·7	93·2
Linoleum	0·14	33	0·3	1·2	67·9	97·2	95·7
					55·1	97·0	94·6
Plywood	0·08	33	0·34	0·95	68·5	97·1	95·7
					58·3	97·1	95·6
					42·6	97·0	95·1
Corkboard	0·03	13	0·4	0·4	67·4	97·3	96·9
					37·8	97·2	96·4

In the present experiments, θ_1 is, of course, 97·5° F. Table 2 shows the observed values of θ_s together with those computed from equation (1) from an approximate knowledge of the three primary constants of the materials. The agreement between theory and experiment in this case is considered satisfactory, when one remembers that the contact between the two surfaces is not necessarily very close, and that the thermal capacity of the copper base of the canister is not large.

The presence of the underlying structure is also of importance in the case of thin floor finishes. The curves in Fig. 5 show the effect observed with a metal covering. In the initial moments of contact, the cooling is very nearly independent of the sub-floor; but in the later stages, cooling is most rapid on a highly conducting layer. A similar effect is observed with a linoleum covering, although the cooling is less rapid than with a metal surface.

As one would expect, the cooling is the more severe the colder the floor surface. This is illustrated in Fig. 6. The effect of surface temperature is not very appreciable with an insulating material such as cork, but is very marked in the case of a conducting material. If one plots the instantaneous fall of temperature against the initial temperature of the surface of the floor specimen, as in Fig. 7, the points appear to lie about a straight line which passes through 97·5° F., the initial temperature of the base of the artificial 'foot'.

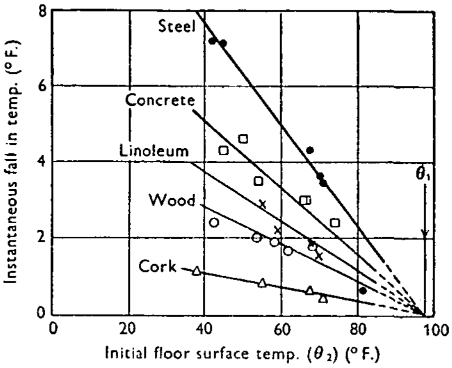

Fig. 7. The variation of instantaneous temperature drop with the surface temperature of the floor.

The instantaneous drop of temperature on a wood floor at 64·5° F. is 1·6° F. Now a wood floor is normally considered to feel sufficiently 'warm' so that persons may walk barefoot on it without discomfort. If we therefore make the assumption that the feeling of warmth is related to the instantaneous temperature drop, we are led to suppose that whatever the floor, it will not feel unduly cold if the immediate fall in temperature does not exceed that on a wood floor, namely 1·6° F. at 64·5° F. From the lines of Fig. 7, we can readily determine the surface temperature of a given material which will cause an instantaneous temperature drop of this magnitude; and under these conditions, the floor should lead to the same sensation of warmth as a wood floor at 64·5° F.

van der Held has calculated, from equation (1), that surface temperature which for various materials gives the same instantaneous temperature, θ_s, of the interface as does a wood floor at 64·5° F. These temperatures, given in Table 3, were computed from an assumed value of b for the human skin, and ought perhaps to be treated with a certain reserve. Nevertheless, it is apparent that the present results are in substantial agreement with van der Held's theory.

Table 3. *Surface temperature of floors having equal sensations of warmth*

	Surface temp. (θ_2)	
Material	From present data (° F.)	From van der Held's paper (° F.)
Wood	64·5	64·5
Cork	10	−40
Linoleum	72	—
Concrete	79	74
Steel	85	80
Marble	—	76·5

The use of a covering on the foot materially reduces the differences between one floor finish and another, although the order is unchanged (Fig. 8).

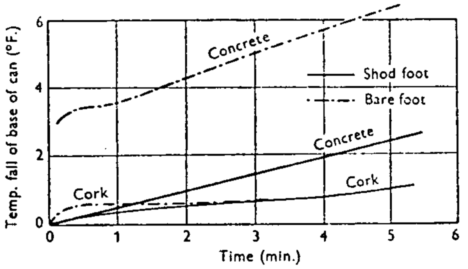

Fig. 8. Effect of shoe on foot.

Again the effect is most marked with a highly conducting flooring material. The differences between the various floors are now small, so that it is doubtful if a person walking from one finish to another would notice the change. Nevertheless, the fact that differences do exist means that there are also differences in the rate of heat loss from the foot; and it may well be that the effect of the 'colder' floor is cumulative, so that after continued standing or walking on the floor for a considerable time, appreciable differences in sensation may be experienced.

It is well to note that when considering the case of persons standing or sitting, it is not the momentary chilling which is of greatest importance, but the gross rate of heat loss. This heat loss, besides depending on the surface temperature and the transmittance of the floor, is affected by convection losses to cool air near the floor and by the cooling of the ankle by floor draughts.

(c) *Results from existing floors*

The results obtained in a few tests on existing floors are shown in Fig. 9. In each case, the floor finish was laid on a concrete sub-floor in contact with the ground.

The floors fall conveniently into four groups. The first consists of a cork floor, where the initial sensation is one of warmth; but the final temperature is of the same order as that for floors in the second group. This group includes wood-block flooring, and some types of newly developed materials. The third group appears similar to concrete in its properties, and includes a pitch mastic floor and a tiled floor. The anhydrite floor would appear to feel very cold indeed.

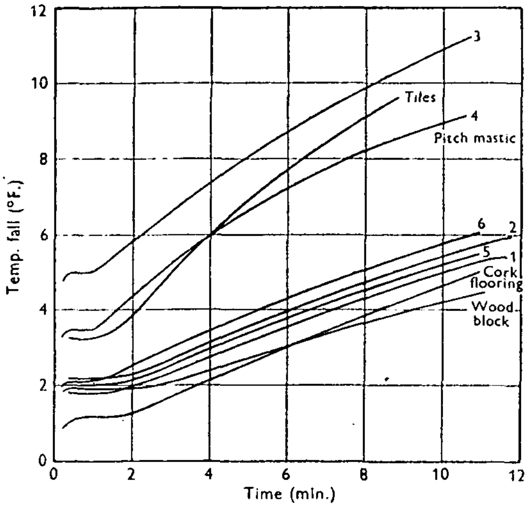

Fig. 9. The cooling of experimental foot on actual floors.
(All floor finishes laid on concrete.)

Panel	Materials	k B.TH.U./ft.^{2}/hr./° F./in.	ρ lb./ft.^{3}
1	¼ in. cement, woodchips, rubber crumb emulsion	1·4	70
2	¼ in. cement, woodchips, plastic emulsion	1·4	70
3	½ in. anhydrite	5·7	135
4	⅛ in. tiles of waste rubber, asbestos and phenolic resin	—	134
5	¼ in. cement, woodchips, emulsion	2·0	80
6	¼ in. cement, woodchips, plastic emulsion	1·7	77

CONCLUSIONS

The present experiments lend support to the common belief that a concrete floor feels colder than a wooden floor at the same temperature; although when shoes are worn, the difference due to the actual nature of the floor finish seems likely to be small. It appears possible to assess the feeling of warmth of a floor finish (for barefoot walking) by reference to the conductivity and volumetric specific heat of the material. The instantaneous fall in temperature of the base of the artificial 'foot' used in the tests is a function of the product ($k\rho c$), and decreases as this product decreases.

The experiments on existing floors show that the initial behaviour is the same as on laboratory specimens. The final cooling is, however, somewhat greater, and this is probably due to the steady flow of heat into the ground in this case.

The 'warmest' floor is obtained by the use, for the floor finish, of an insulating material of low heat capacity (i.e. low $k\rho c$). For bedrooms, bathrooms and so on, where people are likely to be walking barefoot, such materials should be used where possible. Suitable floors include wood, cork tile, linoleum on wood, and carpeted floors.

For kitchens, nurseries, offices and factories, where people stand or sit for lengthy periods, the 'warmth' of the surface layer is not of prime importance. It is, however, desirable that the sub-floor should be of some warm material, and the thermal transmittance of the complete floor should be low.

It should be possible, by placing an insulating layer beneath a floor finish, to make normally 'cold' materials somewhat less objectionable, both to the bare and the shod foot. The finish should then be as thin as possible.

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