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MEASUREMENT OF THE THERMAL DIFFUSIVITIES OF SOME SINGLE-LAYER WALLS IN BUILDINGS*

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Abstract—Analytical solutions are obtained for periodic heat flow through a large finite plane slab of isotropic material. The results are used to calculate thermal diffusivity values from measurements of the time delay in the passage of a steady periodic temperature variation through solid plane walls of brick and concrete construction.

INTRODUCTION

THE FLOW of heat in a naturally exposed wall of a building is rarely steady. An indication of the kind of fluctuation that may be experienced is given by the temperatures shown in Fig. 1 that were measured in a brick wall during a 24 h period. Though walls may have similar values of thermal transmittance (air-to-air coefficient of heat transfer) they will respond differently to fluctuations in the ambient temperature according to differences in their thermal capacities.

The physical property of a material essential to considering variable heat flow in a body is the thermal diffusivity (K), defined as the ratio of conductivity (k) to the product of density (ρ) and specific heat (c). Whereas thermal conductivity defines heat flow in steady state, diffusivity determines temperature flow in the non-steady state and, by similarity, may be described as the temperature conductivity. Thermal diffusivity may be calculated from the defining formula $K = k/\rho c$ if the component properties are known. Alternatively it may be determined experimentally by measuring a temperature *versus* time relationship in the passage of an applied temperature variation through a test specimen. References to theoretical arrangements with solutions, suitable for experimental application, may be found among the many cases of diffusion phenomena in solids considered by Barrer [1], Carslaw and Jaeger [2], Crank [3] and others. In the work reported below the thermal diffusivities of some essentially homogeneous walls were determined by applying a periodic temperature variation to one surface and measuring the time lag, or interval, between this variation and the resulting temperature change at the opposite face. As a check on the accuracy of the method the ratio of the amplitudes of these temperature variations was calculated using the experimentally determined diffusivity values and compared with the amplitude attenuations observed.

Before proceeding to an account of the experiment and the results obtained the necessary mathematical formulae will first be derived by obtaining an exact solution for the steady periodic temperature change in a large homogeneous slab of finite thickness when exposed at one surface to a thermal domain that is varying harmonically in temperature.

THEORY

A solution of the equation for the linear flow of heat in an isotropic solid bounded by a pair of parallel planes is required defining the amplitude damping and time lag in the temperature variation at one surface (hereafter called the inside surface) due to a sine wave variation in the ambient temperature applied at the opposite

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or outside surface. The large homogeneous slab is a formal representation of a solid wall of uniform material. Since that part of the solution representing steady cyclic flow only is needed, it is convenient to specify the mean ambient temperature over each complete cycle on both sides of the slab at zero level. The mathematical formulation is as follows.

$$\left.\begin{aligned}
&\frac{\partial^2\theta(x,t)}{\partial x^2} = \frac{1}{K}\frac{\partial\theta(x,t)}{\partial t}, \\
&\qquad\qquad 0 < x < l,\ t > 0 \\
&\frac{k\,\partial\theta(x,t)}{\partial x} = h_i\theta(x,t), \\
&\qquad\qquad x = 0, \quad t > 0 \\
&\frac{k\,\partial\theta(x,t)}{\partial x} = h_o[\theta_o\,e^{i\omega t} - \theta(x,t)], \\
&\qquad\qquad x = l, \quad t > 0 \\
&\theta(x) = 0, \quad \text{all } x, \quad t = 0
\end{aligned}\right\} \quad (1)$$

where the notation is

θ, temperature;

t, time;

x, position;

h_o, h_i, surface transfer coefficients, outside, inside respectively;

l, thickness;

ω, angular velocity.

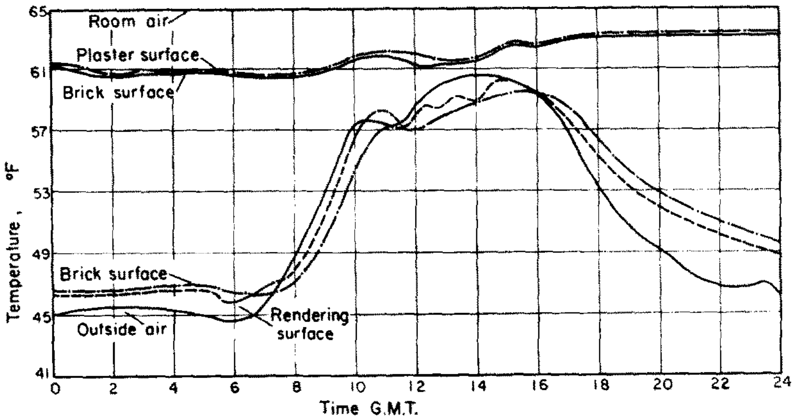

FIG. 1. The diurnal variation of temperature in a 1 ft thick wall of brickwork.

For convenience dimensionless moduli are introduced by writing

$$\xi = x/l, \qquad B_i = h_i\frac{l}{k}, \qquad B_o = h_o\frac{l}{k},$$

$$\tau = \frac{Kt}{l^2}, \qquad \Omega = \frac{l^2\omega}{K}.$$

Multiplying the equations written in dimensionless nomenclature by e^{-pt} and integrating with respect to time between 0 and ∞, the following subsidiary equations are obtained,

$$\left.\begin{aligned}
&\frac{d^2\bar\theta(\xi)}{d\xi^2} - p\bar\theta(\xi) = 0, \\
&\qquad\qquad 0 < \xi < 1, \\
&\frac{d\bar\theta(\xi)}{d\xi} = B_i\bar\theta(\xi), \\
&\qquad\qquad \xi = 0 \\
&\frac{d\bar\theta(\xi)}{d\xi} = B_o\left[\frac{\theta_o}{p - i\omega} - \bar\theta(\xi)\right], \\
&\qquad\qquad \xi = 1
\end{aligned}\right\} \quad (2)$$

Solving (2) for $\bar\theta(\xi)$ and applying the inversion theorem for the Laplace transform, the formal solution for the temperature change of the wall considered from initial time is

$$\theta(\xi, \tau) = \frac{1}{2\pi i} \int_{\nu - i\infty}^{\nu + i\infty} \frac{B_o\theta_o\{(\sqrt{p} + B_i)\exp[\sqrt{p}\xi] + (\sqrt{p} - B_i)\exp[-\sqrt{p}\xi]\}\exp[p\tau]\,dp}{(p - i\Omega)\{(B_o + \sqrt{p})(B_i + \sqrt{p})\exp[\sqrt{p}] - (B_o - \sqrt{p})(B_i - \sqrt{p})\exp[-\sqrt{p}]\}} \quad (3)$$

it passes through a homogeneous wall to the inside surface where the ambient temperature is constant. The diffusivity of the conducting medium can be calculated from these relationships.

The integrand in (3) is analytic with poles at $p = i\Omega$ and the values $p = -\alpha_n^2$, where α_n, $n = 1, 2, 3, \ldots$, are the positive real roots of

$$\tan\alpha + \frac{\alpha(B_i + B_o)}{B_iB_o - \alpha^2} = 0.$$

For the present purpose the steady periodic component of the temperature change at the inside surface only is required. This is obtained by calculating the residue at $p = i\Omega$ with $\xi = 0$, yielding a solution of the form

$$\theta(0, \tau) = \frac{2\sqrt{\Omega}\exp[-\sqrt{(\Omega/2)}]\,\theta_o}{\sqrt{(a^2 + b^2)}} \exp[i\{\Omega\tau - \sqrt{(\Omega/2)} + \psi\}] \quad (4)$$

where

$$\left.\begin{aligned} a = {} & B_i + \sqrt{(\Omega/2)}(1 + B_i/B_o) \\ & - [\{B_i - \sqrt{(\Omega/2)}(1 + B_i/B_o)\} \\ & \cos\sqrt{(2\Omega)} - \sqrt{(\Omega/2)}\{1 \\ & + B_i/B_o - (2/B_o)\sqrt{(\Omega/2)}\} \\ & \sin\sqrt{(2\Omega)}]\exp[-2\sqrt{(\Omega/2)}] \\ b = {} & \sqrt{(\Omega/2)}\{1 + B_i/B_o + (2/B_o) \\ & \sqrt{(\Omega/2)}\} + [\{B_i - \sqrt{(\Omega/2)}(1 \\ & + B_i/B_o)\}\sin\sqrt{(2\Omega)} + \sqrt{(\Omega/2)} \\ & \{1 + B_i/B_o - (2/B_o)\sqrt{(\Omega/2)}\} \\ & \cos\sqrt{(2\Omega)}]\exp[-2\sqrt{(\Omega/2)}] \end{aligned}\right\} \quad (5)$$

and

$$\tan\psi = (a - b)/(a + b).$$

Equations (4) and (5) are the exact solution defining the phase change ψ and amplitude attenuation that develops in a simple harmonic variation of the outside ambient temperature as it passes through a homogeneous wall to the inside surface where the ambient temperature is constant. The diffusivity of the conducting medium can be calculated from these relationships.

In the experiments described below for determining the thermal diffusivities of some homogeneous walls it was found more convenient to calculate this property from observations of the temperature of both surfaces. The solution for this particular case, corresponding to the alternating boundary condition applied as a change in surface temperature instead of ambient temperature as considered above, follows directly from the more general result by putting $1/B_o = 0$ to give

$$\left.\begin{aligned} a = {} & B_i + \sqrt{(\Omega/2)} - [\{(B_i - \sqrt{(\Omega/2)}\} \\ & \cos\sqrt{(2\Omega)} - (\Omega/2)\sin\sqrt{(2\Omega)}] \\ & \exp[-2\sqrt{(\Omega/2)}] \\ b = {} & \sqrt{(\Omega/2)} + [\{(B_i - \sqrt{(\Omega/2)}\} \\ & \sin\sqrt{(2\Omega)} + \sqrt{(\Omega/2)}\cos\sqrt{(2\Omega)}] \\ & \exp[-2\sqrt{(\Omega/2)}] \end{aligned}\right\} \quad (6)$$

The computation of thermal diffusivity may be simplified without significant loss of accuracy by neglecting the exponential term in the expressions for a and b. This is permissible with solid masonry walls conducting a diurnal temperature variation and applies to the present results. The simpler form of the solution cannot apply to very thin walls or temperature waves of period longer than about 24 h without the risk of introducing substantial error.

To summarize, periodic heat flow through a plane finite slab may be computated using the following approximate formulae for the boundary condition as specified:

(i) variation applied in the outside air temperature,

$$a = B_i + \sqrt{(\Omega/2)}(1 + B_i/B_o),$$
$$b = \sqrt{(\Omega/2)}\{1 + B_i/B_o + (2/B_o)\sqrt{(\Omega/2)}\}$$

(ii) variation applied in the outside surface temperature,

$$a = B_i + \surd(\Omega/2)$$
$$b = \surd(\Omega/2)$$

with, in this case,

$$\left.\begin{aligned} \theta(0,\tau) &= \frac{2\theta_o \exp[-\surd(\Omega/2)]}{\surd\{B_i^2 + 2B_i\surd(\Omega/2) + \Omega\}} \\ &\quad \exp[i\{\Omega\tau - \surd(\Omega/2) + \psi\}] \\ \text{and} & \\ \tan\psi &= 1/\{1 + (2/B_i)\surd(\Omega/2)\} \end{aligned}\right\} \quad (7)$$

as the approximate solution. Taking the imaginary part of (7) it follows that the steady periodic temperature at the inside surface of a homogeneous wall, transmitting the steady periodic temperature $\theta_o \sin 2\pi t/T$ where T is the periodicity applied to the outside surface is

$$\left.\begin{aligned} \theta(0,t) &= \frac{2\surd(2\pi/KT)\exp[-l\surd(\pi/KT)]\,\theta_o \sin\{2\pi t/T - l\surd(\pi/KT) + \psi\}}{\surd\{h_i^2/k^2 + (2h_i/k)\surd(\pi/KT) + 2\pi/KT\}} \\ \text{with} & \\ \tan\psi &= 1/\{1 + (2k/h_i)\surd(\pi/KT)\}. \end{aligned}\right\} \quad (8)$$

It may be remarked that the phase lag for a similar temperature function at a distance l into a semi-infinite solid is $l\surd(\pi/KT)$. Comparing this result with (8) indicates that ψ may be regarded as a correction to the semi-infinite solid relationship that allows for the finite thickness of the wall.

A further property in periodic heat flow is the degree of amplitude attenuation that develops as the harmonic function diffuses through the conducting medium. For the present purpose this is defined as the ratio, ϕ, of the amplitude of the steady harmonic temperature variation at the inside surface to that at the outside surface and from (8) is written

$$\phi = \frac{2\surd(2\pi/KT)\exp[-l\surd(\pi/KT)]}{\sqrt{\left\{\left(\frac{h_i}{k}\right)^2 + 2\frac{h_i}{k}\sqrt{\left(\frac{\pi}{KT}\right)} + \frac{2\pi}{KT}\right\}}}. \quad (9)$$

MEASUREMENTS OF PERIODIC HEAT FLOW THROUGH WALLS

The measurements were made on test walls measuring 8 ft square in the Wall Laboratory at the Building Research Station. Behind each wall a cubicle heated electrically to a constant temperature of 65°F gave the required boundary condition of a fixed air temperature at the inside surface. The thermal conductances and surface transfer coefficients of the walls were obtained from mean values of the heat flow and surface temperatures measured over a continuous period of several days.

The periodic heat flux prescribed in (1) was arranged by intermittent switching of an electric heater fixed to the outside surface of the wall. The heater consisted of a resistance winding rated at 500 W embedded in a rectangular plastic-bonded panel measuring 3 ft × 2 ft, the heat output of the panel being adjusted to a suitable value by a variable-ratio auto transformer. This panel formed one face of a shallow box about 7 inches deep which was insulated thermally on the remaining sides with cork and sheets of asbestos–cement. A felt gasket round the edges of the heater-face of the box made contact with the test wall to locate the heater about half an inch away from the wall surface. The gasket sealed the narrow heated space against air infiltration from outside. Current in the heater was controlled by a time-switch set to provide alternate heating and cooling cycles of equal duration. The regular train of heat pulses was applied with a period of 24 h to correspond with the natural diurnal variation of outdoor air temperature. The resulting cyclic variations of temperature at the inner and outer surfaces of the wall were recorded by thermocouples attached to the wall at the centre of the heated area and connected to a recording galvanometer. Because of the small temperature amplitude at the inner surface five thermocouples in series were used in this position to give increased sensitivity. By taking the temperature measurements at the centre of the heated area the experiments approached most closely the requirement of undirectional heat flow which is essential to calculating diffusivities using the formulae given above. A typical record of the steady periodic temperature obtained is shown in Fig. 2 where it will be seen that the temperature pattern at the inside surface is very nearly

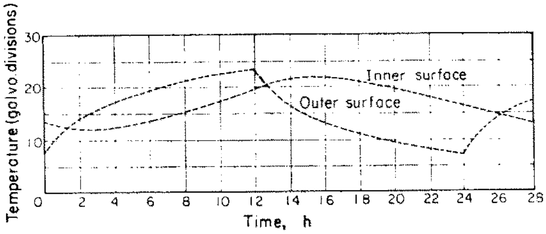

FIG. 2. Part of a typical temperature record.

sinusoidal. Following Parsons and Burnand [4], the succession of rise and decay curves that formed the regular variation at the outside surface was examined by Fourier analysis to determine the first harmonic. This component was then compared with the sine wave at the inside surface to give the time-lag at the switching frequency.

Measurements of time-lag were made on six walls of different material, and of the amplitude on three of them. All the walls were essentially large homogeneous slabs of material commonly used in building. Data were also obtained for a number of cavity walls (non-homogeneous structures) but as that part of the cavity included in the test area constituted an "open" airspace it is probable that the observations were complicated by heat removal due to natural convection in the cavity; an exact interpretation of the data for this more complex case is not at present available.

COMPUTATION OF THERMAL DIFFUSIVITY

The time-lag δ is defined as

$$\delta = \frac{T\lambda}{2\pi} \tag{10}$$

where, from (8), the phase angle λ takes the expression

$$\lambda = l\sqrt{\left(\frac{\pi}{KT}\right)} - \tan^{-1}\frac{1}{1 + 2(k/h_i)\sqrt{(\pi/KT)}}. \tag{11}$$

It is noted above that the arc tan term in the expression for λ appears as a correction to the corresponding solution for the semi-infinite solid case. With this in mind, as a first step in computing K this correcting term may be dropped, so that

$$\delta = \frac{l}{2}\sqrt{\left(\frac{T}{\pi K}\right)}$$

or,

$$K = \frac{T}{4\pi}\left(\frac{l}{\delta}\right)^2. \tag{12}$$

By substituting known values of T, l and δ into (12) a first estimate for K is obtained. Equations (10) and (11) give, as the exact relationship defining K,

$$K = \frac{Tl^2}{4\pi\,[\delta + (T/2\pi)\tan^{-1}\{1 + 2(k/h_i)\sqrt{(\pi/KT)}\}^{-1}]^2}. \tag{13}$$

Using the approximate value of K already obtained to evaluate the correction term, a closer approximation may then be calculated with (13) and the process reiterated until the value of the diffusivity becomes stable.

In Table 1 a comparison of the calculated values of the amplitude ratio ϕ [see equation (9)] with those obtained from the experimental measurements supports the accuracy of the method for calculating the diffusivity using the approximate form of the solution.

RESULTS AND DISCUSSION

Time-lag measurements, calculated values of thermal diffusivity and, in a smaller number of cases the amplitude ratio, are summarized in Table 1. Values of the time-lag for walls 1, 2 and 3 were reported originally by Parsons and Burnand and used by them to obtain diffusivity values which, it is noted, are substantially higher than the present results. Examination has revealed that the earlier values of K were calculated on the simplifying assumption that masonry walls of the type considered respond as semi-infinite solids to a harmonic temperature variation of period 24 h applied at the outside surface. The discrepancy between the two sets of

Table 1. Results of periodic temperature measurements on homogeneous walls

Wall construction	Measured				Calculated	
	k (Btu in ft² h degF)	l (ft)	δ (h)	ϕ	K (ft²/h)	ϕ
1. Solid cast brick aggregate concrete	8·24	0·667	5·8	—	0·0181	—
2. Solid cast gravel concrete	13·5	0·667	4·9	—	0·0259	—
3. Fletton brickwork	6·67	0·750	5·8	—	0·0216	—
4. Aerated concrete blocks, rendered, plastered	3·80	0·583	5·3	0·165	0·0139	0·177
5. Foamed slag concrete 1:2½:7½* rendered, plastered	3·22	0·750	7·5	0·093	0·0129	0·084
6. Foamed slag concrete 1:2:8 rendered, plastered	2·84	0·750	8·0	0·078	0·0115	0·076

* Mix proportions refer to cement:fine aggregate:coarse aggregate.

results is attributed to the error introduced by this assumption.

The results suggest an increase in the thermal diffusivity with conductivity. This may be seen from the plot in Fig. 3 which includes data reported by Billington [5, 6] for other materials covering a similar range of thermal values. A similar variation that exists between conductivity and density probably conditions the trend of results shown in Fig. 3, especially as the specific heat is the least variable among the properties involved.

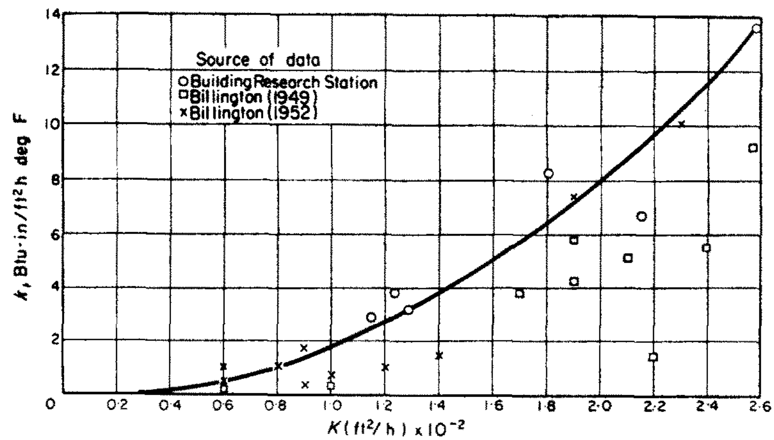

FIG. 3. Variation of thermal conductivity with diffusivity.

Billington [6] summarizes diffusivity values for several building materials; the agreement with corresponding values in Table 1 is fairly good. By employing a method due to Ångström, Billington [5] measured the diffusivities of laboratory specimens of some poorly conducting building materials and obtained results that agree reasonably well with the present values. The agreement is well within the range of the different values of diffusivity for these particular materials when calculated from the defining formulae $K = k/\rho c$, using figures for conductivity, density and specific heat taken from the assortment of data available in the literature.

The thermal diffusivities of various other materials, including metals, have been determined by Strong, Bundy and Bovenkerk [7] from measurements of the temperature propagation through a semi-infinite solid due to a suddenly activated plane heat source.

Increasing interest is now being shown in the extent to which moisture reduces the heat insulating value of porous solids. This is being investigated largely by studying the moisture dependence of thermal conductivity using variable-flow methods of measurement. These methods determine conductivity in a considerably shorter time than the standard steady-state method and are considered therefore to be the more suitable for use with damp material. Depending on the boundary conditions dynamic methods will yield, in addition, the thermal diffusivity and may be considered therefore for examining the effects of moisture on this property also. Hatton [8] describes an experimental arrangement for this purpose and gives results obtained with specimens of damp fibre board and baked cork slab: otherwise very little practical data on the diffusivity of damp material is available.

The form of the relationship between the diffusivity of a porous inorganic solid and its moisture content is readily determined by calculating the ratio $k/\rho c$. For this type of material Jakob [9] and others have demonstrated that, on average, the conductivity varies with moisture content as follows:

Water content ω (vol. %):	Factor f to correct conductivity values of bone-dry material
1	1·30
2·5	1·55
5	1·75
10	2·10
15	2·35
20	2·55
25	2·75

Using this result the curve in Fig. 4 has been calculated for such a material. The form applies generally and similar results, for example, are reported by Rider [10] for soil. The high initial rise in the conductivity with moisture content determines a similar behaviour in the diffusivity.

A common source of error in experiments on heat transfer is the extreme difficulty of compelling heat to flow in the direction prescribed

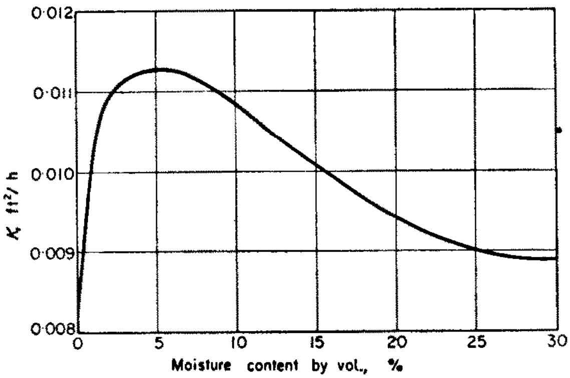

FIG. 4. Variation of thermal diffusivity of cellular concrete with moisture content.

by theory. This usually takes the form of an edge heat-loss effect. Such errors in the present work were minimized by confining the temperature measurements to the centre of the test area on both surfaces. It was assumed that distortion of the isothermals arising at the continuous boundary between the test region and the surrounding mass of wall material did not extend to this central position. This was justified with the aid of a theoretical solution reported by Clarke and Kingston [11] for a problem similar to that now considered.

A COMPUTATION CHART FOR PERIODIC HEAT FLOW

The calculation of K using equation (13) can be tedious. Values may be obtained more simply, though perhaps with slightly less accuracy, from a chart prepared by rewriting (10) as

$$\delta = \sqrt{\left(\frac{T}{2\pi}\right)} \cdot \sqrt{\left(\frac{Q}{C}\right)} - \frac{T}{2\pi} \tan^{-1}\left\{\frac{1}{1 + \frac{2}{h_i}\sqrt{\left(\frac{2\pi}{T}\right)}\, C\, \sqrt{\left(\frac{Q}{C}\right)}}\right\} \quad (14)$$

or functionally

$$\delta = f(C, Q/C)$$

where Q is the quantity of heat contained by the slab in the steady state for unit temperature difference between opposite faces and equal therefore to $\rho cl/2$, and C is the thermal conductance equal to k/l. Choosing C as the parameter and plotting Q/C against δ a family of

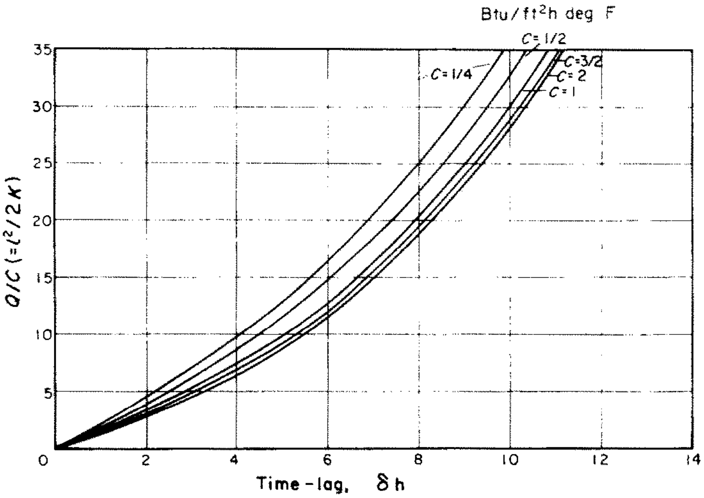

FIG. 5. Periodic heat flow through a uniform slab. Q/C vs. time-lag, δ.

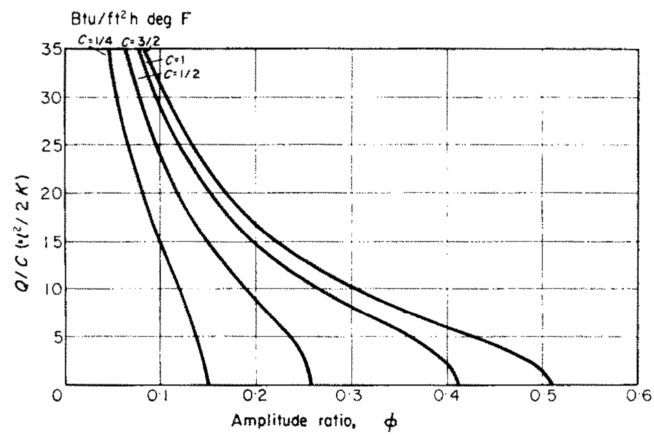

FIG. 6. Periodic heat flow through a uniform slab. Q/C vs. amplitude ratio, ϕ.

curves may be constructed to give the diffusivity directly for the observed time lag and known conductance of the wall, for

$$Q/C = (\rho cl/2)\,(l/k) = l^2/2K.$$

The formula (14) is sufficiently accurate except for small values of Q/C when the following exact expression may be preferred,

$$\delta = \sqrt{\left(\frac{T}{2\pi}\right)}\sqrt{\left(\frac{Q}{C}\right)} - \frac{T}{2\pi}\tan^{-1}\left(\frac{a-b}{a+b}\right)$$

in which the formulae for a and b [see equations (6)] may be written as functions of C and Q/C. Such a chart is shown in Fig. 5. It has been constructed for a sinusoidal variation in the temperature of the outside surface, period 24 h, and a value for the inside surface heat-transfer coefficient h_i of 1·4 Btu/ft^2 h degF. The corresponding chart for the amplitude ratio has been similarly constructed and is shown in Fig. 6.

CONCLUSION

A method is described for determining the thermal diffusivities of uniform solid walls by measuring the time lag in the passage of a steady periodic temperature variation of sinusoidal form through large test panels measuring 8 ft square. Hitherto measurements of diffusivity have been made on a few building materials of low thermal conductivity using small laboratory specimens only; the present results are more applicable therefore to the walls of actual buildings. The smaller size of the applied heat source compared with that of the complete test panel restricted the measurements to solid walls. The method is now being developed for application to walls of cavity construction; this requires a plane heat source uniformly applied to the complete area of the outer surface of the wall.

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Résumé—Des solutions analytiques sont obtenues pour un flux de chaleur périodique à travers une plaque plane de grandes dimensions constituée d'un matériau isotrope. Les résultats sont utilisés pour le calcul des diffusivités thermiques à partir des mesures du délai de propagation d'une variation périodique de température à travers des parois planes de briques et de béton.

Zusammenfassung—Analytische Lösungen erhielt man für den periodischen Wärmestrom durch eine grosse aber endliche, ebene Platte aus isotropem Material. Die Ergebnisse dienen zur Bestimmung der Temperaturleitkoeffizienten auf Grund von Messungen der Verzögerung beim Fortschreiten einer stationären, periodischen Temperaturänderung durch eine feste, ebene Wand aus Ziegel und Beton.

Аннотация—Получены аналитические решения для случая периодических потоков тепла через изотропный материал плоской плиты конечных размеров. Результаты используются для расчета коэффициентов термодиффузии по величинам времен запаздывания при стационарных периодических температурных воздействиях в плоских твердых стенках кирпичных и бетонных сооружений.