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THE THEORY OF FORCED CONVECTIVE HEAT TRANSFER IN BEDS OF FINE FIBRES—I

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Abstract—The theory of forced convective heat transfer in beds of granular solids is investigated experimentally using beds of fine fibres. It is found that the present theory is inapplicable for two reasons; it fails to predict the correct heat-transfer coefficient and also does not indicate the correct functional relations between the experimental variables. A reason for this failure is believed to be unavoidable flow imperfections in the bed.

NOMENCLATURE

A,	amplitude of temperature variation at $x = 0$, degC;
a,	length in x-direction of small section of bed, cm;
a_1, a_2, a_3,	dimensionless constants;
a_s,	surface area, cm^2;
B,	amplitude of temperature variation, degC;
C,	heat capacity of fibres per unit volume of bed, cal degC^{-1} cm^{-3};
d, d_1, d_2,	lengths of sections of bed much larger than a, cm;
F,	cumulative distribution functions of path lengths;
f,	frequency distribution of path lengths;
H,	heat-transfer coefficient per unit area of solid, cal s^{-1} cm^{-2} degC^{-1};
h,	heat-transfer coefficient per unit volume of bed, cal s^{-1} cm^{-3} degC^{-1};
i,	$\sqrt{-1}$;
k,	ratio of local air velocity in bed to velocity of air entering bed;
l,	equivalent path length, cm;
m_1, m_2, m_3,	first, second and third moments of f;
n,	number of sections of bed of length, a;
Q,	heat transferred, cal;
S,	heat capacity of air per unit volume of bed (constant pressure), cal degC^{-1} cm^{-3};
s,	distance along a streamline, cm;
T,	temperature of fibres and air (when assumed identical), degC;
T,	temperature of fibres and air (when assumed identical), degC;
T_A,	temperature of air, degC;
T_S,	temperature of fibres, degC;
$\bar{T}$,	mean value of temperature across a section of bed, degC;
t,	time, s;
U,	unit step function;
u,	velocity of propagation of thermal signal in bed, cm s^{-1};
V,	velocity of air entering bed, cm s^{-1};
v,	local velocity of air in bed, cm s^{-1}. $v = V$ when flow through bed assumed uniform;
x,	distance of a point in the bed from upstream face, cm.

Greek symbols

α,	attenuation constant, cm^{-1};
β,	ratio of m_2 to distance x (constant for model discussed);
Δ,	prefix indicating finite difference;
θ,	phase angle, rad;
λ,	wavelength, cm;
$\lambda a_1(\lambda x)$,	equivalent path length along given streamline in a section of bed of length $a_1(x)$, cm;

λ, mean value of f per unit thickness of bed;
σ, standard deviation of f;
τ, time taken for a thermal signal to travel from upstream face to a point P_1 in the bed, s;
ω, angular frequency, s^{-1}.

INTRODUCTION

THE HEATING of large masses of fine fibres is a process of considerable industrial importance. The common practice is to form the fibres into a more or less uniform bed and blow air of the required temperature through it. Heat is then transferred from the air stream to the fibres and the resulting change of temperature is propagated through the bed in the form of a moving front.

There exists, at present, an apparently well-accepted theoretical treatment of heat transfer between a moving fluid (liquid or gas) and a packed bed of granular solids. The differential equation describing the transfer has been solved by Anzelius [1] and Schumann [2], however the solutions are in the form of infinite series. An approximate analytical solution has been given by Klinkenberg [3] and a solution in the finite difference form by Ledoux [4]. These treatments impose no limitations on the shape or surface to volume ratio of the solid and hence should be applicable to beds of fine fibres. In particular, an application of the theory to measured heat-transfer data in such beds should permit the calculation of the heat-transfer coefficient between the air stream and the fibres. As it was found in the course of a study of the thermal characteristics of fibre beds that an application of the theory gave unlikely values for the heat-transfer coefficient, a critical examination of the existing theory was undertaken. The results of this study are contained in the present paper (Part I) while an improved theory of heat transfer in beds of fine fibres is discussed in a subsequent paper (Part II).

The existing theory was tested experimentally by two methods leading to different boundary conditions for the basic differential equation describing the heat transfer. In one method, the temperature of the air entering the bed was changed abruptly, approximating a step function, while in the second method the temperature of the air was made to vary sinusoidally with respect to time. These boundary conditions lead to two methods of solution of the differential equation and are discussed below.

THEORY

The present theory of convective heat transfer in packed beds of solids rests on two main concepts. One concept is the well-known heat-transfer coefficient which simply signifies that the rate of transfer of heat across the boundary separating two phases (air and fibres) is directly proportional to the temperature difference and the surface area of the boundary. It may be expressed in the form

$$\frac{Q}{t} = H\, as\, \Delta T$$

where Q is the amount of heat transferred in time t across a boundary of area as under a temperature difference ΔT. H is the heat-transfer coefficient per unit area. The second concept is that of an idealized bed which is uniform throughout in density of packing and other properties and the inter-fibre distance being sufficiently small for the methods of the differential calculus to be applicable. Further assumptions are:

(a) The thermal properties of the fluid and solid (i.e. heat capacity, etc.) are independent of temperature in the range considered.
(b) The velocity of air flow is sufficiently high that heat transfer by conduction within the air stream in the direction of flow is unimportant.
(c) The effective temperature difference causing transfer of heat is the difference between the mean temperature of the fluid and the mean temperature of the solid at a given time and place in the bed.
(d) The temperature and flow rate are uniform across any section of the bed at right angles to the direction of flow.

It has been shown by Ledoux [4] that a heat balance over a small volume element of bed of unit cross section and length dx leads to the equations of heat transfer:

$$-Sv\frac{\partial T_A}{\partial x} = C\frac{\partial T_s}{\partial t} = h(T_A - T_S)\,, \qquad (2)$$

from which either T_A or T_S may be eliminated. Here we are interested in the temperature of the solid and hence eliminate T_A from (2), giving

$$\frac{1}{h}\frac{\partial^2 T_S}{\partial x \partial t} + \frac{1}{Sv}\frac{\partial T_S}{\partial t} + \frac{1}{C}\frac{\partial T_S}{\partial x} = 0\,. \qquad (3)$$

For any arbitrary boundary conditions, this differential equation may be evaluated by a numerical method using a finite difference equation. If $\Delta x = x_2 - x_1$ and $\Delta t = t_2 - t_1$ are finite differences in distance and time, it can be shown that [dropping the subscript s in equation (3)]

$$T(x_2; t_2) = \left(\frac{-2CSv + hSv\Delta t + hC\Delta x}{2CSv + hSv\Delta t + hC\Delta x}\right) T(x_1; t_1)$$
$$+ \left(\frac{2CSv - hSv\Delta t + hC\Delta x}{2CSv + hSv\Delta t + hC\Delta x}\right) T(x_2; t_1)$$
$$+ \left(\frac{2CSv + hSv\Delta t - hC\Delta x}{2CSv + hSv\Delta t + hC\Delta x}\right) T(x_1; t_2) \qquad (4)^*$$

$$= a_1 T(x_1; t_1) + a_2 T(x_2; t_1) + a_3 T(x_1; t_2). \qquad (5)$$

Thus, for any given boundary condition $T(x_o; t_o)$, equation (4) will predict the temperature–time curve $T(x\colon t)$ at any point in the bed, provided the constants C, S, v and h are known. In the particular case in which it is desired to evaluate h from the experimental data, trial values of h may be inserted into (4) until a satisfactory fit between the experimental and predicted data is obtained. As (5) is in a suitable form for machine computation the trial and error procedure is not very tedious.

For the second method of evaluating the heat-transfer coefficient we stipulate a boundary condition which is a sinusoidal variation of temperature with time:

$$T(o_1, t) = A\cos\omega t\,. \qquad (6)$$

Assume a steady state solution of the general form

$$T(x, t) = B(x)\cos\left[\omega t + \theta(x)\right] \qquad (7)$$

which at $x = 0$ gives (6).

(6) and (7) are the real parts of

$$T(o, t) = Ae^{i\omega t} \qquad (8)$$

and

$$T(x, t) = B(x)e^{i\omega t} \qquad (9)$$

where B may be complex.

Hence $\dfrac{\partial T}{\partial t} = i\omega T$ and equation (3) becomes

$$\frac{i\omega}{h}\frac{\partial T}{\partial x} + \frac{i\omega}{Sv}T + \frac{1}{C}\frac{\partial T}{\partial x} = 0. \qquad (10)$$

The solution of this equation is

$$T(x, t) = A\exp\left\{\frac{-hx}{Sv\left[1 + (h^2/\omega^2 c^2)\right]}\right\}$$
$$\cos\left\{\omega t - \frac{C\omega x}{Sv\left[1 + (\omega^2 c^2/h^2)\right]}\right\}. \qquad (11)$$

The theory thus predicts that for a sinusoidal heat input into the bed the temperature at a point x along the bed is still a sine function of the same frequency but attenuated by the factor

$$\alpha x = \frac{+hx}{Sv\left[1 + (h^2/\omega^2 C^2)\right]}, \qquad (12)$$

where ω is the angular frequency of the input, and lagging in phase by the angle

$$\theta = \frac{C\omega x}{Sv\left[1 + (\omega^2 C^2/h^2)\right]}. \qquad (13)$$

Both quantities, α and θ may be measured experimentally and hence h determined.

It is sometimes convenient to think in terms of wavelengths instead of phase lag and by using the relation

$$\lambda = \frac{x}{\theta}2\pi \qquad (14)$$

one obtains

$$\lambda = 2\pi Sv\left(\frac{1}{C\omega} + \frac{C\omega}{h^2}\right) \qquad (15)$$

where λ is the wavelength.

* This is a slightly more accurate equation than that used by Ledoux.

Equation (12) is a quadratic and hence yields two values for h. To illustrate the course of this equation the values of $\omega^2 C^2 = 10^{-4}$ and $Sv = 10^{-2}$ have been substituted and α plotted against h in Fig. 1. It is interesting to note that for a given set of constants, a maximum in the attenuation occurs for a particular value of h ($h = C\omega$), otherwise the function is two-valued. The best procedure for deciding which value of h is operative in the bed, is to test the consistency with equation (15). Substituting either value of h into equation (15) gives two values for the wavelength, λ. When these are compared with the wavelength obtained by measurement, the appropriate value of λ and hence of h becomes apparent.

EXPERIMENTAL

A bed of terylene fibres of $18{\cdot}5 \times 10^{-4}$ cm diameter was formed in a tube of "Ozonite" of about 10 cm internal diameter and 2·5 cm wall thickness. "Ozonite" is a commercial lagging material possessing the characteristics of low thermal conductivity and heat capacity. The bed was made as uniform as possible by cutting the fibres to short lengths of about 0·1 to 0·2 cm and distributing them evenly over the cross section of the tube. To avoid the formation of regions of unequal density the bed was compressed until a packing density of 0·108 g/cm^3 was obtained. The final length of the bed was 15·6 cm.

Temperatures within the bed were measured with copper–constantan thermocouples (48 S.W.G.) and recorded to an accuracy of at least $\pm$ 0·05 degC. The temperature indicated by a couple would follow very closely the temperature of the terylene fibres in its immediate vicinity because of the similarity in physical dimensions. If in error, the couple would tend to lag slightly in time because of its larger thermal inertia. However, except very close to the upstream face of the bed the rates of change of temperature were sufficiently slow for the couples to respond with negligible error. In fact, the rates of change were so slow that the difference between air and fibre temperatures were very small compared to the total change taking place, so that the question whether the couples measured the fibre or the air temperature was of academic interest only.

A total of nine thermocouples were placed in the bed in three planes at right angles to the axis, 1·3, 7·8 and 14·3 cm distant from the upstream face. Each plane contained three couples, equidistant from one another and within a radius of 1 cm from the axis of the bed. This arrangement permitted the measurement

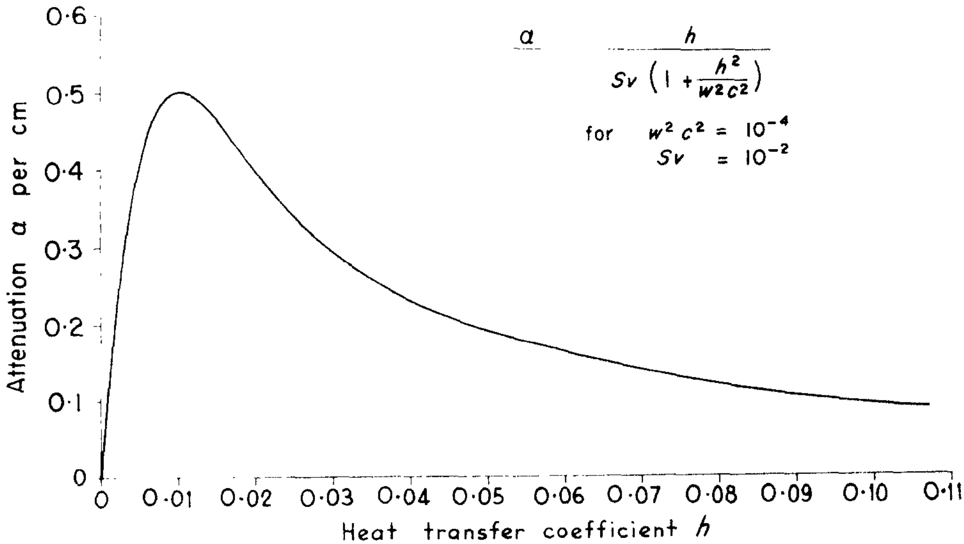

FIG. 1. Dependence of heat-transfer coefficient on attenuation for sinusoidal temperature input.

of the spatial progress of temperature fronts along the direction of the axis of the bed as well as the spread in the times of arrival of these fronts at any one plane.

An approximate step function of temperature was applied to the bed by raising its temperature uniformly with a stream of hot air. The air flow was then reversed so that cool room air passed through the bed in the opposite direction. As a perfect step function was not achieved the data given by Ledoux [4] could not be applied for the analysis of the results. Instead, a procedure was adopted by which the temperature–time record of a thermocouple (No. 2) in the first plane at 1·3 cm from the upstream face was treated as the input temperature function for the three couples (Nos. 4, 5 and 6) in the second plane at 7·8 cm from the face of the bed.

To produce a sinusoidal input of heat into the bed, electric power derived from a cam operated "Variac" following the function voltage $= \sqrt{(1 + \sin \omega t)}$ was applied to a bare wire heater in the air stream about 2·5 cm in front of the bed. The frequency of oscillation and air speed were adjustable. As before, measurements of temperature were made with thermocouples in the three selected planes in the bed. In addition, a second fibre bed of similar characteristics to the first one was built up in which the thermocouples were replaced by fine wire resistance thermometers (48 S.W.G. copper) carefully woven into a glass fibre mesh of open texture so as to cover evenly a disc of about 7 cm diameter in the centre of the bed. The purpose of this was to confirm that the results derived from these measurements were in agreement with those from the thermocouples.

RESULTS AND DISCUSSION

(a) *Arbitrary input function of temperature*

A number of measurements were made for varying rates of air flow, but for the purpose of analysis a test with a flow rate of 25*l*/min, corresponding to a linear flow of 5·1 cm/s is considered here. The temperature–time curve for couples Nos. 2–6, the first two at the distance of 1·3 cm and the last three at 7·8 cm from the front of the bed are shown in Fig. 2. Air at 20·5 degC was blown through the bed, originally at 26 degC. In this figure, and in Fig. 3 only, the absolute change in temperature with respect to time is recorded. Curves 4–6 in Fig. 2 were normalized to allow for small final temperature differences.

It is apparent that couples embedded at equivalent positions along the bed do not show identical temperature–time relations. This is attributed to the fact that although every care was taken in producing a uniform bed, this has obviously not been achieved and either air flow, or density of packing or both were not uniform across any given sections. At the same time, considering couples 4–6, the main difference in behaviour of the temperature front appears to be a shift along the time axis rather than a change in slope. This shift indicates that the local air streams in which the various couples are situated had different equivalent path lengths rather than different heat-transfer coefficients which would have resulted primarily in a change of slope. It is visualized that although the air in the bed moves in streamlines, these need not be straight. Also, adjoining streamlines need not necessarily encounter the same number of fibres in a given distance or be of uniform velocity. Any or all of these three factors may serve as an explanation that the temperature front as indicated by couples Nos. 4–6 appear at different distances along the time axis. The overall effect is the same as if the air in the streamlines in which the individual couples are situated had experienced different (equivalent) path lengths. These concepts will be discussed more rigorously in Part II.

A numerical analysis was considered worth while. The curve for thermocouple No. 2, was chosen as the boundary condition and it was established by trial and error (the calculations were made by "Silliac"*) that a value of the heat-transfer coefficient $h = 0{\cdot}0025$ cal/s^{-1} degC^{-1} cm^{-3} gave a close fit, the predicted shape of the front at distances of 6·4 and 8·3 cm from the first set of couples being shown in Fig. 1. The actual separation of the two sets of couples was 6·5 cm. Had couple No. 3 been chosen as giving the boundary condition, a better value for the path length would have been obtained for couple No. 4.

* Fast digital computer situated at University of Sydney, Australia.

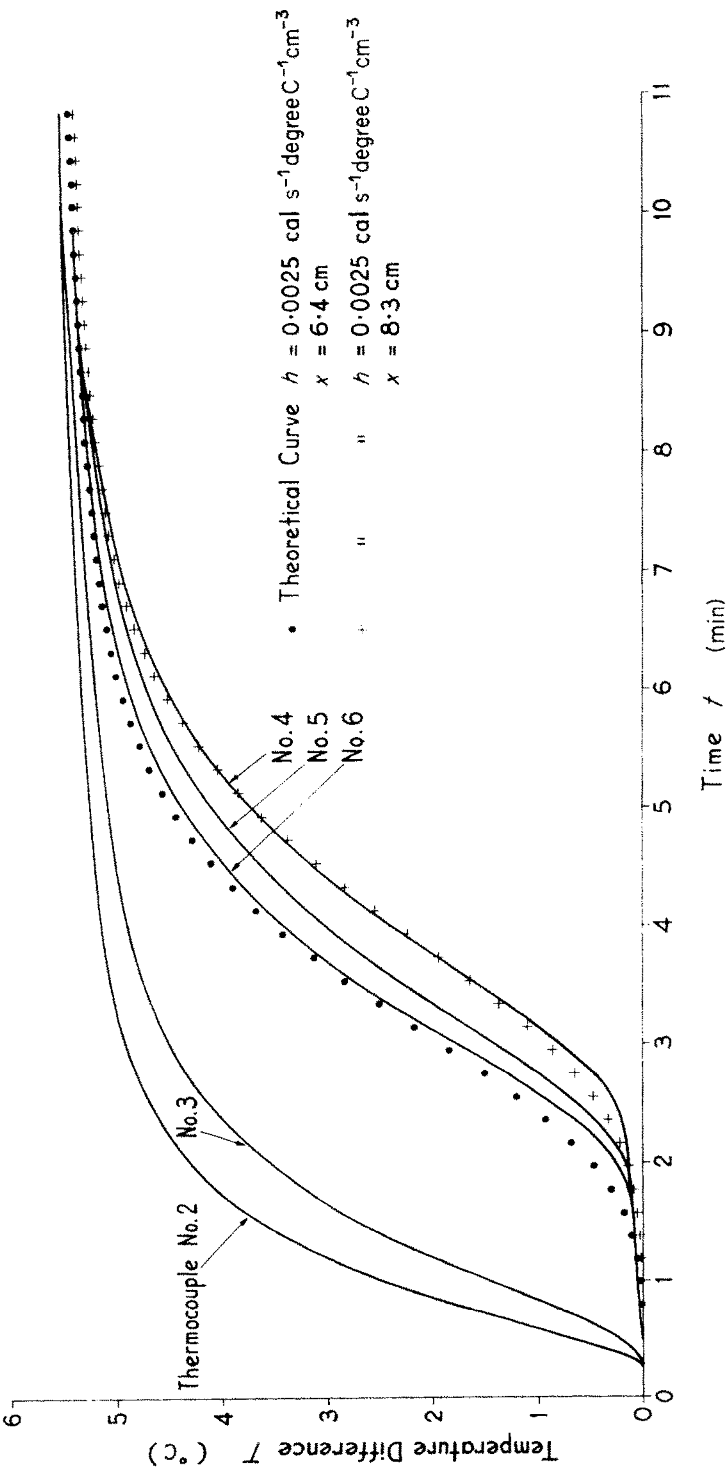

FIG. 2. Experimental and theoretical curves for step function input of temperature. Cooling from 26°C to 20·5°C.

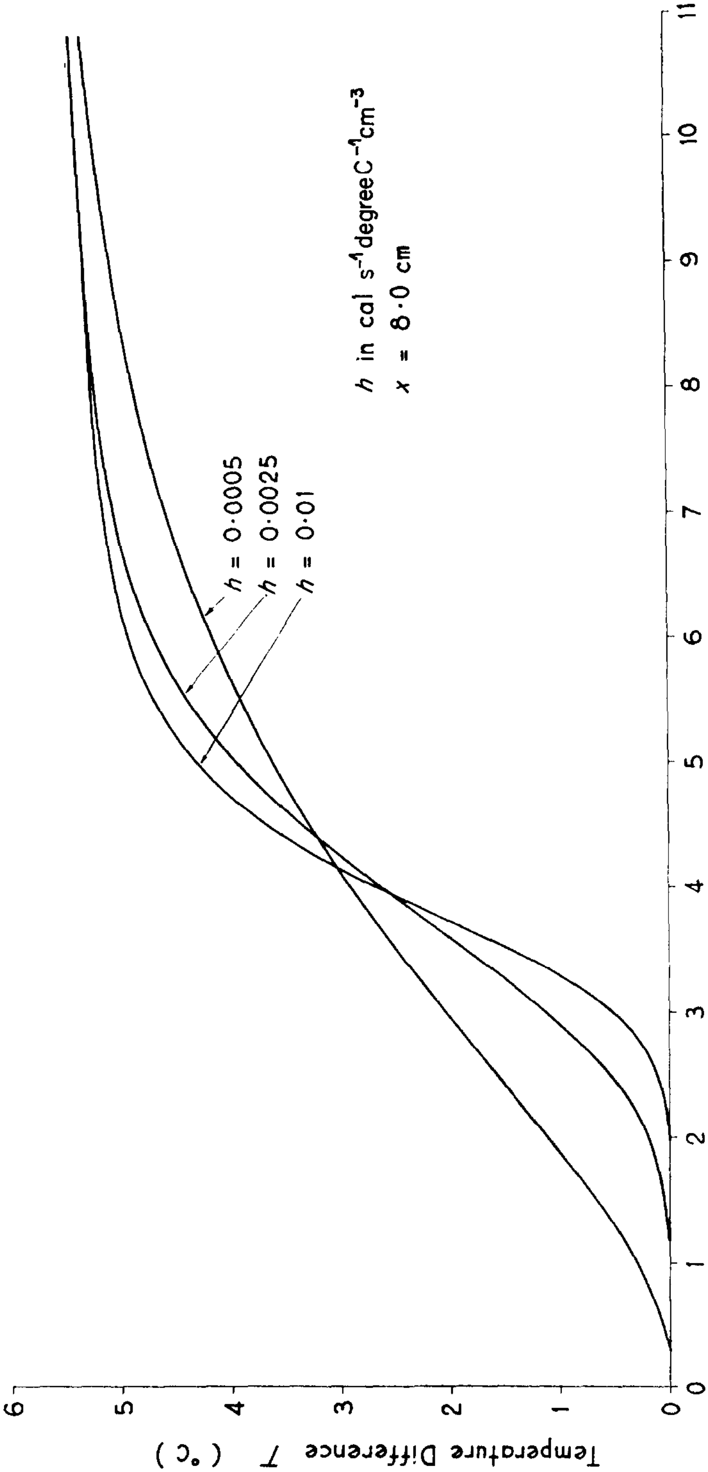

FIG. 3. Effect of variation of heat-transfer coefficient on shape of temperature front. Calculated for a step of 5·5°C.

To illustrate the influence of a change in heat-transfer coefficient values of h of 0·01, 0·0025 and 0·0005 c.g.s. units were chosen to compute the appearance of the front at an equivalent path length of 8 cm. The results are shown in Fig. 3 and it is apparent that the change of slope of the front is a fairly sensitive criterion for the value of h.

It is interesting now to compare the value of h effective in the bed with that of an isolated fibre under the conditions of flow used. MacAdams [5] gives an empirical relation for heat transfer in flow at right angles to isolated cylinders which, under the conditions here give a value of $H = 0{\cdot}14$ cal s^{-1} degC^{-1} cm^{-2}. This value has to be multiplied by the value of the surface area of fibres per unit volume of bed to obtain h as defined above and this gives

$$h = 2{\cdot}5 \text{ cal/s}^{-1} \text{ degC}^{-1} \text{ cm}^{-3}$$

which is 1000 times as large as the value obtained by experiment. This discrepancy is too large to be due to experimental errors, faults in the technique or secondary factors which have been neglected such, for example, as the fact the value for H given by MacAdams is for cross flow at right angles only and includes radiation. Hence the conclusion presents itself that the theory is inadequate to describe heat transfer beds of fibres.

(b) *Sinsoidal input function of temperature*

Several sets of experiments, using either thermocouples or resistance thermometers were performed. As the results were essentially the same and since the work with the resistance thermometers was more complete, only the latter is reported here. The data obtained are summarized in Table 1.

The attenuation α was obtained from the amplitudes of the sinusoidal temperature variations at the first and last resistance thermometers, T_1 and T_3, which were separated by a distance of 14·6 cm.

$$14{\cdot}6\,\alpha = \log_e \frac{T_3}{T_1}. \qquad (16)$$

By using the longest available bed depth, more accurate estimates of α and λ were obtained. The heat-transfer coefficient h was calculated using equation (12) and the wavelength λ by substituting the calculated value of h (the larger of the two values obtained from the quadratic equation) into equation (15). The experimental values of λ were obtained from measured values of the phase lag θ and equation (14).

An examination of the data contained in Table 1 leads to the following conclusion:

(a) There is good agreement between the measured and calculated wavelengths and hence a high degree of certainty that the correct value of h was chosen from the two-valued function. As an example of the effect of the wrong choice the corresponding values h^1 and λ^1 at the flow rate of 90·6 cm/s and period 20·3 s have been included in the table. It is also noted that there is a small but definite bias making the calculated wavelengths longer than the measured ones. This may be due to a small systematic error in the measurement of air flow or other physical data for the bed.

(b) The calculated heat-transfer coefficient is a function of the air flow. This is quite expected in principle and the value of h calculated from MacAdams' data [5] show that for a single fibre h increases by 33 per cent on increasing the flow rate from 20·6 to 61·8 cm/s. However, the data in the table show that at a period of 90 s the corresponding increase is 5 per cent, at 61·5 s 17 per cent and at 30·7 s 70 per cent. It is therefore obvious that although there is a dependence on air flow, it is not the same as for a single fibre.

(c) There is a strong dependence of the apparent heat-transfer coefficient on the frequency of oscillation. For a flow of 90·6 cm/s and a period of 90 s h is 0·0132 c.g.s. units while at a period of 10 s it is 0·147 c.g.s. units. The ratio in h is 1 to 11 which is approximately the inverse of the period. A similar relationship holds for the other frequencies and the results indicate that h is almost inversely proportional to the period of oscillation. The dependence of the measured heat-transfer

Table 1

1 Linear flow (cm/s)	2 Observed attenuation (α)	3 Transfer coefficient h calculated according to (12)	4 Wavelength calculated from h and (15) (λ cm)	5 Wavelength measured from phase lag (14) (λ cm)
Period of oscillation = 90 s				
90·6	0·015	0·0132	75·4	58·4
61·8	0·025	0·0117	51·8	50·0
41·2	0·037	0·0117	34·7	38·5
30·9	0·053	0·0110	26·1	25·0
20·6	0·079	0·0111	17·5	14·8
15·2	0·126	0·0093	13·1	10·0
9·9	0·200	0·0090	8·5	6·2
6·2	0·330	0·0086	5·3	4·5
Period of oscillation = 61·5 s				
90·6	0·023	0·0189	50·0	50·0
61·8	0·032	0·0199	34·1	35·0
41·2	0·050	0·0190	22·9	21·9
30·9	0·070	0·0181	17·1	15·9
20·6	0·113	0·0169	11·5	10·6
15·2	0·179	0·0143	8·5	7·6
9·9	0·304	0·0126	5·5	5·5
Period of oscillation = 30·7 s				
90·6	0·036	0·0570	25·3	25·0
61·8	0·049	0·0528	17·3	17·5
41·2	0·080	0·0508	11·6	11·3
30·9	0·133	0·0382	8·8	8·3
20·6	0·245	0·0305	6·0	5·7
15·2	0·340	0·0297	4·4	4·1
Period of oscillation = 20·3 s				
90·6	0·055	0·0709	16·9	15·3
		$h^1 = 0{\cdot}0016$	$\lambda^1 = 794$	
61·8	0·086	0·0682	11·5	11·3
41·2	0·151	0·0571	7·8	7·6
30·9	0·231	0·0497	5·9	6·0
Period of oscillation = 10 s				
90·6	0·112	0·147	8·3	8·3
61·8	0·215	0·111	5·7	5·7
41·2	0·353	0·0997	3·9	3·9

coefficient on the period of oscillation is not predicted by equation (11) which stipulates that attenuation and frequency should vary in a manner so as to keep h constant. Hence, the observed behaviour constitutes a failure of the theory to account for the experimental results.

(d) The absolute value of the apparent heat-transfer coefficient is smaller than that for a single fibre by factors ranging from 300 to 17. It is interesting to note that if one accepts an inverse proportionality between h and period of oscillation and extrapolates to longer periods, then substantial agreement would be obtained between the sine wave and approximate step function input results. The curve which was used for the boundary condition of the step function case could be subjected to harmonic analysis. By inspection, the dominant frequency appears to have a period of about 300–350 s which would reduce the value of h of 0·0086 c.g.s. units at 6·2 cm/s at a period of 90 s to one-third or one-fourth of its value bringing it close to 0·0025 as found for the step function case.

The results so far have been concerned with heat-transfer coefficients deduced from the behaviour of the fibre bed as a whole unit and these have been found to be much smaller than those expected for single fibres at similar air flows. It has to be established, therefore, whether the discrepancy is caused by the local heat transfer between individual fibres and the air in their immediate vicinity or by a failure of the bed as a whole to conform to the established theory.

To examine this point experimentally, one of the resistance thermometers was used simultaneously as a heater and thermometer simply by increasing the measuring current in the bridge circuit. Air at constant temperature was blown through the bed and the fine wire and the thermometer, kept at a temperature higher than that of the air. Thus heat was transferred under a constant temperature differential, the amount of heat being obtained from the energy input into the wire and the temperature from its resistance. The value of H thus obtained was very close to that calculated from MacAdams' [5] data, being about 10 per cent higher.*

CONCLUSION

The only inference which can be drawn from the foregoing examination of the theory of convective heat transfer in beds of granular solids is that it is inapplicable to fibrous beds. The apparent value of the heat-transfer coefficient is not predicted by the theory nor the correct functional relationship between heat-transfer coefficient flow rate and frequency. Hence one or more of the assumptions made in formulating the theory do not describe the physical conditions prevailing in the bed of fibres. Of the four assumptions made, (d) relating to flow non-uniformities is the most suspect and will be treated in detail in a subsequent paper.

There is a strong possibility, which is not explored here any further, that the failure of fibrous beds to conform with the theoretical treatment is not due to a failure of the conditions of heat transfer in the locality of individual fibres but rather due to flow imperfections. At the same time, it is believed that these flow imperfections are inevitably associated with a matrix of this kind. It is interesting to speculate to what extent these considerations apply to other examples of granular beds where the physical parameters are different. It is quite possible, that in cases where the surface to volume ratios of the solids is lower than in the present case, the conventional theory may well describe the behaviour of the system. On the other hand, there may be systems where an indiscriminate application of the existing theory may lead to error.

* A similar result using a resistance thermometer was obtained some years ago by N. F. Roberts and A. R. Haly of this laboratory. Private communication.

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Résumé—La théorie de la transmission de chaleur par convection forcée dans les lits poreux a éte étudiée expérimentalement sur des lits de fines fibres. On a trouvé que la théorie actuelle n'était pas applicable pour deux raisons: elle ne permet pas d'évaluer le coefficient de transmission de chaleur exact et ne donne pas des relations correctes entre les différents paramètres expérimentaux. On pense qu'une des raisons de cet échec est due à des défaults d'écoulement inévitables dans le lit.

Zusammenfassung—Mit Hilfe von Schüttungen aus feinen Fasern wurde die Theorie des Wärmeüberganges bei erzwungener Konvektion in Festbetten aus gekörntem Material experimentell untersucht. Aus zwei Gründen erweist sich die gegenwärtige Theorie als nicht anwendbar: sie gestattet keine genaue Berechnung des Wärmeübergangskoeffizienten und zeigt auch nicht, welche exakten Beziehungen zwischen den experimentellen Variablen bestehen. Als Grund dafür wird die nicht vermeidbare Unvollkommenheit der Strömung in der Schüttung angesehen

Аннотация—Теория теплообмена при вынужденной конвекции в слоях твердых частиц исследовалась экспериментально для случая тонких волокон. Найдено, что существующая теория неудовлетворительна по двум причинам. Она не позволяет надежно определять коэффициент теплообмена и не дает точных зависимостей между экспериментальными переменными. Предполагают, что причиной этого является неизбежная неравномерность распределения потока в слое.