Int. J. Heat Mass Transfer. Vol. 13, pp. 537–546. Pergamon Press 1970. Printed in Great Britain

A TECHNIQUE FOR PREDICTING THE THERMAL CONDUCTIVITY OF SUSPENSIONS, EMULSIONS AND POROUS MATERIALS

S. C. CHENG
Mech. Engineering Dept., University of Ottawa, Ottawa, Canada

and

R. I. VACHON
Mech. Engineering Dept., Auburn University, Auburn, Alabama

(*Received* 12 *February* 1969)

Abstract—A theoretical technique to predict the thermal conductivity of heterogeneous mixtures, previously derived by the writers, has been applied to suspensions, emulsions and porous materials. Based on the data available from the literature, the technique is shown to predict the values of thermal conductivity within 18·2 per cent for suspensions, 9·5 per cent for emulsions and 9·9 per cent for porous materials.

NOMENCLATURE

- B, constant in the parabolic distribution;
- C, constant in the parabolic distribution;
- d, diameter of pore [cm];
- e, emissivity;
- k, thermal conductivity [Btu/h ft °F or cal/s cm °C];
- P, phase volume fraction;
- P_{cs}, cross-sectional pore fraction;
- P_l, longitudinal pore fraction;
- Q, ratio of k_s/k_a;
- R, thermal resistance [h °F/Btu];
- T, absolute temperature [°R or °K].

Greek letters

- γ, geometrical pore factor;
- σ', radiation constant [erg/cm^2 s °C^4].

Subscripts

- a, air;
- c, continuous phase;
- d, discontinuous phase;
- e, equivalent;
- m, mean;
- s, solid.

INTRODUCTION

A THEORETICAL technique to predict the thermal conductivity of heterogeneous solid mixtures has been developed and reported by the writers [1]. The technique considers the aggregate as a single model as opposed to conventional methods which consider the aggregate as a repetitive array of unit cells. The key assumption of the technique is that the discontinuous phase can be rearranged in the continuous phase, such that the former can be described by a parabolic distribution function with appropriate boundary conditions.

The technique was developed assuming conduction as the predominant mode of heat transfer. The purpose of this paper is to show the applicability of the technique to suspensions, emulsions and porous materials. The assumption that radiative and convective heat transfer are negligible is maintained.

A number of studies [2–13] has been conducted to develop techniques for predicting the thermal conductivity of heterogeneous systems. Table 1 lists some of the equations resulting from the above studies. These equations will be examined and used in conjunction

Table 1. Equations for predicting conductivity of mixtures

A. Maxwell [2]—two-phase mixtures

$$k_m = \frac{k_c[k_d + 2k_c - 2P_d(k_c - k_d)]}{k_d + 2k_c + P_d(k_c - k_d)}. \tag{4}$$

B. Jefferson [5]—two-phase mixtures

$$k_m = k_c\left[1 - \frac{\pi}{4(1 + 2n)^2}\right] + \frac{\pi}{4(1 + 2n)^2}\left[\frac{(0{\cdot}5 + n)k_a k_c}{0{\cdot}5k_c + nk_a}\right]. \tag{5}$$

where

$$k_a = k_c k_d\left[\frac{2k_d}{(k_d - k_c)}\ln\frac{k_d}{k_c} - \frac{2}{k_d - k_c}\right]$$

and

$$n = 0{\cdot}403P_d^{-1/3} - 0{\cdot}5.$$

C. Russell [10]—two-phase mixtures (porous materials)

$$k_m = k_c\left[\frac{P_d^{2/3} + \dfrac{k_c}{k_d}(1 - P_d^{2/3})}{P_d^{2/3} - P_d + \dfrac{k_c}{k_d}(P_d + 1 - P_d^{2/3})}\right]. \tag{6}$$

D. Loeb [11]—porous materials considering radiation

$$k_m = k_s\left[(1 - P_{cs}) + \frac{P_{cs}}{P_j k_s/4\sigma' e\gamma d T_m^3 + (1 - P_j)}\right]. \tag{7}$$

E. Francl and Kingery [12]—porous materials

$$k_m = k_s(1 - P_d). \tag{8}$$

F. Eucken [13]—porous materials

$$k_m = k_s\frac{1 + 2P_d\dfrac{1 - Q}{2Q + 1}}{1 - P_d\dfrac{1 - Q}{2Q + 1}}, \tag{9}$$

where

$$Q = \frac{k_s}{k_a}.$$

G. The Writers' equations [1] can be expressed as

A. $k_c > k_d$.

$$R_e = \frac{2}{\sqrt{\{C(k_d - k_c)[k_c + B(k_d - k_c)]\}}}\tan^{-1}\frac{B}{2}\sqrt{\left\{\frac{C(k_d - k_c)}{k_c + B(k_d - k_c)}\right]} + \frac{1 - B}{k_c}, \tag{10}$$

where

$$B = \sqrt{(3P_d/2)}, \qquad C = -4\sqrt{[2/(3P_d)]}$$

and

$$R_e = 1/k_m.$$

B. $k_d > k_c$.

$$R_e = \frac{1}{\sqrt{\{C(k_c - k_d)[k_c + B(k_d - k_c)]\}}}\ln\frac{\sqrt{[k_c + B(k_d - k_c)]} + \dfrac{B}{2}\sqrt{[C(k_c - k_d)]}}{\sqrt{[k_c + B(k_d - k_c)]} - \dfrac{B}{2}\sqrt{[C(k_c - k_d)]}} + \frac{1 - B}{k_c}, \tag{11}$$

Table 1. Continued

where $R_e = \frac{1}{k_m}$. If $k_d \gg k_c$, then equation (11) takes a very simple form, i.e.

$$R_e = \frac{1 - B}{k_c} \qquad (12)$$

as shown in [1].

with data from the literature. Hamilton [6] has classified mixtures as follows:

Class I: $k_c \gg k_d$ or $k_c/k_d > 100$

Class II: $k_d \gg k_c$ or $k_d/k_c > 100$

Class III: $1 < k_c/k_d < 100$

Class IV: $1 < k_d/k_c < 100$

and these classifications will be used in this paper.

Suspensions, emulsions and porous materials are discussed as follows.

SUSPENSIONS

A suspension refers to solid particles suspended in a liquid. The density of the discontinuous phase must be comparable to that of the continuous phase for a suspension to exist. A number of techniques have been proposed to predict the thermal conductivity of suspensions. Maxwell [2], Rayleigh [3], Bruggeman [4], Jefferson [5], Hamilton [6], Tsao [7], Baxley [8] and Russell [10] constitute some of the major contributors. Table 2 presents some existing experimentally determined values of conductivity for various suspensions and predicted values of thermal conductivity as determined from the techniques developed by Maxwell [2], Baxley [8], Russell [10] and equations (11) and (12) of Ref. [1]. All the predicted values by Maxwell, Baxley and Russell in Table 2 are taken directly from Table 15 of Ref. [8]. The average percentage of deviation of predicted values from the measured values of thermal conductivity is shown in Table 5 (A). None of these methods predict a consistently satisfactory result. In general, as the ratio of k_d/k_c increases, the percentage of deviation from the measured value of thermal conductivity increases. The ratio of k_d/k_c in Class IV mixtures is less than that of Class II mixtures. Therefore, the existing equations including the writer's equations predict the thermal conductivity of Class IV mixtures better than the Class II mixtures.

Many suspensions are Class II mixtures, i.e. $k_d \gg k_c$. Hence equation (12) which is an approximation of equation (11) takes a very simple form for Class II mixtures and can be used to predict the thermal conductivity as satisfactorily as any of the other techniques. As can be seen equation (12) predicts almost the same values as equation (11). Equation (12) is not a function of k_d as can be seen. Thus the thermal conductivity of the discontinuous phases is insignificant in comparison to the conductivity of the mixture in Class II mixtures. Equations (11) and (12) give acceptable results, and equation (12) is simpler in form than any of the other techniques.

EMULSIONS

An emulsion refers to liquid droplets distributed throughout an immiscible liquid. The characteristics of emulsions [9] are;

1. The density of the continuous phase and discontinuous phase should be comparable.
2. The discontinuous phase droplets are spherical.
3. The continuous phase is viscous enough

Table 2. Comparison of the predicted thermal conductivities with experimental data of suspensions

Classification of mixtures	System of mixtures: Solid	System of mixtures: Liquid	P_d	k^*_{exp}	Reference of experiment	Maxwell: k_m	Maxwell: Percentage of deviation
Class II mixtures	Graphite $k_d = 93$	Water $k_c = 0.325$	0·161	0·685	Jefferson [5]	0·5089	−25·60
			0·247	0·978		0·6404	−34·50
			0·321	1·237		0·7789	−37·00
	Graphite $k_d = 93$	Silicone oil $k_c = 0.0875$	0·194	0·241		01505	−37·60
			0·251	0·282		0·1751	−37·90
			0·310	0·344		0·2050	−40·40
			0·375	0·453		0·2443	−46·10
			0·423	0·546		0·2790	−28·90
	Aluminum $k_d = 118$	Water $k_c = 0.380$	0·055	0·440	Johnson [14]	0·4457	1·29
			0·115	0·560		0·5365	−5·98
			0·175	0·810		0·6190	−23·60
			0·210	1·000		0·6794	−32·10
	Copper $k_d = 221$	Water $k_c = 0.380$	0·055	0·430		0·4460	3·72
			0·115	0·540		0·5273	−2·36
			0·175	0·660		0·6203	−6·01
			0·210	0·740		0·6811	−7·96
			0·245	0·830		0·7474	−9·95
			0·295	1·050		0·8536	−18·70
	Iron $k_d = 37.8$	Lard $k_c = 0.114$	0·108	0·115		0·1550	0·01
			0·194	0·218		0·1954	−10·40
			0·322	0·339		0·2743	−19·10
Class IV mixtures	Zinc sulphate $k_d = 0.354$	Lard $k_c = 0.114$	0·238	0·143	Lees [15]	0·1512	5·75
			0·375	0·179		0·1766	−1·36
			0·555	0·203		0·2155	6·16
	Marble $k_d = 1.72$	Vaseline $k_c = 0.107$	0·250	0·153		0·1916	25·20
			0·430	0·262		0·2865	9·35
			0·600	0·432		0·4285	−0·80
	Selenium $k_d = 3$	PPG $k_c = 0.081$	0·100	0·104	Baxley [6]	0·1057	1·45
			0·200	0·123		0·1360	7·53
			0·300	0·182		0·1741	−4·51
			0·400	0·244		0·2233	−8·57
			0·500	0·281		0·2893	3·07
Average percentage of deviation							16·3

* Units of k: Btu/h ft°F.

Baxley		Russell		Equation (11)		Equation (12)	
k_m	Percentage of deviation	k_m	Percentage of deviation	k_m	Percentage of deviation	k_m	Percentage of deviation
0·4646	−32·20	0·7029	2·62	0·6250	−8·75	0·638	−6·86
0·6186	−36·70	0·8595	−12·10	0·8070	−17·50	0·829	−15·24
0·8762	−29·20	1·0144	−18·00	1·0370	−16·20	1·065	−13·90
0·1333	−44·50	0·2070	−14·10	0·1890	−27·50	0·190	−21·20
0·1722	−38·90	0·2360	−16·30	0·2240	−20·50	0·226	−19·88
0·2416	−29·80	0·2696	−21·60	0·2730	−20·70	0·276	−19·80
0·3792	−16·30	0·3123	−31·10	0·3450	−23·70	0·350	−22·75
0·7743	41·80	0·3492	−36·00	0·4260	−21·90	0·433	−20·70
0·4179	−5·01	0·6051	37·50	0·5260	19·55	0·530	21·00
0·4641	−17·10	0·7304	30·40	0·6390	14·10	0·650	16·10
0·5646	−30·30	0·8513	5·10	0·7630	−5·80	0·779	−3·83
0·6029	−39·70	0·9246	−7·54	0·8450	−15·50	0·863	−13·70
0·4166	−3·11	0·6088	41·60	0·5290	23·00	0·533	23·80
0·4738	−12·30	0·7347	36·10	0·6440	19·30	0·650	20·40
0·5392	−18·30	0·8564	29·80	0·7700	16·70	0·779	18·00
0·6697	−9·50	0·9303	25·70	0·8530	15·30	0·864	16·76
0·7363	−11·29	10·079	21·40	0·9480	14·20	0·962	15·90
1·0025	−4·53	1·1280	7·43	1·1150	6·20	1·134	8·00
0·1394	10·10	0·2151	38·80	0·1880	21·30	0·191	22·90
0·1786	−18·10	0·2674	22·70	0·2430	11·46	0·248	13·76
0·3180	−6·20	0·3574	5·43	0·3620	6·78	0·374	10·32
0·1407	−1·64	0·1577	10·30	0·1530	7·00		
0·1578	−11·90	0·1829	2·21	0·1780	−0·56		
0·1789	−11·90	0·2203	8·51	0·2190	7·74		
0·1689	10·40	0·2325	51·90	0·2130	39·20		
0·2473	−5·63	0·3303	26·10	0·3340	27·60		
0·3557	−17·70	0·4683	8·39	0·6020	39·50		
0·0964	−7·50	0·1376	32·00	0·1213	16·40		
0·1202	−5·01	0·1776	39·50	0·1580	24·90		
0·1585	−13·10	0·2192	20·20	0·2069	13·50		
0·2162	−11·50	0·2709	10·90	0·2805	14·90		
0·2958	5·39	0·3378	20·30	0·4067	45·00		
	17·4		21·6		18·2		

Table 3. Comparison of the predicted thermal conductivities with experimental data of emulsions

Systems of mixtures	k_d^*	k_c	P_d	Temp. (°F)	k_{exp}	Maxwell		Jefferson		Russell		Equation (11)	
						k_m	Percentage of deviation	k_m	Percentage of deviation	k_m	Percentage of deviation	k_m	Percentage of deviation
Cellosize in EPO	0·269	0·078	0·1	40·0	0·0806	0·0884	9·68	0·0861	6·83	0·092	14·50	0·091	12·65
	0·318	0·096	0·1	100·0	0·1100	0·1090	− 0·91	0·1070	− 2·73	0·114	3·64	0·111	0·91
	0·332	0·110	0·1	140·0	0·1210	0·1240	2·48	0·1210	0·00	0·128	5·78	0·126	4·13
	0·269	0·078	0·3	40·0	0·1040	0·1140	9·61	0·1100	5·77	0·120	15·40	0·116	11·54
	0·318	0·096	0·3	100·0	0·1360	0·1400	2·94	0·1350	− 0·74	0·146	7·35	0·141	3·68
	0·332	0·110	0·3	140·0	0·1480	0·1550	4·73	0·1510	2·03	0·161	8·78	0·157	6·08
Cellosize in PPG	0·269	0·064	0·1	40·0	0·0672	0·0747	11·16	0·0723	7·59	0·079	17·86	0·077	−13·84
	0·318	0·087	0·1	100·0	0·1050	0·1000	− 4·76	0·0971	− 3·24	0·105	0·00	0·102	− 2·86
	0·332	0·089	0·1	140·0	0·1040	0·1020	−1·92	0·0992	−4·61	0·107	2·88	0·105	0·96
	0·269	0·064	0·3	40·0	0·0897	0·0994	10·80	0·0953	6·25	0·106	18·20	0·101	12·60
	0·318	0·087	0·3	100·0	0·1350	0·1300	−3·70	0·1250	−7·40	0·137	1·48	0·132	−2·12
	0·332	0·089	0·3	140·0	0·1570	0·1330	−15·30	0·1280	−18·50	0·141	−10·20	0·136	−13·40
Water in petroleum solvent	0·349	0·105	0·2	75·3	0·1540	0·1360	−11·70	0·1310	−14·93	0·142	−7·80	0·137	−11·04
	0·356	0·093	0·2	86·3	0·1270	0·1230	−3·15	0·1180	−7·09	0·131	3·15	0·126	−0·79
	0·342	0·118	0·4	64·0	0·2250	0·1830	−18·70	0·1780	−20·90	0·189	−16·00	0·184	−18·20
	0·352	0·100	0·4	80·2	0·1800	0·1670	−7·22	0·1610	−10·55	0·174	−3·34	0·169	−6·11
	0·341	0·119	0·6	62·4	0·2690	0·2260	−16·00	0·2190	−18·60	0·229	−14·90	0·230	−14·50
	0·349	0·106	0·6	74·6	0·2340	0·2180	−6·84	0·2110	−9·83	0·222	−5·13	0·223	−4·70
Water in mineral oil	0·340	0·095	0·2	60·5	0·1660	0·1240	−25·30	0·1200	−27·70	0·131	−21·10	0·123	−24·10
	0·352	0·086	0·2	80·1	0·1350	0·1160	−14·10	0·1110	−17·80	0·123	−8·90	0·118	−12·60
	0·344	0·094	0·4	62·0	0·1970	0·1590	−19·30	0·1540	−21·80	0·166	−15·74	0·162	−17·80
	0·347	0·090	0·4	71·1	0·1840	0·1550	−15·80	0·1500	−18·50	0·163	−11·40	0·158	−14·10
	0·353	0·086	0·4	81·4	0·1690	0·1520	−10·06	0·1460	−13·60	0·160	−5·33	0·155	−8·29
	0·342	0·094	0·6	63·0	0·2580	0·2040	−20·95	0·1970	−23·65	0·209	−19·00	0·211	−18·20
	0·348	0·089	0·6	72·7	0·2270	0·2010	−11·45	0·1940	−14·52	0·206	−9·25	0·209	−7·93
	0·353	0·086	0·6	81·3	0·2000	0·1990	−0·50	0·1920	−4·00	0·205	2·50	0·209	4·50
Average percentage of deviation							10·0		11·1		9·6		9·5

* Units of k: Btu/h ft °F.

Table 4. Comparison of the predicted thermal conductivities with experimental data of porous materials

Characteristics of porous materials	P_d	K_{exp}	Russell		Loeb		Eucken		Equation (10)	
			k_m	Percentage of deviation	k_m	Percentage of deviation	k_m	Percentage of deviation	k_m	Percentage of deviation
Alumina, Al_2O_3, with	0·10	0·0450	0·0445	−1·110	0·0460	2·22	0·0435	−3·33	0·0445	−1·11
isometric pores at 200°C	0·20	0·0400	0·0390	−2·500	0·0410	2·50	0·0375	−6·25	0·0373	−6·75
$k_c^* = 0·051$ [12]	0·30	0·0350	0·0335	−4·280	0·0360	2·86	0·310	−11·44	0·0300	−14·30
Alumina, Al_2O_3, with	0·10	0·0452	0·0448	−0·885	0·0460	1·77	0·0436	−3·54	0·0445	−1·55
cylindrical pores of diameter	0·20	0·0400	0·0390	−2·500	0·0410	2·50	0·0376	−6·00	0·0373	−6·75
0·146 cm at 200°C	0·30	0·0350	0·0340	−2·860	0·0360	2·86	0·0304	−13·15	0·0300	−14·30
$k_o^* = 0·051$ [12]										
Iwaki sandstone with	0·10	1·25	1·424	13·90	1·45	16·00	1·376	10·10	1·40	12·00
air saturated at 50°C	0·20	0·96	1·232	28·30	1·29	34·40	1·185	23·44	1·17	21·88
$k_c^† = 1·6$ [17]	0·30	0·76	1·056	39·00	1·13	48·70	0·976	28·40	0·94	23·70
Diaspore brick	0·10	$0·88k_c$	$0·89k_c$	1·136	$0·905k_c$	2·84	$0·87k_c$	−1·14	$0·895k_c$	1·71
$k_c/k_d = 50$ [18]	0·20	$0·76k_c$	$0·77k_c$	1·316	$0·805k_c$	5·92	$0·74k_c$	−2·63	$0·732k_c$	−3·68
	0·30	$0·66k_c$	$0·66k_c$	0·000	$0·705k_c$	6·82	$0·61k_c$	−7·50	$0·588k_c$	−10·90
Average percentage of deviation				8·2		10·8		9·8		9·9

* Units of k: cal/s cm °C.
† Units of k: kcal/h m°C.

to avoid settling and coalescence, thus preventing convection.

4. The thermal conductivities of continuous phase and discontinuous phase of emulsions are of the same order of magnitude.

5. The volume fraction of the discontinuous phase, P_d, should be low to prevent coalesence.

The above characteristics are compatible with the assumptions made by Maxwell and Jefferson in deriving equations (4) and (5) to predict the thermal conductivities of two-phase mixtures. One would thus expect these two equations to predict satisfactory results for emulsions. In fact, they do predict satisfactory results as shown in the following paragraph.

A number of other equations have also been proposed to predict the thermal conductivity of emulsions. Rayleigh [3], Bruggeman [4], Hamilton [6], Tsao [7] and Russell [10] have developed some of these relations. Table 3 presents some experimental data of Nahas and Couper [9] for various emulsions. Predicted values of conductivity by Maxwell [2], Jefferson [5], Russell [10] and equation (11) are compared with the experimental data. All the predicted values of Maxwell, Jefferson and Russell in Table 3 are taken from the Tables 1, 2 and 12 and Figs. 14 and 15 of Ref. [9]. The average percentage of deviation of predicted values from the measured values of thermal conductivity is shown in Table 5 (B). Equation (11) is seen to give satisfactory results.

Table 5. Summary of the average percentage of deviation of predicted values from the measured values of thermal conductivity

Predicted values of thermal conductivity	Average percentage of deviation from the measured values of thermal conductivity
A. Suspensions as given in Table 2	
Maxwell	16·3
Baxley	17·4
Equation (11)	18·2
Russell	21·6
B. Emulsions as given in Table 3	
Equation (11)	9·5
Russell	9·6
Maxwell	10·0
Jefferson	11·1
C. Porous materials as given in Table 4	
Russell	8·2
Eucken	9·8
Equation (10)	9·9
Loeb	10·8

POROUS MATERIALS

The mechanism of heat transfer in porous materials in general is very complicated and involves conduction as well as convection and radiation. Convection and radiation which occur in the pore spaces can be neglected for small pore size and low or intermediate temperature. One of the important aspects of the thermal conductivity in porous materials as indicated by Barrett [16] is the effect of the orientation of the pores on the direction of heat flow. The porous materials studied in this investigation primarily belong to the "air-cell" type of mixture rather than "granular-solid" type of mixture. Contact resistance can be neglected for the "air-cell" type of porous materials. A number of equations have been proposed to predict the thermal conductivity of porous materials. Equations by Russell [10], Loeb [11], Francl and Kingery [12] and Eucken [13] are the most used. Table 4 presents the experimental data for porous materials by Francl and Kingery [12], Sugawara and Yoshizawa [17], and Austin [18] and the predicted values by Russell [10], Loeb [11], Eucken [13] and equation (10). All the predicted values by Russell, Loeb and Eucken of the first two mixtures in Table 4 are taken from the Figs. 5, 6, 11 and 12 of Ref. [12]. The average percentage of deviation of predicted values from the measured values of the thermal conductivity is shown in Table 5 (C). The Russell and Loeb techniques predict values within a range of 2–3 per cent of measured values for the first two mixtures in Table 4. These samples contain known distributions of the pores rather than a random distribution of the pores. The technique of [1] is for a random distribution as approximated by the assumed parabolic distribution. Francl and Kingery [12] point out that Russell's equation, equation (6), is not applicable to anisometric pores but Loeb's equation, equation (7), is applicable to both isometric and anisometric pores. Also, for low temperature Loeb's equation can be reduced to equation (8) simply by neglecting the radiation effect in the pores. Again, one sees that the proposed technique gives acceptable results.

SUMMARY

Equations (10)–(12) have been compared with existing equations for predicting the thermal conductivity of two-phase mixtures. These equations are seen to give acceptable results for suspensions, emulsions and porous materials.

Table 6. Summary of the average percentage of deviation of the predicted thermal conductivities by equations (10) *and* (11) *with some of the existing methods for various systems of two-phase-mixtures*

Type of mixtures	Average percentage of deviation predicted by equations (10) and (11)	Average percentage of deviation predicted by the best method investigated in this study
Solid–solid mixtures	6·4 [1]	7·5 by Maxwell, equation (4)
Suspensions	18·2	16·3 by Maxwell, equation (4)
Emulsions	9·5	10·0 by Maxwell, equation (4)
Porous materials	9·9	8·2 by Russell, equation (6)

Table 6 gives a summary of the results. Equations (10) and (11) give better results for solid–solid mixtures and emulsions.

Two conclusions can be drawn:

1. The assumed parabolic distribution of the discontinuous phase for a random distribution of the discontinuous phase in the continuous phase is acceptable.

2. The technique of [1] provides a simple means of calculating thermal conductivity for emulsions, suspensions and porous materials ("air-cell" type) when the portions and properties of the constituents are known.

REFERENCES

1. S. C. Cheng and R. I. Vachon, The prediction of the thermal conductivity of two and three phase solid heterogeneous mixtures *Int. J. Heat Mass Transfer* **12**, 249–264 (1969).
2. J. C. Maxwell, *A Treatise on Electricity and Magnetism*, 3rd edn., Vol. I, Chapter 9, Article 314. Dover, New York (1954).
3. Lord Rayleigh, On the influence of obstacles arranged in rectangular order upon the properties of a medium, *Phil. Mag.* **34**, 481–502 (1892).
4. D. A. G. Bruggeman, Dielectric constant and conductivity of mixtures of isotropic materials, *Ann. Phys.* **24**, 636–679 (1935).
5. T. B. Jefferson, O. W. Witzell and W. L. Sibbitt, Thermal conductivity of graphite–silicone oil and graphite–water suspensions, *Ind. Engng Chem.* **50**, 1589–1592 (1958).
6. R. L. Hamilton and O. K. Crosser, Thermal conductivity of heterogeneous two-component systems, *Ind. Engng Chem.* **1**, 187–191 (1963).
7. G. T-N. Tsao, Thermal conductivity of two-phase materials, *Ind. Engng Chem.* **53**, 395–397 (1961).
8. A. L. Baxley and J. R. Couper, Thermal conductivity of two-phase systems. Part IV: Thermal conductivity of suspensions, Research Report Series-No. 8, Engineering Experiment Station, University of Arkansas (March 1966).
9. C. Nahas and J. R. Couper, Thermal conductivity of two-phase systems. Part III: Thermal conductivity of emulsions, Research Report Series-No. 7, Engineering Experiment Station, University of Arkansas (March 1966).
10. H. W. Russell, Principles of heat flow in porous materials, *J. Am. Ceram. Soc.* **18**, 1–5 (1935).
11. A. J. Loeb, Thermal conductivity: VIII, A theory of thermal conductivity of porous materials, *J. Am. Ceram. Soc.* **37**, 96–99 (1954).
12. J. Francl and W. D. Kingery, Thermal conductivity: IX, Experimental investigation of effect of porosity on thermal conductivity, *J. Am. Ceram. Soc.* **37**, 99–107 (1954).
13. A. Eucken, Thermal conductivity of ceramic refractory materials; calculation from thermal conductivity of constituents, *Forsch. Geb. Ing. Wes.* **B3**, Forschungsheft No. 353, 16 (1932). *Ceramic Abstr.* **11**, 576 (1932); **12**, 231 (1933).
14. F. A. Johnson, The thermal conductivity of aqueous thoria suspensions, Atomic Research Establishment, Harwell, Berkshire, AERE R/R 2578 (1958).
15. C. H. Lees, On the thermal conductivity of single and mixed solids and liquids and their variation with temperature, *Proc. R. Soc.* **A191**, 339–440 (1898).

16. L. R. BARRETT, Heat transfer in refractory insulating materials: I, Texture and insulating power, *Trans. Br. Ceram. Soc.* **48**, 235–262 (1949).
17. A. SUGAWARA and Y. YOSHIZAWA, An experimental investigation on the thermal conductivity of consolidated porous materials, *J. Appl. Phys.* **33**, 3135–3138 (1962).
18. J. B. AUSTIN, Symposium on thermal insulating materials, A.S.T.M., p. 3 (1939).

TECHNIQUE DE PREVISION DE LA CONDUCTIVITE THERMIQUE DES SUSPENSIONS, DES EMULSIONS ET DES MATERIAUX POREUX

Résumé—Une technique théorique pour prédire la conductivité thermique de mélanges hétérogènes, obtenue précédemment par les auteurs, a été appliquée aux suspensions, aux émulsions et aux matériaux poreux. On montre que la technique basée sur les résultats disponibles dans la littérature, prédit les valeurs de la conductivité thermique à 18,2 pour cent près pour les suspensions, 9,5 pour cent pour les émulsions et 9,9 pour cent les matériaux poreux.

EIN VERFAHREN ZUR VORAUSBESTIMMUNG DER THERMISCHEN LEITFÄHIGKEIT VON SUSPENSIONEN, EMULSIONEN UND PORÖSEN MATERIALIEN

Zusammenfassung—Ein theoretisches Verfahren zur Vorausbestimmung der thermischen Leitfähigkeit von heterogenen Gemischen, das von den Autoren schon früher entwickelt worden ist, wurde auf Suspensionen, Emulsionen und porösen Materialien angewendet. Durch Vergleich mit Angaben aus der Literatur wird gezeigt, dass die Methode die Werte der thermischen Leitfähigkeit mit einer Genauigkeit von 18 Prozent für Suspensionen, 9,5 Prozent für Emulsionen und 9,9 Prozent für poröse Materialien wiedergibt.

ТЕХНИКА ПРЕДСКАЗАНИЯ ТЕПЛОПЕРЕДАУИ ЭМУЛЬСИОННЫМИ СУСПЕНЗИЯМИ И ПОРИСТЫМИ МАТЕРИАЛАМИ

Аннотация—Теоретические методы расчета теплопроводности гетерогенных смесей, ранее разработанные авторами, применены к суспензиям, эмульсиям и пористым материалам. На основании данных, имеющихся в литературе, показано, что с помощью такой методики можно рассчитать теплопроводность таких суспензий с точностью до 18.2%, эмульсий до 9.5% и пористых материалов до 9.9%.