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HEAT-TRANSFER CHARACTERISTICS OF PACKED BEDS WITH STAGNANT FLUIDS

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Abstract—Temperature distributions were measured in steady state in packed beds of solid particles with stagnant fluids, from which both the effective thermal conductivities and the apparent wall-film coefficients of heat transfer were obtained. Measurements were made for each of twelve kinds of particles with five fluids, i.e. water, air, carbon dioxide, helium and hydrogen.

Experimental data of the effective thermal conductivities showed good agreement with the theoretical equations proposed by the authors before.

The authors' theoretical equation for the apparent wall-film coefficient of heat transfer was modified here and applied to the analysis of the present experimental data.

NOMENCLATURE

C_p, specific heat of fluid [kcal/kg degC];
D_p, diameter of solid particle [m];
G, superficial mass velocity of fluid based on sectional area [kg/m^{2}h];
h_{r_s}, heat-transfer coefficient of thermal radiation, solid surface to solid surface [kcal/m^{2}h degC];
h_{r_v}, heat-transfer coefficient of thermal radiation, void space to void space [kcal/m^{2}h degC];
h_w, apparent wall-film coefficient of heat transfer in packed bed with fluid flowing [kcal/m^{2}h degC];
h_w^0, apparent wall-film coefficient of heat transfer in packed bed with stagnant fluid [kcal/m^{2}h degC];
k_e, effective thermal conductivity in packed bed with fluid flowing [kcal/m h degC];
k_e^0, effective thermal conductivity in packed bed with stagnant fluid [kcal/m h degC];
$k_{e_w}^0$, effective thermal conductivity in packed bed with stagnant fluid in the vicinity of the wall [kcal/m h degC];
k_f, thermal conductivity of fluid [kcal/m h degC];
k_s, thermal conductivity of solid [kcal/m h degC];
k_m, thermal conductivity of marble plate [kcal/m h degC];
L, thickness of marble plate [m];
p, emissivity of solid surface;
Pr, Prandtl number, $= C_p \mu/k_f$;
q, heat flux [kcal/m^{2}h];
Re_m, modified Reynolds number, $= G\, D_p/\mu$;
t_{a_p}, apparent wall temperature extrapolated from temperature distribution in packed bed to the wall surface [°C];
t', temperature at $D_p/2$ from the wall surface [°C];
t_m, mean temperature in packed bed [°C];
t_{w_1}, t_{w_2}, wall temperature [°C];
x, distance from surface of cooling jacket, m;

Greek symbols

α, (mass velocity in packed bed in the direction of heat transfer)/(superficial mass velocity of fluid based on sectional area of empty tube in the direction of fluid flowing);
α_w, α-value in the vicinity of the wall;
β, (effective length between two neighbouring particles in the direction of heat flow)/D_p;
ϵ, void fraction;
ϵ_w, void fraction in the vicinity of the wall;
ϕ, (effective thickness of fluid film)/D_p;
ϕ_w, ϕ-value in the vicinity of the wall;
μ, viscosity [kg/m h].

INTRODUCTION

In connection with design calculations of catalytic reactors and heat exchangers of pebble heater type, it is very important to know the heat-transfer properties of packed bed. In addition to a number of studies [1–6], Hatta and Maeda [7] analysed their experimental data of heat transfer in packed beds by means of their theoretical procedure including both the effective thermal conductivity k_e and the apparent wall-film coefficient of heat transfer h_w. Coberly and Marshall [1], Plautz and Johnstone [2], Yagi and Kunii [3], Campbell and Huntington [5], and then Maeda and Kawazoe [8] analysed their experimental data in almost the same way as Hatta and Maeda [7].

The effective thermal conductivity k_e^0 of packed bed with stagnant fluid has been studied by a number of investigators, and there have been proposed many empirical and theoretical equations. Kunii and Smith [9] surveyed previous works, proposed a model for heat transfer in packed bed and gave a theoretical equation of stagnant conductivities, which takes account of thermal conductivity of both solid and fluid phases,

$$\frac{k_e^0}{k_f} = \epsilon\left(1 + \frac{h_{r_v} D_p}{k_f}\right) + \left[(1-\epsilon)\Big/\left(\frac{1}{1/\Phi + h_{r_s} D_p/k_f} + \frac{2}{3}\frac{k_f}{k_s}\right)\right] \quad (1)$$

where

$$h_{r_v} = 0{\cdot}1952\,.\left[1\Big/\left(1 + \frac{\epsilon}{2(1-\epsilon)}\frac{1-p}{p}\right)\right] \times \left(\frac{t_m + 273}{100}\right)^3 \quad (2)$$

$$h_{r_s} = 0{\cdot}1952\,\frac{p}{2-p}\left(\frac{t_m + 273}{100}\right)^3$$

$$\phi = \phi_1 + (\phi_1 - \phi_2)\,\frac{\epsilon - 0{\cdot}260}{0{\cdot}216}$$

Equation (1) can explain almost all experimental data of the effective thermal conductivities in packed beds with stagnant fluid, and can be used for their estimation.

On the other hand, several groups of investigators have measured the apparent wall coefficients of heat transfer h_w in packed beds through which gases were flowing. Coberly and Marshall [1], Campbell and Huntington [5], Plautz and Johnstone [2], Calderbank and Pogoroski [11] and Quinton and Storrow [12] correlated their experimental data by their empirical equations, Yagi and Wakao [13] by j-factors. Hanratty [14] and Yagi, Kunii and Shimomura [15] proposed semi-empirical equations, applying surface renewal theory and boundary-layer theory, respectively. Most of these equations are represented by the following form:

$$\frac{h_w D_p}{k_f} = C\,Re_m^n \qquad (C, n : \text{constant}) \quad (3)$$

However, this is not available for flow condition of small Reynolds numbers, because $(k_w D_p/k_f)$ tends to zero when $Re_m = 0$. From heat transfer measurements in annular packed beds at low Re_m, Yagi and Kunii [16] ascertained that h_w does not reduce to zero when Re_m tends to zero. They proposed the following theoretical equation for h_w.

$$\frac{h_w D_p}{k_f} = \frac{h_w^0 D_p}{k_f} + \alpha_w\,Pr\,Re_m \quad (4)$$

In equation (4) h_w^0 represents the apparent wall-film coefficient of heat transfer in packed bed with stagnant fluid. Yagi and Kunii [17] have obtained the following equation based on their heat-transfer model of a packed bed:

$$\frac{1}{h_w^0 D_p/k_f} = \frac{1}{k_w^0/k_f} - \frac{0{\cdot}5}{k_e^0/k_f} \quad (5)$$

$$\frac{k_w^0}{k_f} = \epsilon_w\left(2 + \frac{h_{r_v} D_p}{k_f}\right) + \left[(1-\epsilon_w)\Big/\left(\frac{1}{1/\phi_w + h_{rs} D_p/k_f} + \frac{1}{3}\cdot\frac{k_f}{k_s}\right)\right] \quad (6)$$

In these equations, k_w^0 is twice of the effective thermal conductivity near wall $k_{e_w}^0$ (the distance of $D_p/2$ from the wall). Though the first term of the right-hand side of equation (4), $h_w^0 D_p/k_f$, plays very important role at small Re_m, there are a few experimental data of them. Some of them were obtained from extrapolation of previous data with flowing gases to $Re_m = 0$ by Yagi and Kunii [16], and others were measured in annular packed beds by Yagi and Kunii [16] and Hill and Wilhelm [18]. Since equations (5) and (6) have not sufficient experimental backgrounds, the authors made a number of heat-transfer measurements in packed beds containing stagnant fluid where heat flowed completely in one direction in order to test the adequacy of the theoretical equations, namely equations (5) and (6).

EXPERIMENT AND PROCEDURE

The experimental apparatus, similar to that used for the measurement of thermal conductivity of concrete solid, is shown schematically in Fig. 1. The upper and lower jackets have flat heat-transfer surfaces made of 15 mm thick copper plates which are held at constant temperatures by steam and water, respectively. An annular Dewar tube, made of acrylonitrile-resin, is used as the container of the packed bed to prevent radial heat loss. The packed bed, 200 mm in diameter and 50 mm in length, was formed upon a cylindrical marble plate which have the same dimensions as the packed bed. On the both flat surfaces of the marble plate are attached thermocouples to measure the surface temperatures. Thermal conductivity of marble plate was measured to be 1·79 kcal/m h degC in the same apparatus by comparison with the thermal conductivities of copper and iron plates. The temperature distribution in packed bed was measured by ten thermocouples. The thermocouples used here were made of alumel–chromel and were 0·3 mm in diameter.

In the vicinity of the wall surface the orientation of particles and void fraction differ from those of the interior of the packed bed, resulting in a difference of the thermal conductivity near the wall from that of the inside. Thus the apparent wall-film coefficient of heat transfer h_w^0 in packed beds is interpreted as a correction term when the thermal conductivity is assumed to be constant throughout the bed. Measurements of void distribution [19] showed that these wall effects were restricted to about half the diameter of a solid particle from the wall surface. Thus we may take two mean values of the effective thermal conductivities in packed bed, i.e. $k_{e_w}^0$ near the wall surface (see Fig. 2) and k_e^0 in the core of the bed.

In the present experiments, heat flowed completely in one direction, so that the temperature distribution in the packed bed was linear, as shown in Fig. 2. The heat flux is expressed as:

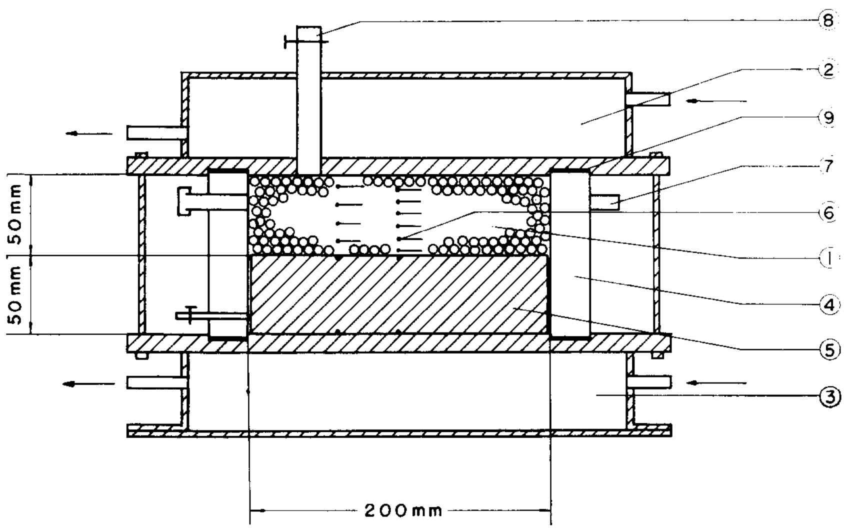

FIG. 1. Experimental apparatus.

1. Packed bed
2. Steam jacket
3. Cooling water jacket
4. Annular Dewar tube
5. Marble plate
6. Thermocouples
7. Vacuum tap
8. Fluid inlet
9. Rubber gasket

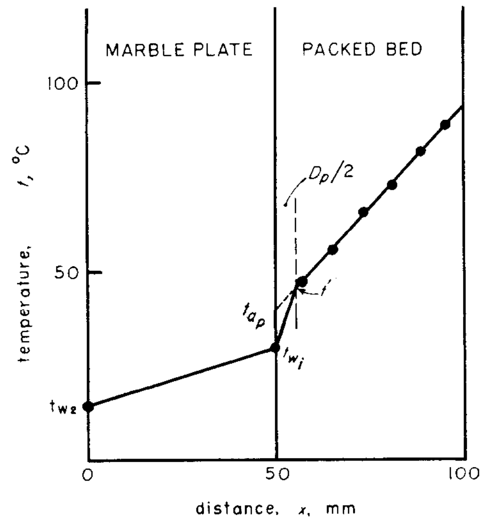

FIG. 2. Schematic diagram of temperature distribution in packed bed.

$$q = k_e^0 \frac{dt}{dx} = k_{e_w}^0 \frac{t' - t_{w_1}}{D_p/2} = h_w^0(t_{a_p} - t_{w_1})$$
$$= k_m \frac{t_{w_1} - t_{w_2}}{L} \quad (7)$$

Temperature gradients in packed bed dt/dx were obtained by averaging of temperature distribution by delta–sigma method. From equation (7) the following expression is derived,

$$\frac{1}{k_e^0} + \frac{1}{h_w^0 D_p/2} = \frac{1}{k_{e_w}^0} \quad (8)$$

Comparing equation (5) with equation (8), it is found that $k_{e_w}^0 = 0{\cdot}5\ k_w^0$.

RESULTS

Measurements were made for each of twelve kinds of solid particles with five fluids, i.e. water, air, carbon dioxide, helium and hydrogen. Experimental conditions are shown in Table 1. Reproductivity of results was examined by repacking of solid particles. Comparison of experimental results with the values of calculated by the authors' theoretical equations are shown in Table 2, Figs. 4 and 5. In Fig. 4, $k_{e_w}^0/k_f$ are plotted against k_s/k_f, in which the solid line illustrates equation (6), with the assumption that $k_{e_w}^0 = 0{\cdot}5\ k_w^0$ and $\epsilon_w = 0{\cdot}40$, with no radiation contribution. Figure 5 shows $h_w^0\ D_p/k_f$ vs. k_s/k_f) with a solid line calculated from equation (8), $k_{e_w}^0$ and k_e^0 from equations (6) and (1), where $\epsilon_w = 0{\cdot}40$ and $\epsilon = 0{\cdot}34$, respectively.

Table 1. Experimental conditions

Solid	Glass spheres (D_p = 1·15, 2·26, 3·69, 6·38, 8·70 and 12·1 mm) Steel balls (D_p = 3·09, 6·32 and 10·9) Raschig rings (D_p = 5·12 and 8·18) Cement clinckers (D_p = 7·31) Nickel catalyst pellets (cylinder, D_p = 4·75) River sands (the Akikawa river, D_p = 2·45)
Fluid	water, air, carbon dioxide, helium and hydrogen
void fraction	0·338 ~ 0·603
bed temperature	30 ~ 90°C, t_m = 50°C

COMPARISON OF CALCULATED AND OBSERVED VALUES

Equation (1) was applied for calculation of stagnant thermal conductivities k_e^0 in packed beds and equation (6) with $k_{e_w}^0 = 0{\cdot}5\ k_w^0$ for the effective thermal conductivities in the vicinity of the wall surface with stagnant fluid $k_{e_w}^0$. The values of k_s, k_f and p were taken from physical tables [20]. The unknown term ϵ_w, average void fraction in the vicinity of the wall surface, was estimated as the following way. In the present measurements, as solid particles were packed upon a horizontal plate, it was observed that the arrangement of particles near wall was almost in the closest packing. Thus ϵ_w was determined the volume average void fraction from the wall surface to $D_p/2$ for the closest packing of spherical particles on a horizontal plate, i.e. $\epsilon_w = 1 - \pi/(3\sqrt{3}) \doteqdot 0{\cdot}40$. The quantities ϕ_1, ϕ_2 and ϕ_w can be read from Fig. 3, which was taken from reference [4]. Thus calculated values of k_e^0 and $k_{e_w}^0$ were compared with the observed ones, Figs. 6 and 7, where the average deviations are smaller than 15 and 25 per cent, respectively. Then it can be reasonably concluded that equation (6) can be used to estimate $k_{e_w}^0$, so that h_w^0 from equations (1), (6) and (8). In case of ordinary packed beds, the arrangement of particles in the vicinity of the wall may be different from the present case, i.e. the packed

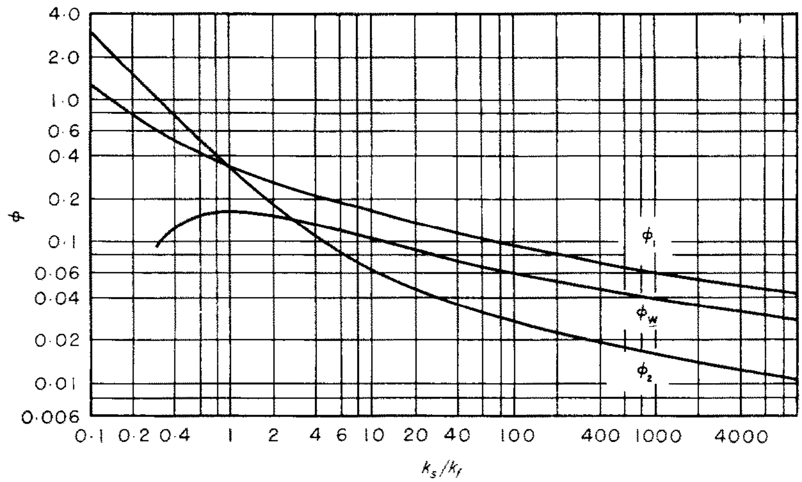

FIG. 3. ϕ-chart.

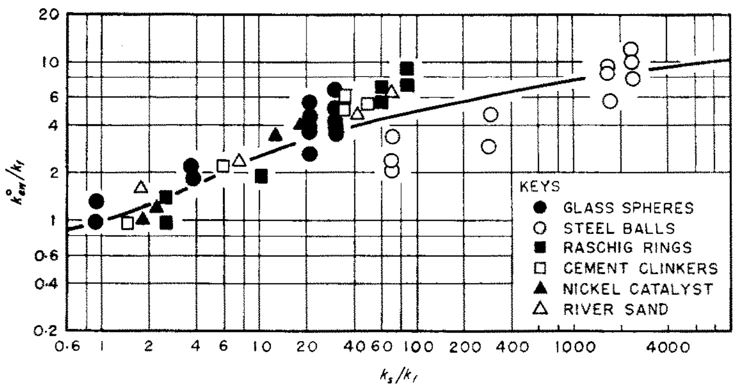

FIG. 4. $k_{e_w}{}^0/k_f$ vs. k_s/k_f

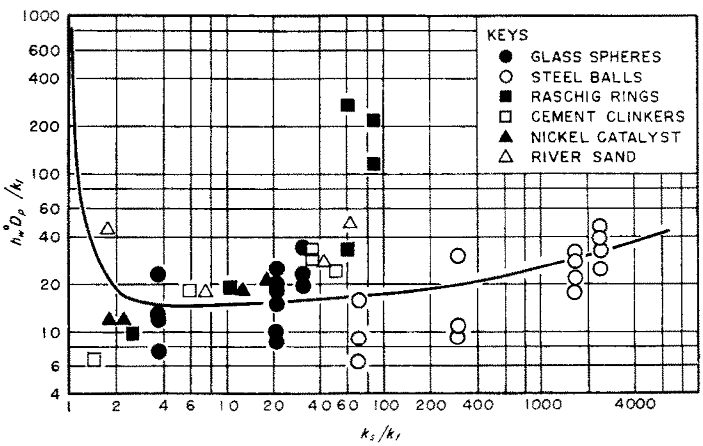

FIG. 5. $h_w{}^0 D_p/k_f$ vs. k_s/k_f

Table 2. Experimental results and comparison with calculated values

Solid	Fluid	D_p (mm)	ϵ	k_s/k_f	k_e^0 (kcal/m h °C)	k_e^0/k_f obs.	k_e^0/k_f calcd.	$k_{e_w}^0$ (kcal/m h °C)	$k_{e_w}^0/k_f$ obs.	$k_{e_w}^0/k_f$ calcd.	h_w^0 (kcal/m²h °C)	$h_w^0 D_f/k_f$
Glass spheres	Air	1·15	0·34	21	0·153	6·38	6·40	0·0588	2·45	3·23	176	8·43
		1·15	0·346	21	0·147	6·15	6·42	0·093	3·86	3·23	430	20·7
		2·66	0·34	21	0·162	6·73	6·64	0·068	2·82	3·39	88·1	9·73
		3·69	0·34	21	0·151	6·24	6·79	0·064	2·65	3·48	60·6	9·22
		3·69	0·338	21	0·158	6·61	7·10	0·104	4·31	3·47	160	24·7
		3·69	0·369	21	0·163	6·71	7·03	0·086	3·54	3·50	98·7	15·0
		6·38	0·337	21	0·171	7·13	7·38	0·098	4·10	3·77	71·6	19·0
		6·38	0·358	21	0·179	7·49	6·97	0·101	4·23	3·74	73·4	19·5
		8·70	0·369	21	0·186	7·78	7·26	0·102	4·23	4·00	51·3	18·6
		12·1	0·376	21	0·182	7·65	7·68	0·105	4·39	4·31	42·3	20·6
		12·1	0·465	21	0·218	9·05	7·11	0·139	5·82	4·53	68·4	34·2
	CO_2	1·15	0·346	31	0·116	7·16	7·64	0·069	4·23	3·68	293	20·8
		2·66	0·34	31	0·127	7·75	8·21	0·070	4·33	3·91	121	19·6
		3·69	0·338	31	0·138	8·52	8·60	0·083	5·07	4·07	110	25·0
		3·69	0·369	31	0·142	8·61	8·89	0·114	6·92	4·22	315	70·5
		6·38	0·337	31	0·135	8·24	9·25	0·074	4·55	4·49	49·9	19·4
		8·70	0·369	31	0·154	9·40	9·07	0·083	5·05	4·74	41·3	21·9
		12·1	0·376	31	0·150	9·20	9·50	0·098	6·00	5·37	46·7	34·7
	He	1·15	0·346	3·7	0·317	2·34	2·32	0·251	1·86	1·43	2160	7·5
		3·69	0·338	3·7	0·328	2·41	2·42	0·238	1·76	1·46	481	13·1
		3·69	0·369	3·7	0·334	2·46	2·40	0·351	2·58	1·66	−3870	−105
		6·38	0·358	3·7	0·332	2·46	2·38	0·239	1·77	1·96	266	12·6
		8·70	0·369	3·7	0·339	2·49	2·43	0·279	2·05	2·18	362	23·1
	Water	1·15	0·34	0·90	0·500	0·90	0·94	0·710	1·28	0·96	−2970	−6·16
		2·66	0·34	0·90	0·496	0·90	0·94	0·782	1·41	0·96	−1050	−5·04
		3·69	0·34	0·90	0·496	0·90	0·94	0·776	1·40	0·96	−748	−4·99
		3·69	0·369	0·90	0·534	0·96	0·94	0·810	1·46	0·96	−631	−4·2
		6·38	0·337	0·90	0·520	0·94	0·94	0·545	0·98	0·96	−3920	−45·2
		8·70	0·369	0·90	0·496	0·90	0·94	0·623	1·13	0·96	−560	−8·9
		12·1	0·376	0·90	0·478	0·87	0·94	0·527	0·95	0·96	−915	−20·0
Steel Balls	Air	3·09	0·342	1650	0·366	15·0	21·5	0·150	6·17	8·06	165	21
		3·09	0·413	1650	0·271	11·2	13·9	0·210	8·64	8·35	595	76
		3·09	0·390	1650	0·237	10·1	16·6	0·144	5·90	8·20	219	28
		6·32	0·352	1650	0·713	29·0	20·9	0·231	9·50	8·38	110	28
		6·32	0·396	1650	0·251	10·4	17·2	0·110	4·58	8·44	64	17
		10·9	0·403	1650	0·454	18·6	15·5	0·208	8·55	8·57	72	32

	CO_2	3·09	0·342	2370	0·375	22·1	22·9	0·129	7·64	8·82	120	23
		3·09	0·413	2370	0·206	12·5	14·3	0·135	8·20	8·97	255	48
		6·32	0·352	2370	0·726	42·7	22·5	0·215	13·3	8·99	104	39
		10·9	0·403	2370	0·406	24·3	17·1	0·166	9·85	9·21	58·5	33
	He	3·09	0·39	294	0·905	6·65	12·1	0·411	3·03	6·14	503	11
		3·09	0·413	294	0·979	7·09	8·63	0·672	4·86	6·21	1390	31
		6·32	0·396	294	0·931	6·75	8·98	0·381	2·76	6·25	204	9·4
	Water	3·09	0·342	70	3·30	5·80	10·1	1·19	2·07	4·11	1190	6·4
		3·09	0·413	70	2·85	5·08	8·32	1·24	2·44	4·11	1710	9·4
		6·32	0·352	70	3·27	5·72	8·60	1·92	3·35	4·40	1460	16·1
		6·32	0·396	70	2·72	4·79	8·34	1·30	2·29	4·40	792	8·8
		10·9	0·403	70	3·57	6·28	8·54	1·27	2·23	4·40	259	5·0
Raschig rings	Air	5·12	0·603	59	0·158	6·64	5·32	0·155	6·45	5·31	2210	475
		5·12	0·572	59	0·175	7·39	5·56	0·124	5·16	4·81	159	34·3
		8·18	0·475	59	0·177	7·47	6·69	0·170	7·08	5·03	794	274
	CO_2	5·12	0·603	87	0·128	7·95	6·38	0·103	7·00	5·46	364	116
		8·18	0·475	87	0·160	10·0	8·51	0·148	9·15	5·85	420	215
	He	5·12	0·572	10·4	0·312	2·31	2·66	0·252	1·87	2·08	507	19·2
	Water	5·12	0·603	2·53	0·540	0·98	1·39	0·760	1·37	1·21	−734	−6·78
		8·18	0·475	2·53	0·610	1·11	1·53	0·500	0·90	1·21	653	9·74
Cement clinkers	Air	7·31	0·370	34	0·177	7·40	8·10	0·123	5·15	4·40	111	34
		7·31	0·366	34	0·213	8·92	9·10	0·133	5·56	4·40	96	29
	CO_2	7·31	0·370	50	0·146	9·02	10·0	0·084	5·20	5·20	54	24
	He	7·31	0·366	5·9	0·453	3·34	2·70	0·347	2·22	2·97	246	13
	Water	7·31	0·370	1·44	0·688	1·24	1·13	0·500	0·90	1·17	500	6·6
River sands	Air	2·45	0·359	42	0·195	8·20	8·50	0·123	5·15	2·46	256	28
	CO_2	2·45	0·359	62	0·142	8·82	9·9	0·105	6·50	3·07	308	49
	He	2·45	0·359	7·4	0·434	3·19	3·5	0·318	2·34	2·25	930	18
	Water	2·45	0·359	1·78	0·996	1·77	1·4	0·922	1·64	1·26	10300	45
Nickel catalyst pellets	Air	4·75	0·384	12·6	0·130	5·46	4·92	0·081	3·40	4·43	91	18
	CO_2	4·75	0·384	18·5	0·109	6·73	6·17	0·066	4·05	5·53	70	21
	He	4·75	0·384	2·22	0·196	1·45	1·69	0·180	1·16	1·47	332	12
	H_2	4·75	0·384	1·82	0·197	1·20	1·48	0·165	1·00	1·24	420	12

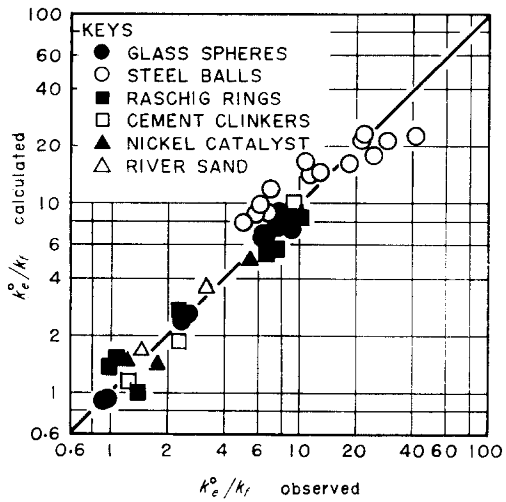

FIG. 6. Comparison of experimental and calculated values of $k_e{}^0/k_f$.

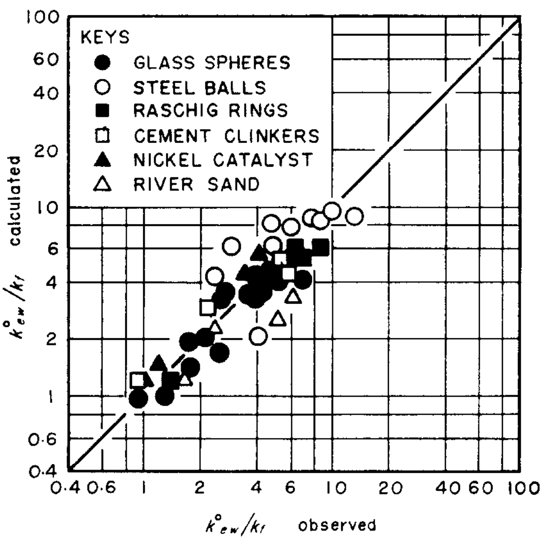

FIG. 7 Comparison of experimental and calculated values of $k_{e_w}{}^0/k_f$.

bed on a horizontal plate. However, this effect can be attributed to ϵ_w alone, which may be estimated as the function of the ratio of the diameter of solid particles to that of the tube and of the mean void fraction in the packed bed. Therefore, equation (6) can be used for estimating $k_{e_w}^0$ of the packed bed in a tube.

CONCLUSIONS

(1) Heat-transfer measurements were made in packed beds with stagnant fluid. Finite values of the apparent wall-film coefficients of heat transfer were observed. Thus at small Re_m equations (3) cannot be used for estimating h_w.

(2) Many experimental values of k_e^0, $k_{e_w}^0$ and h_w^0 were obtained under various conditions, from which it was found that the theoretical equations proposed by the authors [17], equations (5) and (6), can give good estimation of h_w^0.

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Résumé—Les distributions de température ont été mesurées en régime permanent dans des lits fixes de particules solides avec des fluides au repos, à partir desquelles les conductivités thermiques effectives et les coefficients apparents de transfert de chaleur par film pariétal ont été obtenus à la fois. Les mesures ont été faites pour chacune de douze espèces de particules avec cinq fluides, c'est-à-dire l'eau, l'air, le gaz carbonique, l'hélium et l'hydrogène.

Les données expérimentales des conductivités thermiques effectives montraient un bon accord avec les équations théoriques proposées auparavant par les auteurs.

L'équation théorique de film pariétal a été modifiée ici et appliquée à l'analyse des données expérimentales actuelles.

Zusammenfassung—Im stationären Zustand wurden die Temperaturverteilungen in Schüttungen fester Teilchen mit stillstehenden Flüssigkeiten gemessen, wodurch man sowohl das tatsächliche Wärmeleitvermögen wie auch die scheinbaren Wärmeübergangszahlen des Wandfilmes erhält. Für jede von zwölf Arten von Teilchen wurden mit fünf Flüssigkeiten, d.h. Wasser, Luft, Kohlendioxyd, Helium und Wasserstoff Messungen gemacht.

Die Versuchsergebnisse des tatsächlichen Wärmeleitvermögens zeigten gute Übereinstimmung mit den von den Autoren vorher vorgeschlagenen Gleichungen.

Die theoretische Gleichung der Autoren für den scheinbaren Wandfilmkoeffizienten wurde hier modifiziert und bei der Analyse der vorliegenden Versuchsergebnisse angewendet.

Аннотация—Измерялось распределение температур в стационарном состоянии плотных слоев твердых частиц в застойных течениях, что позволило получить как эффективные коэффициенты теплопроводности, так и отдельно коэффициенты для пленок на стенке. Измерения проводились для частиц двенадцати видов в пяти жидкостях—в воде, воздухе, двуокиси углерода, гелии и водороде.

Эффективные коэффициенты теплопроводности, полученные экспериментально, хорошо согласуются с теоретическими уравнениями, предложенными авторами ранее.

В данной статье теоретическое уравнение авторов для истинного пленочного коэффициента на стенке изменено и применяется для анализа представленных экспериментальных данных.