Effective thermal conductivities of packed beds of chromite ores

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SYNOPSIS

The effective thermal conductivities in stagnant air of packed beds of fines, lumps, and indurated and pre-reduced pellets of two chromite ores with different chromium-to-iron ratios were determined in the temperature range 300 to 1100 °C by the heat-sink technique.

Packed beds of fines, whether of the size fraction between 20 and 65 mesh, between 65 and 100 mesh, or between 100 and 150 mesh, were found to have the same values of effective thermal conductivity. For one ore, the effective thermal conductivities of packed beds of fines between 20 and 48 mesh at temperatures above 600 °C were higher than those for finer particles. This difference is explained as being due to the increase in importance of radiation heat transfer, but no definite conclusions are reached about the relative contributions of conduction and radiation heat transfer to the effective thermal conductivities of packed beds of fines between 20 and 48 mesh.

Two published models were used for the theoretical prediction of values for thermal conductivities of the indurated and pre-reduced pellets as well as of lump ore. The experimental and theoretical results were in good agreement in view of the uncertainties in the assumed values of emissivity and thermal conductivity of the chromite ore.

SAMEVATTING

Die effektiewe warmtegeleivermoë in dooie lug van gepakte lae fyn materiaal, klonte en verharde en voorafgereduseerde pastille van twee chromietertse met verskillende chroom/ysterverhoudings is volgens die hittedissipeerdertegniek in die temperatuurbestek 300 tot 1100 °C bepaal.

Daar is gevind dat lae fyn materiaal of dit nou die groottefraksie tussen 20 en 65 maas, tussen 65 en 100 maas, of tussen 100 en 150 maas is, dieselfde effektiewe warmtegeleivermoëwaardes het. Vir een erts was die effektiewe warmtegeleivermoë van gepakte lae van fyn materiaal tussen 20 en 48 maas by temperature bo 600 °C hoër as dié vir fyner partikels. Hierdie verskil word toegrskryf aan die toename in die belangrikheid van stralingswarmteoordrag, maar daar word geen definitiewe gevolgtrekkings omtrent die relatiewe bydrae van geleidings- en stralingswarmteoordrag tot die effektiewe warmtegeleivermoë van gepakte lae van fyn materiaal van tussen 20 en 48 maas gemaak nie.

Twee gepubliseerde modelle is vir die teoretiese voorspelling van waardes vir die warmtegeleivermoë van die verharde en voorafgereduseerde pastille en van die erts in klonte gebruik. Die eksperimentele en teoretiese resultate het goed ooreengestem, gesien in die lig van die onsekerheid wat betref die aanvaarde waardes van die uitstraal- en warmtegeleivermoë van die chromieterts.

Introduction

The heat-transfer characteristics of packed beds of chromite ore are important because of their influence on heat transfer in the operation of submerged-arc furnaces producing high-carbon ferrochromium, charge chromium, and ferrochromium silicide, and of rotary kilns producing pre-reduced chromite ore. (Alternative processes for the pre-reduction of chromite ore are also being investigated, and the design of, for example, tunnel kilns requires data on the heat-transfer characteristics of packed beds.) For these reasons, the effective thermal conductivities of packed beds of two chromite ores were determined.

The ores were in the form of fine particles and indurated and pre-reduced pellets, and had different chromium-to-iron ratios. To avoid complications due to chemical reaction and the presence of materials with different emissivities and thermal conductivities, carbonaceous reducing agents and fluxes were not included in the packed beds, which contained stagnant air.

Heat Transfer in Packed Beds

Heat transfer in a packed bed containing stagnant fluid occurs by conduction and radiation. These modes of heat transfer can occur in various combinations of series and parallel paths, and the following mechanisms can be identified:

Conduction Mechanisms

(1) Conduction through the solid particles
(2) Conduction through the points of contact between particles
(3) Conduction through the fluid film near the contact surfaces of solid particles
(4) Conduction across the stagnant gas

Radiation Mechanisms

(5) Radiation between adjacent particle surfaces
(6) Radiation through the gas.

Previous investigations[1–6] of heat transfer in packed beds have neglected heat transfer by natural convection, a procedure that is supported by the finding[7] of Verschoor *et al.* that the amount of heat transferred by natural convection is small in comparison with that transferred by radiation and conduction.

Heat transfer by radiation can be neglected for packed beds of fine particles. Schotte[3] states that radiation becomes important for 1 mm particles above 400 °C and 0,1 mm particles above 1500 °C. Similarly, in most studies[4, 6, 8–10] of the thermal conductivity of packed beds of fine materials, it has been assumed that heat transfer by radiation can be neglected.

Models for the determination of the effective thermal conductivities of packed beds containing a stagnant fluid

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can be divided into two categories, which can be summarized as

$$k_e^o = k_e + k_r \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and $$k_e^o = f(k_{e_1}, k_r), \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where k_e^o=effective thermal conductivity of the packed bed,

k_e=effective thermal conductivity by conduction only, and

k_r=effective thermal conductivity by radiation only.

There are a number of models[1, 6, 9, 11–22] for the prediction of k_e. Other models[2, 3, 9, 23–30] are available in which k_r can be added to k_e, as well as models[1, 18–20] in which k_e and k_r interact. Young[31] has discussed all these approaches in more detail.

The models that were found to be most useful for analysis of the experimental results were that of Schotte[3] and that developed by Yagi and Kunii[18], Kunii and Smith[19], and Yagi, Kunii and Wakao[20]. Schotte[3] considered a lattice of particles for heat transfer by radiation and conduction in parallel and showed that

$$k_r = \frac{1-\epsilon}{\frac{1}{k_s} + \frac{1}{h_r D_p}} + \epsilon h_r D_p, \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where ϵ=porosity,

D_p=particle diameter,

$h_r = 0{,}1952\, e \frac{T^3}{10^6}$=overall radiation heat transfer coefficient,

e=emissivity

T=temperature (K), and

k_s=bulk solid thermal conductivity.

The first term of equation (3) represents radiation heat transfer to the particle [mechanism (5)] in series with conduction through the particle. The second term accounts for radiation across the void [mechanism (6)]. The radiation thermal conductivity, k_r, is then added to the conduction term. For conduction, Schotte[3] uses the semi-empirical relationship given by Deissler and Eian[16].

Kunii and his co-workers[18–20] derived the following equation for the effective thermal conductivity of a packed bed when interactions between heat transfer by radiation and by conduction are considered:

$$\frac{k_e^o}{k_g} = \epsilon\left(1 + \frac{h_{rv} D_p}{k_g}\right) + \frac{1-\epsilon}{\frac{1}{\frac{1}{\Phi} + \frac{h_{rs} D_p}{k_g}} + \gamma \frac{k_g}{k_s}}, \quad \ldots\ldots (4)$$

where k_g=thermal conductivity of gas,

Φ=thickness of the gas layer in the gas-solid series path,

$\gamma = L_s/D_p$, and

L_s=effective length of a solid particle for heat transfer by conduction.

These investigators distinguished between mechanisms (5) and (6), and showed that h_{rs} and h_{rv}, the heat transfer coefficients for radiation from the solid and the gas respectively, were given by

$$h_{rv} = \frac{0{,}1952}{1 + \frac{\epsilon}{2(1-\epsilon)} \frac{1-e}{e}} \left(\frac{T^3}{100}\right) \quad \ldots\ldots (5)$$

and $$h_{rs} = \frac{e}{2-e}\, 0{,}1952 \left(\frac{T^3}{100}\right) \quad \ldots\ldots\ldots (6)$$

Yagi, Kunii, and Wakao[20] compared experimental data for iron spheres, porcelain cylinders, and cement clinkers with equations (3) and (4), and concluded that both theoretical models are sufficient for correlation of almost all experimental data on effective thermal conductivities in packed beds.

Experimental Method

Two Transvaal chromite ores with the analyses given in Table I were crushed and screened to give the particle-size distributions listed in Table II. For the measurements of the effective thermal conductivities of packed beds of fines of a particular size fraction, the average particle diameter was calculated from the formulae of Leva[32], and these average diameters are also included in Table II.

TABLE I

CHEMICAL ANALYSES OF TWO TRANSVAAL CHROMITE ORES

Component	Type A % (by mass)	Type B % (by mass)
Cr_2O_3	43,7	51,4
Al_2O_3	16,3	14,2
Total Fe as Fe_2O_3	28,1	21,7
MgO	10,1	8,5
SiO_2	1,8	2,3
Chromium-to-iron ratio	1,5	2,3

TABLE II

SCREEN ANALYSES OF TWO TRANSVAAL CHROMITE ORES

Mesh size	Average particle diameter, Dp mm	Mass per cent retained on each screen	
		Type A	Type B
+20	—	3,1	0,1
−20+48	0,50	48,1	2,8
−48+65	0,25	21,8	13,3
(−20+65)*	(0,33)	(69,9)	(16,1)
−65+100	0,18	14,8	31,2
−100+150	0,12	9,5	33,0
−150	—	2,8	17,5

*Consists of 50 per cent (by mass) of −20+48 mesh fines and 50 per cent (by mass) −48+65 mesh fines respectively

The Mineralogy Division of the National Institute for Metallurgy analysed all the size fractions of both ores to determine whether the particles showed porosity and fractures. The fraction between 48 and 65 mesh of type A ore contained silicate impurities (1 per cent) and was almost non-porous and completely unfractured. The type B sample contained impurities in the form of hematite–ilmenite intergrowths (up to 5 per cent by volume), generally as separate grains. Some 50 per cent of the chromite grains of this sample were fractured, giving a considerable increase in the surface area.

Preparation of Pellets

Indurated pellets of the two ores were made as follows: the ores were ground to 75 per cent (by mass)

minus 200 mesh Tyler, the fines were mixed with 0,75 per cent by mass of Ocean bentonite, the mixture was placed in a standard 60 cm pelletizer, and the pellets, after being dried overnight in an oven, were fired at 1200 °C for two hours. The indurated pellets were then screened so that three different sizes could be selected to represent type A ore and one size to represent type B ore. Pellets of type B ore were made to show whether a different chromium-to-iron ratio had any effect on the effective thermal conductivities of the packed beds of indurated pellets. The average pellet diameters calculated from the equations of Leva[32] were 14,20 mm, 11,00 mm, and 7,77 mm for size fractions between $\frac{3}{4}$ and $\frac{1}{2}$ inch, between $\frac{1}{2}$ and $\frac{3}{8}$ inch, and between $\frac{3}{8}$ and $\frac{1}{4}$ inch respectively.

In the preparation of the pre-reduced pellets, the ores were ground to 75 per cent minus 200 mesh and mixed with Rand Carbide char of the same mesh size and the following chemical composition (mass per cent): fixed carbon 74,8; volatiles 3,0; ash 12,2; SiO_2 4,8; Al_2O_3 3,94; CaO 0,61; MgO 0,63; P 0,007 to 0,001. The amount of Ocean bentonite added was 0,75 per cent of the total mass of ore and char.

Four types of pellets with an average diameter of 11 mm were obtained by the addition as char of 20, 40, 60, and 80 per cent of the stoichiometric carbon required to reduce both the oxides of iron and chromium completely to the respective metals. The pellets were made as previously described, except that the amount of Ocean bentonite added was 0,75 per cent of the total mass of ore and char. After overnight drying, the pellets were reduced at 1550 °C for two hours in an induction furnace. A leaching method[31] was used in the determination of the degree of metallization of the pellets, and the average metallization for type A and type B pellets is given in Table III.

TABLE III

AVERAGE METALLIZATION OF PRE-REDUCED PELLETS OF TYPE A AND TYPE B TRANSVAAL CHROMITE ORES

Percentage of stoichiometric carbon addition	Per cent metallization	
	Type A	Type B
20	10,9	11,6
40	32,3	—
60	49,1	—
80	62,4	62,0

Porosities and Densities

The picnometric method with water as the displaced medium was used in the determination of the real densities of type A and type B ores and pre-reduced pellets made from these ores.

The mineralogical analysis showed that the fines of both ores had virtually no internal porosity, and the density of the bed was therefore obtained by measurement of the volume occupied by a given mass of fines, pellets, and lumps in a small measuring cylinder. The porosity of the bed was calculated from its density and the real density of the ore. Ten density tests were conducted for each size fraction of the fines, pellets, and lumps of ore, and the results are shown in Table IV. The fines agglomerated in the packed beds at high temperatures, and, because this method could not be used for the determination of porosities of packed beds of agglomerated ores, the procedure specified in the appropriate A.S.T.M. standard[33] was adopted. Each determination was repeated three times.

The internal porosities of the pellets were determined by measurement of the average diameter and the mass of the pellets, and these results are also given in Table IV.

Effective Thermal Conductivities of Packed Beds

The heat-sink technique was used in the measurement of the effective thermal conductivity. This technique is similar in principle to the more common cylindrical-envelope technique[1, 3, 4, 9, 10, 18, 29], the only difference being in the method of determination of the heat flux, q. The thermal conductivity is calculated from the heat flow in the heat sink and the radial temperature drop across the specimen, which is packed between the heat sink and the walls of the cylinder. The equation for the calculation of thermal conductivity, k, is

$$k=\frac{q}{2\pi L}\,\frac{\ln(r_1/r_2)}{(T_1-T_2)} \qquad \ldots\ldots\ldots\ldots\ldots (7)$$

and $T_1>T_2$ and $r_1>r_2$ because the heat flux, q, flows in a direction opposite to the increase in radius r.

The heat flux, q in equation (7), was determined by a heat balance across the heat sink, which is illustrated schematically in Fig. 1. Under steady-state conditions, the amount of heat passing through the sample equals the amount of heat required to increase the temperature of the water in the heat sink.

A major problem in the use of the heat-sink technique is the assumption, from equation (7), that the heat flow

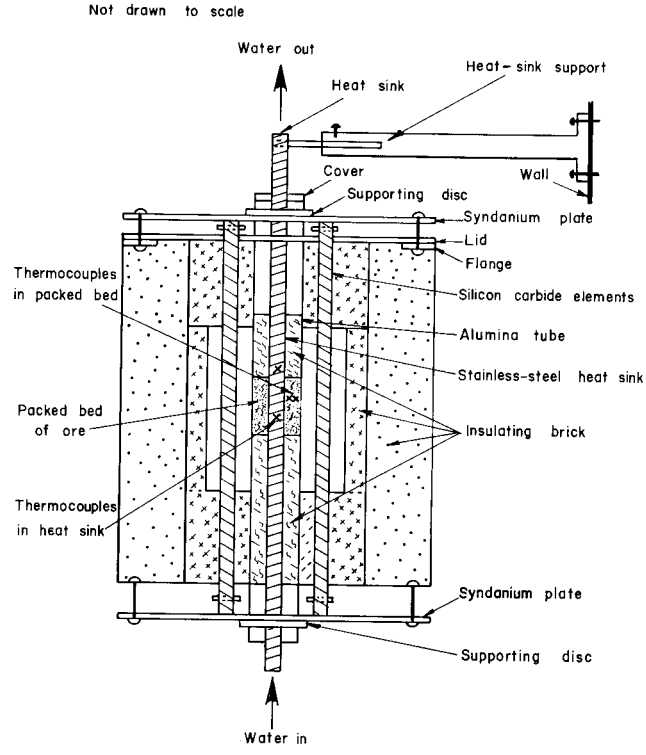

Fig. 1—Schematic representation of the furnace in vertical cross-section

TABLE IV

DENSITIES AND POROSITIES OF FINES, PELLETS, AND PACKED BEDS OF TYPE A AND TYPE B TRANSVAAL CHROMITE ORES

Bed packings	Real density g/cm³	Internal porosity %	Bed porosity %
Type A chromite ore			
Fines, Dp=0,50mm	4,49	—	47,3
0,33 mm	4,49	—	47,1
0,18 mm	4,49	—	48,3
0,12 mm	4,49	—	49,5
Agglomerates of fines, Dp=0,50 mm	4,49	39,8*	—
0,33 mm	4,49	40,0	—
0,18 mm	4,49	44,5	—
0,12 mm	4,49	46,3	—
Indurated pellets, Dp=14,20 mm	4,49	25,2	40,8
11,00 mm	4,49	26,6	40,9
7,77 mm	4,49	30,6	37,8
Pre-reduced pellets, 20 %C addition	4,49	24,7	40,6
40 %C addition	4,51	14,1	40,0
60 %C addition	4,59	10,6	40,2
80 %C addition	4,63	9,8	41,0
Lump ore, Dp=11,00 mm	4,49	0,98	50,2
Type B chromite ore			
Fines, Dp=0,18 mm	4,36	—	43,0
Agglomerates of fines, Dp=0,18 mm	4,36	43,0	—
Indurated pellets, Dp=11,00 mm	4,36	27,6	41,2
Pre-reduced pellets, 20 %C addition	4,36	14,6	40,8
80 %C addition	4,52	24,3	40,1

*For these fines, the term *internal porosity* is used, rather than *bed porosity*, to indicate that the fine particles were bonded together.

is in the same direction at every point. Such an assumption is not necessarily valid because temperature isotherms in the bed will be non-linear if there is sufficient heat flux perpendicular to the major direction of heat flux. The ratio of length to diameter of the packed bed used in this investigation was not as high as that considered the optimum[34] because of the difficulty in maintaining a hot zone of adequate length. Thus, it was necessary to check the influence of the heat flux from the ends of the packed bed on the temperature isotherms within the bed. This was done from a comparison of the experimental system with an analystical model. Details of this comparison are given by Young[31] and indicate that the minimum possible error in the experimental technique was about 8,3 per cent for an assumed boundary temperature of 25 °C.

The Furnace Assembly

The furnace assembly is also shown in Fig. 1. Heat was transferred from the external heating elements to the central water-cooled stainless-steel pipe (2,16 cm internal diameter) by radiation to the outer surface of a cylindrical alumina tube (15,24 cm internal diameter), followed by radial conduction through the sample packed in the annular space between the alumina tube and the water-cooled heat sink. A constant-head tank and a rotameter maintained a constant flow of water (5 l/min) through the heat sink to give turbulent flow in the heat sink.

The furnace was heated by eight silicon carbide elements on a pitch-circle diameter of 26,2 cm. The highest furnace temperature was about 1200 °C. Temperatures were measured inside the packed bed by six Pt-6 per cent Rh/Pt-30 per cent Rh thermocouples inside double-bore alumina tubes covered by pythagoras tubes. Three pairs of thermocouples were used to ensure experimental accuracy. These thermocouples showed that the hot zone in the furnace was 8 cm thick with an overall temperature variation of 5 °C, and that the temperature outside the hot zone decreased very gradually.

Two copper–Constantan thermocouples inside stainless-steel tubes indicated the rise in temperature of the water in the heat sink. The two thermocouples were connected to form a differential thermocouple, the temperature difference being measured by a d.c. microvoltmeter.

Experimental Procedure

The same experimental procedure was used for fines as for indurated and pre-reduced pellets. The amount of ore needed for each run was reduced by the placing of crushed refractory bricks above and below the hot zone containing the ore sample.

The water supply to the heat sink was turned on, and the power was switched on. When the required constant temperature was reached, temperature measurements were taken in the packed bed and the heat sink. The power was then increased until the next required steady-state temperature was reached. When all the temperature measurements had been taken for the required temperature range of 300 to 1200 °C, the transformer was switched off and the furnace cooled to room temperature. The packed material was then removed from the furnace through its top, the next sample was packed in the furnace, and the experimental cycle was repeated.

Calibration of the Furnace

Measurements of the heat flux in the runs with Raschig rings, type A fines (between 20 and 48 mesh), and indurated pellets (14,20 and 11,00 mm) gave the following curve based on a least-squares fit for the heat

flux, q, into the heat sink as a function of the input power, P_f, to the furnace:

$$q=2{,}083+(0{,}439\times10^{-2})\,P_f+(0{,}10\times10^{-4})\,P_f^2 +(0{,}61\times10^{-9})\,P_f^3. \quad (8)$$

For the thirty experimental values of q, the average percentage error between the experimental and calculated values of equation (8) was 1,53 per cent, with a maximum absolute error of 13,0 per cent and a minimum absolute error of 0,2 per cent. Equation (8) was obtained for the four different types of packings and thus was used in the determination of the heat flux for each power input during all the subsequent experiments. No previous data were available on the effective thermal conductivities of packed beds of chromite ores. As a check of the accuracy of the experimental technique, it was decided to determine the effective thermal conductivity of packed beds of porcelain Raschig rings, for which published data were available[3, 18].

The experimental values were found to be in better agreement with the results of Schotte[3] than with those of Yagi and Kunii[18]. However, a precise comparison was difficult because of the assumed values of the emissivity, e, and the empirical nature of the models. It was considered that sufficient agreement had been obtained with the results of previous investigators to prove the accuracy of the experimental technique.

Experimental Errors

The main sources of error in the experimental method were the measurements of temperature and heat flux, the positioning of the thermocouples, and the estimation of the length of the hot zone.

The maximum theoretical error was estimated by the method described by Mickley, Sherwood, and Reed[35], and was 24 per cent at 282 °C and 16 per cent at 1032 °C[31]. This error does not include the error in the experimental technique of 8,3 per cent due to non-linear temperature isotherms in the packed bed of ore. The overall errors compare very favourably with values calculated by Puslatov[10] for the cylindrical-envelope technique. These overall errors are systematic in that they occur for all the experimental data points.

Results

Type A and B Fines

Figs. 2 and 3 show the experimental values of effective thermal conductivities of type A and type B fines as a function of temperature. The experimental points for these runs and the runs with pellets were used to obtain best curves based on the method of least squares.

Fig. 2 shows that there was no difference in effective thermal conductivities for the three size fractions of type A ore. However, there was a marked difference between the effective thermal conductivities for fines between 20 and 48 mesh and those for the finer material at temperatures above about 600 °C.

All the fines formed agglomerates owing to the high temperature inside the bed, giving the reduction in bed porosities shown in Table IV. In a determination of the effect of this change in porosity on the effective thermal conductivity, the bed was packed with fines between 100 and 150 mesh and was heated up to its maximum temperature. The bed was cooled down to room temperature, and a run was then carried out with the agglomerated fines, to give the curve in Fig. 2.

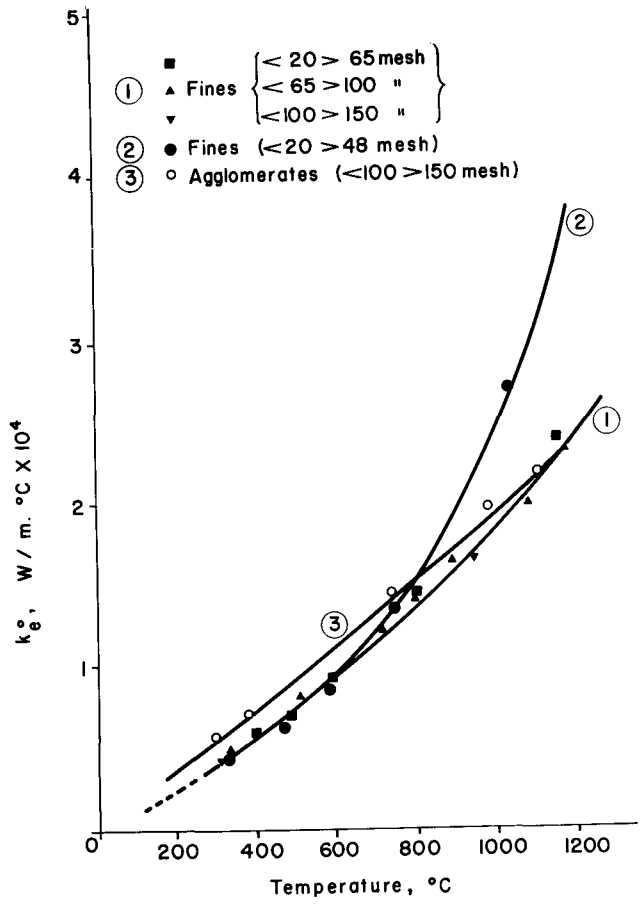

Fig. 2—Variation of the experimental effective thermal conductivity with temperature for fines and agglomerates of type A ore

Fig. 3 shows the points for k_e^o for the size fraction of type B ore between 65 and 100 mesh. The curve in this diagram for fines of type A ore from Fig. 2 show that there was very little difference in effective thermal conductivities between the two chromite ores. Fines of type B ore formed less strongly bonded agglomerates than did type A fines and gave the points for type B agglomerates shown in Fig. 3.

Indurated Pellets and Lump Chromite

Fig. 4 shows curves for k_e^o versus temperature for three pellet sizes of type A ore, whilst Fig. 5 shows curves for 11 mm pellets of types A and B ore. In an examination of the effect of particle shape on k_e^o, lumps of type A ore were crushed and screened to between $\frac{1}{2}$ and $\frac{3}{8}$ inch, which corresponds to an average particle diameter of 11 mm. The effective thermal conductivity of these lumps is also shown in Fig. 5.

Pre-reduced Pellets

Fig. 6 shows k_e^o versus temperature for 11 mm dia-

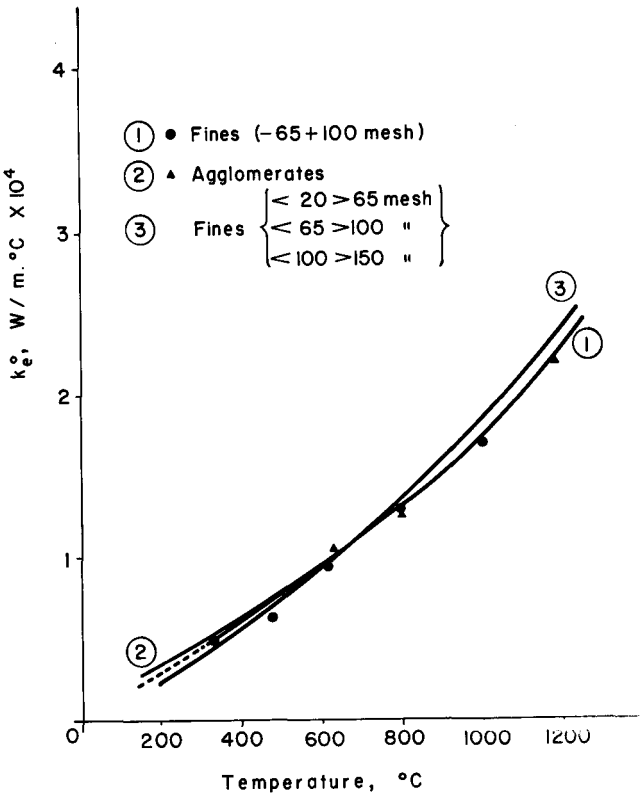

Fig. 3—Variation of the experimental effective thermal conductivity with temperature for fines and agglomerates of type B ore

meter pellets of type A ore with four different degrees of metallization. Fig. 7 shows values of k_e^o for packed beds of 11 mm diameter pellets of type B ore containing stoichiometric carbon additions of 20 and 80 per cent compared with the results for 11 mm diameter pellets of type A ore containing the same carbon additions.

Discussion

Chromite-ore Fines

Figs. 2 and 3 show that, for type A and B ores with the exception of the fines between 20 and 48 mesh, differences in composition and particle size do not significantly affect the values of effective thermal conductivity. Hence, only the results for type A ore fines will be discussed in detail.

Puslatov[10] obtained similar results in investigations on refractory powders with particle sizes of 2 to 5 mm, 1 to 0,2 mm, and less than 0,2 mm. At temperatures up to 1000 °C, he showed that variations in the effective thermal conductivities of powders were dependent only on grain size, being independent of the nature of the material.

If the curves for the three size fractions of type A ore in Fig. 2 and for fines between 65 and 100 mesh of type B ore in Fig. 3 are extrapolated to temperatures below 300 °C, a k_e^o value of $2,3 \times 10^{-5}$ W/m.°C is obtained at 195 °C for the type A ore and at 150 °C for the type B ore. For temperatures between 100 ° and 200 °C, Puslatov also found that the effective thermal conductivity of refractory powders was independent of particle size and had the constant value of $2,3 \times 10^{-5}$ W/m.°C.

Fig. 2 suggests that, for average particle sizes between 0,12 and 0,38 mm, the amount of radiation heat transfer above about 600 °C is negligible compared with that for particles with average diameters of 0,50 mm. Puslatov[10] also observed that, for temperatures above about 300 °C, particle size began to affect radiation heat transfer, although no heat transfer by radiation occurred in a powder with a particle size of 0,2 mm and a porosity of 10 per cent.

In the work described in this paper, it was initially assumed that the difference in effective thermal conductivity between packed beds of 0,50 mm diameter particles and the other particle sizes would be attributed to radiation alone. On the basis of this assumption, some models[2, 9, 23-30] for radiation heat transfer in packed beds and two-phase systems were used to predict the radiation thermal conductivity of the 0,50 mm fines. All these models considered that the radiation thermal conductivity was added to the conduction thermal conductivity. Two other models[27, 28] were not used because some of the parameters in the equations were not known or could not be determined.

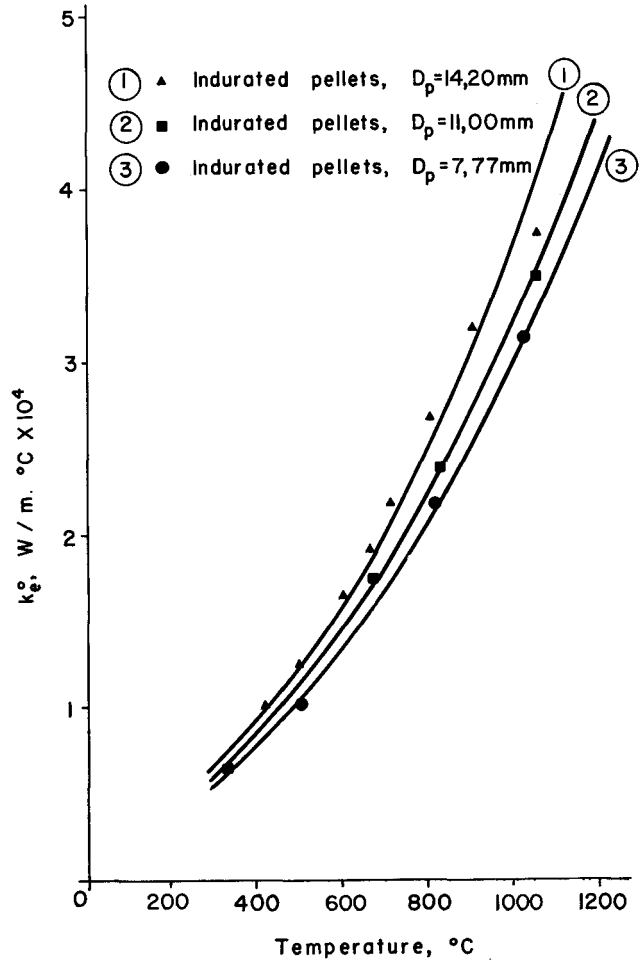

Fig. 4—Variation of the experimental effective thermal conductivity with temperature and particle size for indurated pellets of type A ore

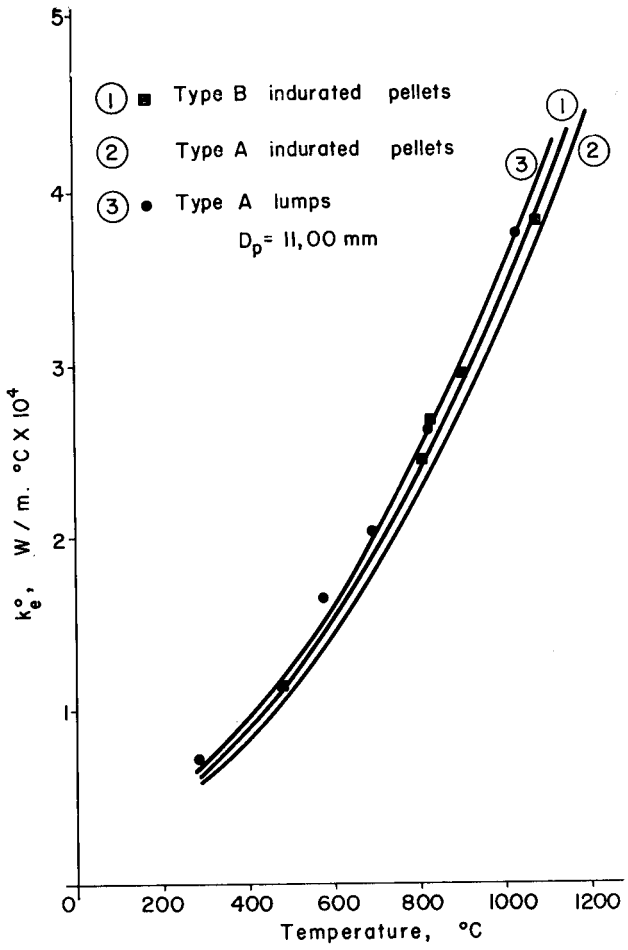

Fig. 5—Comparison between the experimental effective thermal conductivity of indurated pellets of type A and B ores and lumps of type A ore

Emissivity values were not available for chromites and were estimated by the procedure summarized by Young[31]. For type A chromite ore, the emissivity was between 0,75 and 0,80 for the temperature range 200 to 1000 °C.

Values of k_r calculated from the seven published models were compared with the experimental values for particles of average diameter 0,50 mm obtained from Fig. 2, by subtraction of the values of k_e^o for the three smallest size fractions of type A ore from the values for the size fractions between 20 to 48 mesh of type A ore. At temperatures above 650 °C, all these models underestimated the value of k_r. The closest approach to the experimental value for k_r was for the model of Godbee and Ziegler[9], which, for an emissivity of 0,80 at a temperature of 1000 °C, gave a value of k_r of $1,7 \times 10^{-5}$ W/m. ° C, compared with the value of 6×10^{-5} W/cm. °C determined from the experimental results.

The discrepancy between the experimental results and the theoretical predictions could not be explained in terms of the structure of the packed bed of chromite fines or by errors in estimation of the emissivity of the ore. Hence, the packed bed of agglomerated chromite particles was considered to be a porous solid material on the basis of a microscopic examination[31] and the porosities given in Table IV.

The experimental values of k_e^o for the agglomerates in Fig. 2 were assumed to represent k_e, the effective thermal conductivity of the packed bed, if radiation were neglected. Values of the effective radiation thermal conductivity, k_r, from the appropriate models[2, 9, 23–30] could then be added to k_e in a determination of whether it was possible to predict values of k_e^o for the fines of type A ore between 20 to 48 mesh in spite of the uncertainties about the extent of agglomeration that occurred during the heating of these fines. The procedure followed has been outlined by Young and See[36] and involved testing of the assumption that the experimental curve for the agglomerated fines of type A ore between 100 and 150 mesh represented k_e, the effective thermal conductivity of the packed bed, if radiation were neglected.

A number of different models[8, 11, 13, 15, 37–40] for the calculation of the conduction thermal conductivity for a porous solid, k_p, were reviewed to see if the prediction of k_e was possible. The use of these models required the assumption that k_e was identically equal to k_p, which meant that the contribution to k_e of heat transfer by

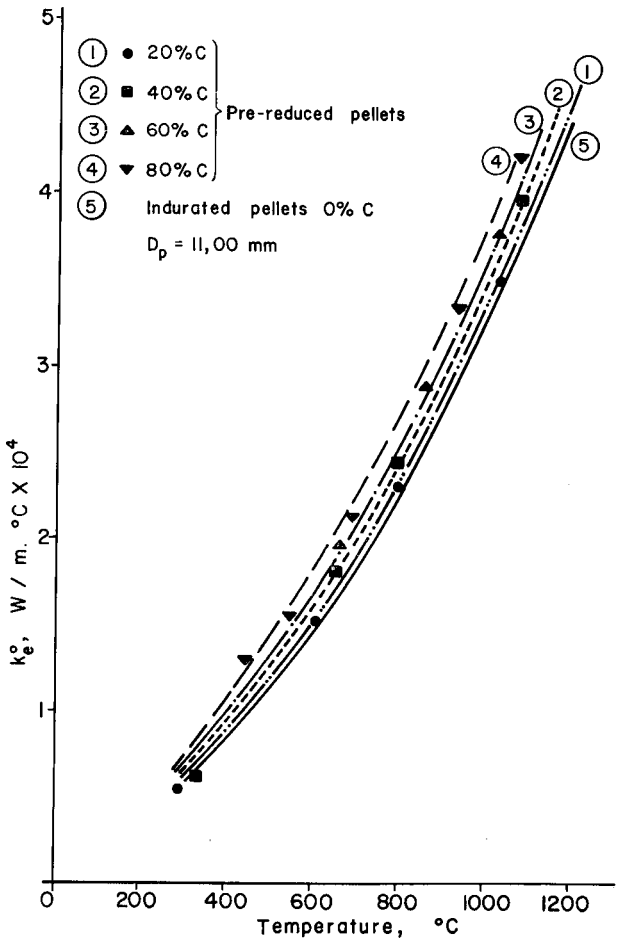

Fig. 6—Variation of the experimental effective thermal conductivity with temperature and percentage metallization for pre-reduced pellets of type A ore

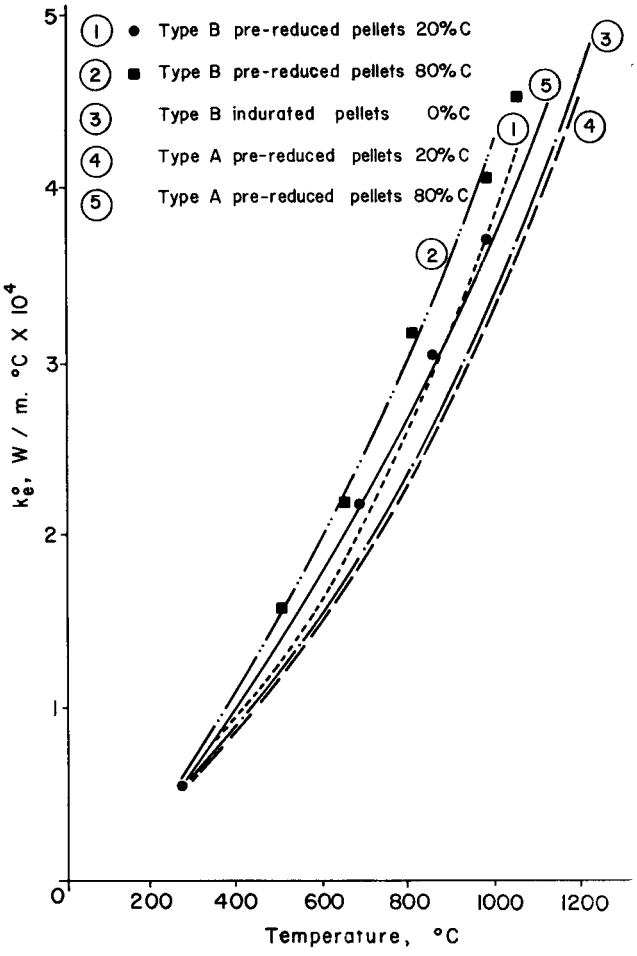

Fig. 7—Comparison between the experimental effective thermal conductivities of pre-reduced and indurated pellets of both types of ore

natural convection was considered to be negligible. The equations also required estimates of values for the bulk thermal conductivity of the solid chromite, k_s, and the thermal conductivity of the air, k_g. It was not possible to determine whether the approach adopted for the calculation of k_e^o for fines was satisfactory because for only one point at temperatures above 900 °C was there reasonable agreement between the experimental and the calculated values of k_e^o. Hence, the solid thermal conductivity must be determined experimentally rather than estimated theoretically[36] since a large uncertainty exists in the use of models for the calculation of the thermal conductivity of agglomerated ore. This uncertainty means that the tentative conclusions about the relative contributions of conduction and radiation heat transfer to the effective thermal conductivities of packed beds of fines and agglomerates should be treated with caution.

The calculated values of thermal conductivity for chromite ores were used in the interpretation of the results for indurated and pre-reduced pellets. The predictions of models for k_e^o in the discussion of these results are sufficiently accurate to indicate that any errors in the values of k_s are not of critical importance in the application of these models.

Indurated Pellets

Previous investigations[2, 3, 9, 23–30] have shown that the radiation conductivity and the effective thermal conductivity increase with increasing particle size. This behaviour was observed in Fig. 3, which shows a plot of the experimental effective thermal conductivity versus temperature for the indurated pellets of type A ore with diameters of 14,20 mm, 11,00 mm, and 7,77 mm.

The models derived by Yagi and Kunii[18] and by Schotte[3] were used to predict the effective thermal conductivity of packed beds of the three pellet sizes using the estimated emissivity values of Young[31]. Other models such as that of Beveridge and Haughey[1] were not used because certain parameters in those equations must be determined experimentally. The internal porosity of the pellets (Table IV) affected heat transfer by conduction inside the pellets, and the term k_s in the theoretical models was replaced by k_p, the thermal conductivity of a porous material. This value of k_p was obtained from the average values of k_s calculated for agglomerated fines[36] and Maxwell's relation[15], on the assumption that the ore in the pellet was the continuous phase.

A comparison of the predictions of the two models with the experimental values can be obtained from Fig. 8. For the pellets of 14,20 and 11,00 mm diameter,

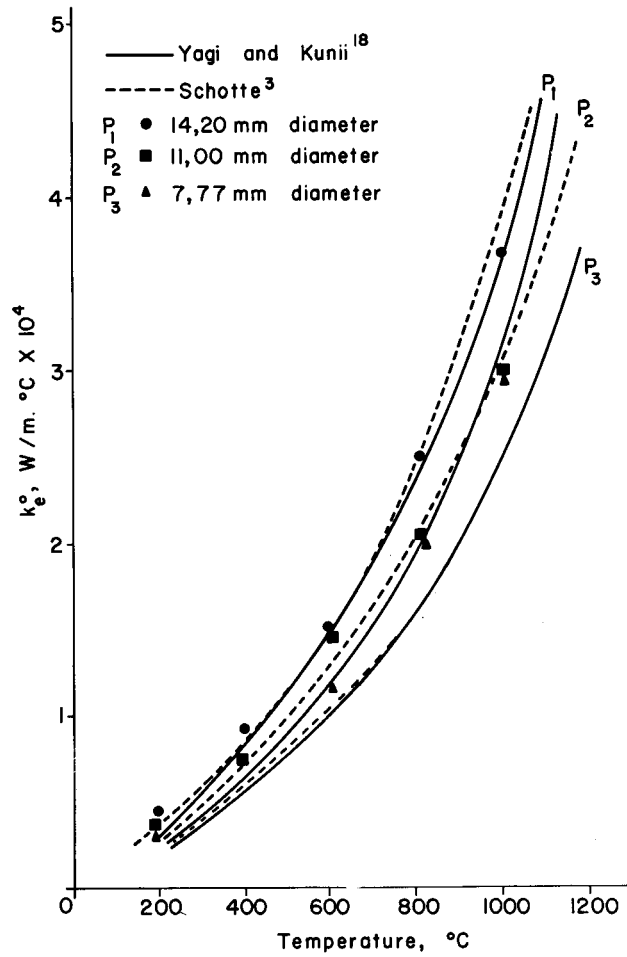

Fig. 8—Comparison between the values for the effective thermal conductivities of indurated pellets of type A ore and those values obtained from the models of Schotte and of Yagi and Kunii

the values of k_e^o calculated from both models generally slightly underestimated the experimental values.

For the temperature range 200 to 1000 °C, the experimental values obtained for the pellets of 7,77 mm diameter were higher than the calculated values by up to about 25 per cent.

Calculations[31] indicated that the values of k_e^o predicted by these two models were extremely sensitive to variations in the values of emissivity and $k_p(\equiv k_e)$. Prediction of k_p depends on the value of k_s, and it should be emphasized once again that the true value of k_s for the ore is essential for meaningful comparisons between the experimental effective thermal conductivities and those obtained from published models. The emissivity values used in the calculation of the effective thermal conductivity of the indurated pellets of type A ore were those for the fines. However, these values may have varied as a result of the difference in grain size. The fines had a grain size of 0,5 mm, while the pellets were made of ore crushed to 75 per cent minus 200 mesh, or 75 per cent of particles had a nominal diameter of less than 0,053 mm. Furthermore, the mixture of different oxides making up the ore may not always be distributed uniformly in the system, and emissivities are dramatically influenced by such variations in composition[31].

Fig. 5 shows that the effective thermal conductivities for type B pellets of 11,00 mm diameter are larger than those for pellets of type A ore of the same size. This difference can be attributed to differences in the thermal conductivities and emissivities of the two ores. It is unlikely that the value of k_s will be very different for the two types of ores because the total amount of Cr_2O_3 and Fe_2O_3 present is virtually the same. In addition, as shown by Fig. 3, k_e^o for the fines of both ores is almost the same.

The higher emissivity of type B ore might be due to a difference in experimental procedure. Type A ore was ground to 95 per cent minus 200 mesh, while type B ore was ground to 75 per cent minus 200 mesh. Thus, the pellets of type B ore were made from larger, rougher grains. No quantitative predictions are possible for the effect of the degree of roughness on the emissivity, but calculations[31] indicated that small variations in the emissivity cannot be neglected when the models of Schotte[3] and of Yagi and Kunii[1]: are used.

Fig. 5 also shows the differences in conductivity between pellets and lumps of the same size of type A ore.

Equations (3) and (4) were once again used in a prediction of the effective thermal conductivity of the lumps. Fig. 9 compares the theoretical and experimental values for the effective thermal conductivity of the lumps and indurated pellets of type A ore with diameters of 11,00 mm. The experimental values of k_e^o obtained for the lumps were higher than those obtained for the pellets by about 16 per cent at 400 °C, and by 8 per cent at 1000 °C. The discrepancy between the experimental and theoretical values of k_e^o for the lumps decreased with increasing temperature, although the experimental values were always higher than the theoretical predictions.

The theoretical models were derived for spherical particles, and the lumps were more ellipsoidal in shape than sperical. Attempts have been made by other investigators to describe the deviation of particle shape from the spherical by a shape factor, which, for packed beds, affects not only the contact conductivity between particles but also the radiation term because the view factor is always dependent on the geometry of the surfaces subjected to radiation heat transfer. More research is required on the influence of shape factor before a more general model can be developed for k_e^o.

Pre-reduced Pellets

Four types of pellets of type A ore with diameters of 11 mm and stoichiometric carbon additions of 20, 40, 60, and 80 per cent were packed in the bed, and their effective thermal conductivities were measured as shown in Fig. 6. Increasing degree of metallization increases the effective thermal conductivities of the packed beds of pellets.

The values of k_e^o for the packed beds of pellets of different degrees of metallization were again calculated from the equations of Yagi and Kunii[18] and Schotte[3]. These calculations and the evaluation of k_p from the equation of Eucken[38] were based on the following assumptions[31].

(a) The degree of metallization was assumed to be the same as the stoichiometric carbon addition.

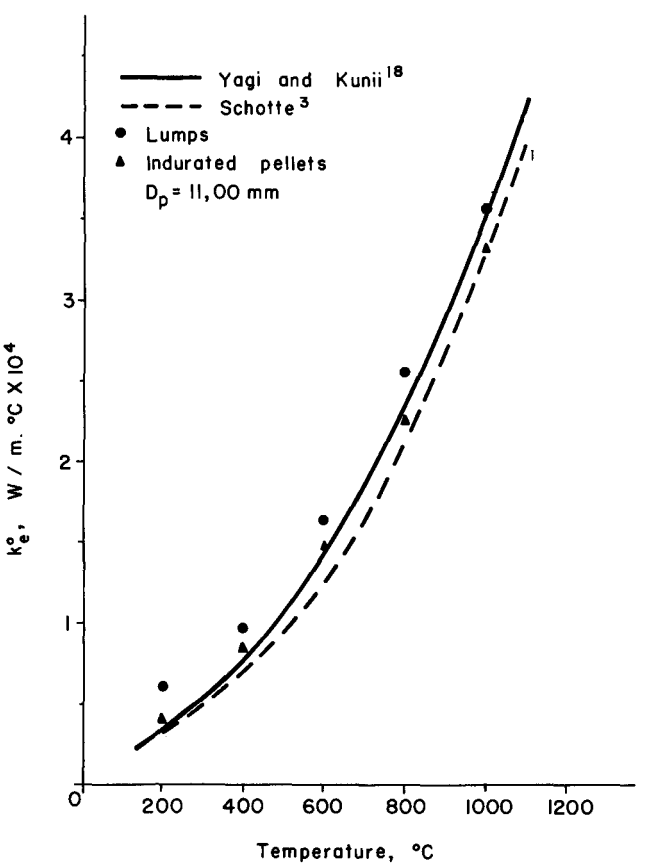

Fig. 9—Comparison between experimental and theoretical predictions of effective thermal conductivities for indurated pellets and lumps of type A ore

(b) The unreacted ore is the continuous phase.

(c) The solid thermal conductivity of the mixture of iron and chromium and their carbides is approximated by the thermal conductivity of pure iron.

The emissivity values estimated by Young[31] were again used because microscopic examination of the boundaries of the cross-sections of the pre-reduced pellets showed that the metal was formed in the bulk of the pellet and not on the surface.

The comparison of the experimental results with those calculated from the equation of Yagi and Kunii[18] for pellets of 11 mm diameter is shown in Fig. 10, which also shows the experimental values of the effective thermal conductivity obtained for type A ore with carbon additions of 20 and 80 per cent. For clarity, the values for carbon additions of 40 and 60 per cent were not included.

Fig. 10 shows reasonable agreement between the experimental and theoretical effective thermal conductivities for the pre-reduced pellets. The emissivities of the pellets do not change with an increase in the amount of metal in the pellet, and the increase in the effective thermal conductivity of the pellets of type A ore can be attributed almost solely to the increase of the conductivity of the pellet, k_p, due to an increase in the amount of metal present.

Fig. 7 shows the effective thermal conductivities of pre-reduced pellets of both ores with carbon additions of 20 and 80 per cent. As with the indurated pellets (Fig. 5), type B ore has a higher value of k_e^o than has type A ore.

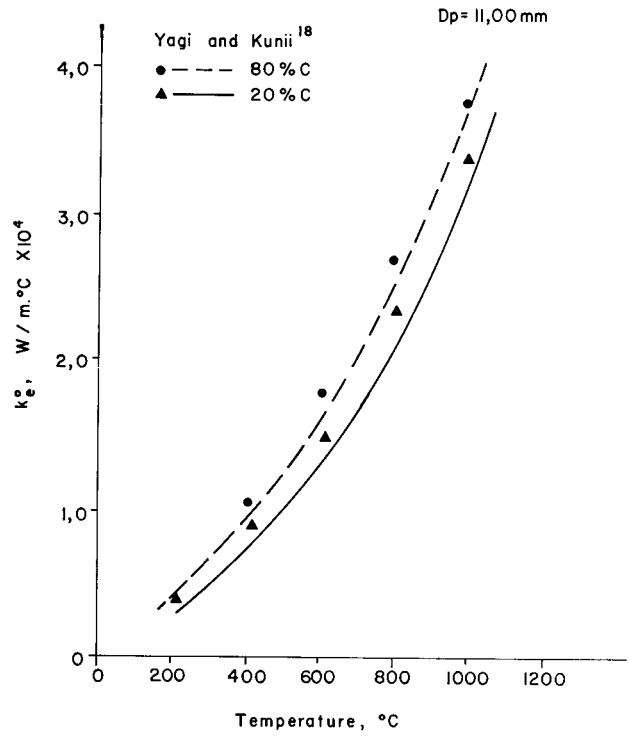

Fig. 10—Comparison between experimental and theoretical effective thermal conductivities for pre-reduced pellets of type A ore

This effect may result either from differences in emissivities or, much less likely, from differences in the value of k_s for type B ore. At 1000 °C, the difference in conductivity for the indurated pellets of both types of ore is $1,5 \times 10^{-5}$ W/m.°C. The pre-reduced pellets of type B ore also have a higher conductivity than that of the corresponding pellets of type A ore. A difference of $5,5 \times 10^{-5}$ W/m.°C in the effective thermal conductivity is given by an increase in the carbon addition from 20 per cent to 80 per cent of the stoichiometric value.

Table IV shows that the indurated pellets have more or less the same internal porosity, while, for the carbon additions of 20 per cent, type A ore has an internal porosity of 24,7 per cent compared with 14,6 per cent for type B ore. For a carbon addition of 80 per cent, type A has a porosity of 9,8 per cent compared with 24,3 per cent for type B ore. The differences in the values of k_e^o might be due to these differences in internal porosity. More information is required on the thermal conductivities and emissivities of both ores to permit further comparisons.

Summary and Conclusions

(1) Packed beds of type A and type B chromite ore fines of the three particle sizes investigated had the same values of effective thermal conductivity. At temperatures between 100 and 200 °C, the effective thermal conductivity was $2,3 \times 10^{-5}$ W/m. °C, which is in agreement with the work of Puslatov[10].

(2) The effective thermal conductivities of packed beds of type A ore between 20 and 48 mesh at temperatures above 600 °C were higher than those for finer particles. This difference was explained by the increase in the importance of radiation heat transfer. Attempts were made to predict the effective thermal conductivity for the larger particles on the initial assumption that the conduction thermal conductivity for the larger particles was equal to the experimental value of the effective thermal conductivity for the fines of the three other particle sizes. No definite conclusions were reached about the relative contributions of conduction and radiation heat transfer to the effective thermal conductivities of packed beds of fines between 20 and 48 mesh.

(3) The experimental and theoretical results for effective thermal conductivities of packed beds of lumps and pellets were in good agreement in view of the uncertainties in the assumed values of emissivity and thermal conductivity of the chromite ores.

(4) The experimental effective thermal conductivities of packed beds of three sizes of indurated pellets of type A ore increased with particle size as a result of the increase in radiation thermal conductivity.

(5) The effective thermal conductivities of packed beds of indurated pellets of type B ore were higher than those of type A ore. This difference may have been due to differences in the degree of roughness between the pellets that affected emissivity values.

(6) The effective thermal conductivities for packed beds of lumps of type A ore differed from those of

pellets of the same average size, probably because of the influence of the shape on the heat transfer in packed beds.

(7) The effective thermal conductivity of a packed bed of pellets increased with the degree of metallization of the pellets because heat transfer by conduction is the dominant heat-transfer mechanism for metals at high temperatures. Thus, the difference in effective thermal conductivities between packed beds of indurated and pre-reduced pellets with different degrees of metallization was due to increases in the solid thermal conductivities of the pellets with increasing metallization.

(8) Packed beds of metallized pellets of type B ore had a higher effective thermal conductivity than packed beds of metallized pellets of type A ore probably because of differences in the values of emissivity of the ore resulting from differences in the degree of roughness of the two ores.

(9) Much more detailed examination of the heat-transfer properties of chromite ores is necessary. In particular, emissivity should be determined as a function of composition and surface roughness, and the thermal conductivity should also be measured. Determination of these properties will permit more detailed discussion of the theoretical implications of the use of particular models.

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References

1. Beveridge, G. S. G., and Haughey, D. P. Axial heat transfer in packed beds — stagnant beds between 20 and 750°C. *Int. J. Heat Mass Transfer*, vol. 14. 1971. pp. 1093-1113.
2. Argo, W. B., and Smith, J. M. Heat transfer in packed beds — prediction of radial rates in gas–solid beds. *Chem. Engng Prog.*, vol. 49, no. 8. 1953. pp. 443-451.
3. Schotte, W. Thermal conductivity of packed beds. *AIChEJ.*, vol. 6, no. 1. 1960. pp. 63-67.
4. Koya, T., and Kunii, D. Measurement of thermal conductivities of solid particles in packed beds. *Int. Chem. Engng*, vol. 12, no. 1. 1972. pp. 162-167.
5. Gorring, R. L., and Churchill, S. W. Thermal conductivity of heterogeneous materials. *Chem. Engng Prog.*, vol. 57, no. 7. 1961. pp. 53-59.
6. Woodside, W., and Messmer, J. H. Thermal conductivity of porous media (Pt I and II). *J. Appl. Phys.*, vol. 32, no. 9. 1961. pp. 1688-1706.
7. Verschoor, J. D., Greebler, P., and Manville, N. J. Heat transfer by gas conduction and radiation in fibrous insulators. *Trans. ASME*, vol. 74. 1952. pp. 961-968.
8. Woodside, W. Calculation of the thermal conductivity of porous media. *Can. J. Phys.*, vol. 36. 1958. pp. 815-823.
9. Godbee, H. W., and Ziegler, W. T. Thermal conductivities of MgO, Al_2O_3 and ZrO_2 powders to 850°C (Pt I and II). *J. Appl. Phys.*, vol. 37, no. 1. 1966. pp. 40-65.
10. Puslatov, V. V. Thermal conductivity of refractory materials. *Izdatel 'stvo Metallurgiya*, 1966 (translated from Russian). Published by the Indian National Scientific Documentation Centre, New Delhi.
11. Kingery, W. D. Thermal conductivity: XIV, Conductivity of multicomponent systems. *J. Am. Ceram. Soc.*, vol. 42, no. 12. 1959. pp. 617-627.
12. Lord Rayleigh. On the influence of obstacles arranged in rectangular order upon the properties of a medium. *Phil. Mag.*, vol. 34. 1892. pp. 481-502.
13. Fricke, H. A mathematical treatment of the electric conductivity and capacity of disperse systems. *Phys. Rev.*, no. 24. 1924. pp. 575-587.
14. Hamilton, R. L., and Crosser, O. K. Thermal conductivity of heterogeneous two-component systems. *I & E C Fundamentals*, vol. 1, no. 3. 1962. pp. 187-191.
15. Maxwell, J. C. *A treatise on electricity and magnetism.* vol. 1, 3rd edition. New York, Dover, 1954.
16. Deissler, R. G., and Eian, C. S. Investigation of effective thermal conductivities of powders. Washington, National Advisory Council on Aeronautics, RM E52CO5. 1952.
17. Tsao, G. T. Thermal conductivity of two-phase materials. *Ind. Engng Chem.*, vol. 53, no. 5. 1961. pp. 395-396.
18. Yagi, S., and Kunii, D. Studies on effective thermal conductivities in packed beds. *AIChEJ*, vol. 3, no. 3. 1957. pp. 373-381.
19. Kunii, D., and Smith, J. M. Heat transfer characteristics of porous rocks. *AIChEJ*, vol. 6, no. 1. 1960. pp. 71-78.
20. Yagi, S., Kunii, D., and Wakao, N. Radially effective thermal conductivities in packed beds. International Developments in Heat Transfer, Proceedings of the 1961/62 International Heat Transfer Conference, New York, ASME., 1962. no. 90. pp. 742-749.
21. Yagi, S., and Kunii, D. Studies on heat transfer in packed beds. *Ibid.*, no. 91. pp. 750-759.
22. Wilhite, G. P., Kunii, D., and Smith, J. M. Heat transfer in beds of fine particles. *AIChEJ*, vol. 8. no. 3. 1962. pp. 340-345.
23. McAdams, W. H. *Heat transmission.* 3rd edition, New York. McGraw-Hill. 1954.
24. Damköhler, G. *Der chemie ingenieur.* vol. 3. Leipzig, Akademische Verlagsgesellschaft, 1937 (quoted in Reference no. 6).
25. Laubitz, M. J. Thermal conductivity of powders. *Can. J. Phys.*, vol. 37. 1959. pp. 798-808.
26. Bosworth, R. C. L. *Heat transfer phenomena.* New York, Wiley. 1952.
27. Van der Held, E. F. M. The contribution of radiation to the conduction of heat. *Appl. Sci. Res.*, A3. 1952. pp. 237-249.
28. Chen, J. C., and Churchill, S. W. Radiant heat transfer in packed beds. *AIChEJ*, vol. 9, no. 1. 1963. pp. 35-41.
29. Wakao, N., Kato, K. and Foruya, N. View factor between two hemispheres in contact and radiation heat transfer coefficient in packed beds. *Int. J. Heat Mass Transfer*, vol. 12. 1969. pp. 118-120.
30. Duln'ev, G. N., and Sigalova, Z. V. The thermal conductivity of granular systems. *Int. Chem. Engng*, vol. 5, no. 2. 1965. pp. 218-221.
31. Young, M. L. M.Sc. (Eng.) thesis. University of the Witwatersrand, Johannesburg, 1975. 240 pp.
32. Leva, M. *Fluidization.* New York, McGraw-Hill, Chemical Engineering Series. 1959.
33. American Society For Testing And Materials. Standard methods of test for apparent porosity, water absorption, apparent specific gravity and bulk density of burned refractory brick. The Society, Pt 5, 1958. pp. 374-376.
34. Newman, A. B. Heating and cooling rectangular and cylindrical solids. *Ind. Engng Chem.*, vol. 28. 1936. pp. 545-548.
35. Mickley, H. S., Sherwood, T. K., and Reed, C. E. *Applied mathematics in chemical engineering.* 2nd edition. New York, McGraw-Hill, Chemical Engineering Series. 1957.
36. Young, M. L., and See, J. B. Effective thermal conductivities of packed beds of chromite ores. Paper presented at the 105th AIME Annual Meeting, Las Vegas, Nevada, 1976.
37. Russel, H. W. Principles of heat flow in porous insulators. *J. Am. Ceram. Soc.*, vol. 18, no. 1. 1935. pp. 1-5.
38. Eucken, A. Thermal conductivity of ceramic refractory materials — calculation from thermal conductivity of constituents. *Forsch. Gebiete Ingenieurw.*, B3, Forschungshaft no. 353. 1932. 16 pp. (in German).
39. Ribaud, M. Theoretical study of thermal conductivity of porous and pulvurent materials. *Chaleur et Ind.*, vol. 18. 1937. pp. 36-43 (in French).
40. De Vries, D. A. Thermal conductivity of soil. Wageningen (Nederlands), *Mededel. Landb. Hogesch.*, vol. 52. 1952. p. 1.