Effect of Firing Temperature and Porosity on Thermal Conductivity and Diffusivity of Iron Ore Pellets

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The thermal diffusivity and conductivity of iron ore pellet were determined by measuring temperature at surface and centre of pellet during heating and applying heat balance. The effect of firing temperature of pellets and its porosity on thermal conductivity were determined. The mineralogical changes on firing were investigated. The results were analysed by applying model equation and on the basis of basic sintering parameters to determine effective thermal conductivity at zero porosity with radial heat transfer.

KEY WORDS: thermal diffusivity/conductivity measurements; thermal properties of iron ore pellet; pellet properties; mineralogical changes on heating of pellet.

1. Introduction

The knowledge of thermal properties of iron ore agglomerate at higher temperatures are essential to analyse the heat transfer in iron making processes. Wynnyckyj and McCurdy¹⁾ examining the induration process observed that a three fold increase in thermal conductivity of pellet resulted in a ten fold increase in their propensity to develop shrinkage cracks. The role of thermal properties and heat transfer on the reaction kinetics of magnetite coalchar composite pellets were emphasised by Seaton²⁾ and co-workers. With these facts in mind an attempt was undertaken to measure thermal properties of iron ore pellets.

Enormous literatures are available to measure thermal properties of materials. The methods used by an investigator was directed by some specific needs and reasons and varied from simple steady state conduction³⁾ method to sophisticated laser flash method.⁴⁾ Modified laser flash method was reported by Ohta⁵⁾ and subsequently used by Akiyama^{6–8)} to measure thermal diffusivities of dense and porous iron ore agglomerates. These non-contact methods are accurate but limited to flat surface geometries and axial heat flow. Abzalov *et al.*⁹⁾ also determined the thermal conductivities of small cylinders of compressed magnetite concentrates over a range of temperatures and heating rates.

Measurements of thermal diffusivity and emissivity of fired spherical hematite pellets and dried pellets using transient state conduction equation for radial heat flow were reported by Watt and his co-workers.^{10,11)} They measured the temperatures at half radius and at centre of the pellet by inserting thermocouples to evaluate thermal diffusivity. The insertion of two thermocouples in a small pellet is not desirable specially when effect of

factors like porosity or firing temperature are to be investigated.

In the present investigation an attempt has been made to measure the temperature of pellets at surface and centre and apply principles of heat balance to analyse the results. The effect of bulk density and porosity of pellet obtained by firing at different temperatures were investigated. An attempt has been made to explain the results on the basis of existing models and phase changes on heating.

2. Experimental

2.1. Materials

The lumps of iron ore procured from Rajhara mines of India were crushed and ground to fine size. The size analysis of the powder is indicated in **Table 1**. **Table 2**

Table 1. Size analysis of iron ore powder.

Mesh	Microns	% Present
– 100 + 170	– 152 + 80	1.90
– 170 + 200	– 88 + 76	6.00
– 200 + 300	– 76 + 65	51.50
– 250 + 300	– 65 + 54	4.50
– 300 + pan	– 54	36.10
Total		100.00

Table 2. Chemical analysis of iron ore.

Constituent	Percentage
Total iron	64.0
SiO ₂	3.3
CaO	1.1

Fig. 1. X-ray diffraction pattern of iron ore, raw and fired.
 (a) raw ore
 (b) fired at 1223 K
 (c) fired at 1473 K

indicates the chemical analysis of the ore. The colour of the ore was orange brown. The X-ray analysis of this ore powder was carried out in Rigaku-D. Max III X-ray diffractometer. The analysis (Fig. 1) indicates the presence of goethite ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$) along with hematite in the ore. The peaks at 'd' values of 4.189, 2.449 and at 1.717 represent goethite corresponding to crystal planes of (110), (111) and (221) respectively. The peaks at 'd' values of 3.689, 2.701, 2.52, 2.207, 1.84 are of hematite.¹²⁾ The density of the raw powder and its density after firing at higher temperatures, were measured by specific gravity bottle using kerosene as medium.

Pure iron oxide was prepared by precipitation of ferric hydroxide from analytical grade ferric chloride using ammonium hydroxide. The precipitated hydroxide was washed, dried and then fired at 1273 K for 90 min to decompose the hydroxide. The completeness of decomposition is confirmed by X-ray analysis.

2.2. Preparation of Pellets

The ore powder was pelletised in a disc pelletizer of 0.6 m diameter and 0.15 m lip height. One percent dextrin was used as binder. The overall rolling time was about 90 min. The green pellets of size 10–16 mm and spherical shape were picked, dried at 423–473 K for 2 hr and then fired at 1223 K for 1 hr to attain workable strength of pellet. These pellets were furnace cooled. The weight and volume were measured to calculate their bulk densities and porosities. The true density of fine powder was measured by density bottle using kerosene as medium. The pellets of pure iron oxide were made by prolonged hand rolling and then on glass plate.

A radial hole of 0.1 cm diameter was drilled upto the centre of pellets and classified according to their porosities. The pellets were subsequently fired at temper-

atures of 1303, 1393, 1473, 1488, 1523 and 1548 K for 1 hr in a silicon carbide tube furnace and for higher temperatures in platinum wound tube furnace.

2.3. Thermal Property Studies

The method used is similar to one suggested by Watt *et al.*^{10,11)} with modification and different analysis. The method is selected for its suitability to spherical geometry and radial heat transfer. Watt measured the temperature at half radius and at the centre of the pellet and applied transient conduction equation to evaluate thermal diffusivity. Positioning of a thermocouple at centre and at surface of pellet is more reliable and easier than to place at any radial distance for its accurate positioning. It was reported¹¹⁾ that a ten percent error in positioning of thermocouple at half radial distance gives about twenty percent error in thermal diffusivity values due to sharper temperature profiles. On the other hand, the temperature profile near centre is almost flatter minimising such errors. Moreover, it is not desirable to insert two thermocouples in pellet body specially when the effect of bulk density and porosity needs to be investigated. In view of the above facts, the surface and centre temperature were measured and results analysed by applying principles of heat balance.

In the present setup the pellet is fixed between three chromel–alumel thermocouples so that one thermocouple penetrates the pellet through drilled hole with its bead at the centre. The other two thermocouples are diagonally opposite to the pellet diameter with their beads touching the surface. The insulators are inserted to the wires keeping certain distance from pellet surface. The short circuit between wires is avoided by coating the wire with thin layer of iron oxide (slurry/dried) and maintaining safe distance between two wires. Loose iron ore powder was filled to avoid any air gap between thermocouple and pellet hole. Both the outer thermocouples were tied to a thin walled hollow stainless steel tube containing centre thermocouple and clamped. (Fig. 2)

An independently controlled, preheated tube furnace is lowered on the pellet and the rise in surface and centre temperature of the pellet were recorded by two pen strip chart recorder at a chart speed of 10 cm/min. Relationship between surface temperature and centre temperature was also recorded in an omniscrite x–y recorder with accurate scale (1 cm = 1 mv). As tube furnace does not produce an isothermal reservoir but establishes a temperature plateau some where at the centre of the tube, its design is modified, by using reflectors above and below pellet location. These reflectors made of stainless steel are almost of same diameter as the furnace tube. Their use decreases the convective air inspiration, if any, from the bottom of the furnace and also provide configuration similar to an enclosed chamber. It also increases the length of hot zone and variation of temperature within it is decreased. This is also helpful in maintaining the pellet position at the centre of furnace tube. The direct radiation from furnace wall to thermocouple bead was avoided by placing a dome shaped ceramic/metallic shield on the lower reflector to envelop the pellet. This decreases the lateral

temperature gradient and hence allows to measure surface temperature more accurately. The heat flux passing through the thermocouple wire is likely to cause some error in evaluation of thermal diffusivity. Assuming the thermal contact between the pellet and wire to be sufficiently good to produce similar temperature gradient, it was estimated that error of about 2.5% in thermal diffusivity value.¹¹⁾ Same order of error may be anticipated in the present case.

3. Results and Discussion

Figure 3 indicates the rise in surface (average of two thermocouples) and centre temperature of a pellet with time for one of the sets. The relationship between surface temperature (T_s) and centre temperature (T_c) is

Fig. 2. Location of pellet, thermo couples, reflectors and shield.

Fig. 3. Variation of surface and centre temperature of pellet with time.

indicated in Fig. 4.

Attempts were made to correlate ' T_s ' and ' T_c ' with time ' t '. Out of the expressions attempted, the expression of the type

$$T_c = T_s(1 - e^{-kt}) + T_0 e^{-kt} \quad \text{.....(1)}$$

was found to suit best, ' T_0 ' is the initial temperature of pellet and ' k ' is a parameter. Ray *et al.*¹³⁾ derived such an equation assuming exponential rate of heating of volume element of sample.

Validity of the Eq. (1) in the present work was tested by plotting a curve between $-\log_e((T_s - T_c)/(T_s - T_0))$ with time and represented in Fig. 5 for two sets of readings. The linear plot confirms the suitability of the expression for most of the region of heating, except at final stages when ' T_c ' approaches ' T_s ' and the curve tends to be asymptotic. A similar type of expression correlating temperature of a volume element at a radial distance ' r ' can be envisaged as

$$T_r = T_s(1 - e^{-k't}) + T_0 e^{-k't} \quad \text{.....(2)}$$

where ' k' ' is another parameter.

Relation between k and k' is necessary for further analysis of the results and needs to be evaluated.

Taking

$$k' = k(R/(R-r))^n \quad \text{.....(3)}$$

where ' R ' is the radius of the pellet, Eq. (2) modifies to

$$T_r = T_s(1 - e^{-kt(R/(R-r))^n}) + T_0 e^{-kt(R/(R-r))^n} \quad \text{.....(4)}$$

The above equation satisfies our boundary conditions for any value of ' n '. The value of ' n ' in the present case was determined experimentally. The temperature at surface and the half radial distance $r = R/2$ were measured during heating of a pure iron oxide pellet when exposed to furnace. Subsequently for the same pellet, a hole of half radius was extended to centre and ' T_s ' and ' T_c ' were recorded. Three runs were taken to check reproducibility in each case. Figure 6 represents the variation of temperature at surface, half radius and at centre of the iron oxide pellet with time. The parameter k' and k were evaluated by plotting $-\log_e((T_s - T_{r/2})/(T_s - T_0))$ and $-\log_e((T_s - T_c)/(T_s - T_0))$ vs. time for this pellet. The

results are indicated in Fig. 7. The ratio between the slopes of these two linear plot k'/k was found to be 1.238 and the value of 'n' in Eq. (3) as 0.3.

Thus the expression modifies to

$$T_r = T_s(1 - e^{-kt(R/(R-r))^{0.3}}) + T_o e^{-kt(R/(R-r))^{0.3}} \dots (5)$$

on simplification

$$T_r = T_s - (T_s - T_o)e^{-kt(R/(R-r))^{0.3}} \dots (6)$$

Ray¹³⁾ reported that the parameter 'k' is not a constant but may vary with process conditions. In view of the above the temperature ' T_r ' is calculated with instantaneous 'k' value at any time. The temperature of elements of 1 mm thickness and with radial distance 'r' equal to (R-0.05), (R-0.15), (R-0.25) ... is calculated using expression (6) for various time intervals. The results for one of the set is indicated in Fig. 8, which in fact, indicate the temperature profile within pellet at various intervals.

Fig. 4. Relationship between surface and centre temperatures.

The average temperature of pellet at an instant was further calculated by using an expression¹⁴⁾

$$T_{av} = \frac{\int_0^R 4\pi r^2 T_r dr}{\int_0^R 4\pi r^2 dr} \dots (7)$$

and substituting the value of ' T_r ' from Eq. (6) and further integration.

The calculated value of ' T_{av} ' with time is plotted in Fig. 9 for two sets of experiment and other values are indicated in Table 3.

3.1. Calculation of Thermal Diffusivity by Heat Balance

The heat balance at the surface of pellet dictates that amount of heat passing through the pellet surface inside is utilised in heating the pellet.

Thus,

$$K \cdot A \cdot \frac{dT}{dr} = V \cdot B \cdot C \cdot \frac{dT_{av}}{dt} \dots (8)$$

where, K: thermal conductivity of pellet,

V: volume,

B: density,

C: heat capacity, and

A: surface area of pellet.

Rearranging Eq. (8)

$$\frac{dT_{av}}{dt} = (K \cdot A / (V \cdot B \cdot C)) \cdot (dT/dr) \dots (9)$$

substituting for ' α '

$$\frac{dT_{av}}{dt} = (3\alpha/R) \cdot (dT/dr) \dots (10)$$

The thermal diffusivity (α) can be evaluated for known values of (dT_{av}/dt) and (dT/dr) . The value of (dT_{av}/dt) for various time interval, can be evaluated from ' T_{av} ' values indicated in Table 3 and Fig. 9. Evaluation of dT/dr is difficult and require certain assumptions. Many expressions relating dT/dr with heat transfer parameter

Fig. 5. Validity of Eq. (1).

Fig. 6. Variation of surface, half radial and at centre of temperature of pellet with time.

Fig. 7. Evaluation of "n" by ratio of slopes k, k' .

' α ' for different boundary conditions are available in literature.¹⁵⁾ These expressions are not useful in present case as the basic aim is to evaluate ' α ' through dT/dr . Figure 8 indicates that the thermal profile within the pellet could be approximated to linear except at surface and initial stages of heating. It is also evident that the depth of major temperature fall from T_s to T_c , change with time of exposure. Initially the heat front is concentrated at narrow depth near surface and with time it penetrates inside. In present study 90% of temperature fall from T_s to T_c is assumed at major change and the depth at which it occurs is calculated by Eq. (5) to calculate dT/dr . One such model calculation is shown in Table 4. The average of best (7–8) readings are considered to calculate average thermal diffusivity.

The X-ray diffraction analysis of the powder samples heated at 1 223 K (950°C) and 1 473 K (1 200°C) are given

Fig. 8. Temperature profile and movement of heat front $0.9(T_s - T_c)$ point.

Fig. 9. Average temperature rise of pellet.

in Fig. 1 along with X-ray peaks of raw ore powder. The phase analysis indicates that goethite peak ($d=4.189$) disappears due to its decomposition which is expected to occur⁸⁾ between (300–500°C) (573–773 K). New peaks at ' d ' values of 4.07, 2.98, 2.78, 2.44 and 2.03, matches with 20, 100, 40, and 50% intensity (I/I_0) peaks of β -CaSiO₃ (Triclinic).¹²⁾ The equilibrium diagram¹⁶⁾ of CaO–SiO₂ system also indicate the possibility of this phase at the temperature and compositions under considerations. Laybidi¹⁷⁾ and co-workers working on Kudremukh iron ore observed the mineralogical changes

Table 3. Average temperature of pellet (Data rounded off to nearest integer).

Time	1	.6921	.6839	.6249	.5854	.6146	.6154	.6921	.636	.6294	.6154	.7863
(s)	2	2812	2914	3154	3521	3650	3031	2812	3057	3154	3031	2654
	3	1223	1393	1488	1523	1548	1473	1303	1473	1488	1473	1303
15	309	311	323	—	330	320	313	316	323	321	307	
30	355	362	377	372	400	380	358	367	369	382	356	
45	418	431	449	448	474	457	445	451	436	461	418	
60	489	578	537	534	553	541	530	518	513	544	492	
75	563	610	622	620	633	626	620	603	593	625	569	
90	634	692	698	702	703	702	696	680	664	702	639	
105	698	760	760	768	757	770	763	746	737	766	702	
120	749	817	821	826	819	823	808	800	793	813	756	
135	793	865	863	868	855	868	857	845	835	854	801	
150	829	897	904	908	891	903	892	885	877	891	837	
165	862	919	926	939	920	—	919	915	913	921	872	
180	886	935	—	958	—	—	938	937	939	942	895	

 1: Size in cm, 2: Density kg/m³, 3: Temperature K.

Table 4. Calculation of thermal diffusivity. Pellet size 0.6291 cm, fired at 1303 K, $T_o = 293$ K.

Time	T_s (K)	T_c (K)	$T_s - T_c$	$T_s - T_o$	$0.9(T_s - T_c)$	Radial distance	dT/dr	dT_{av}/dt	α (m ² /s)
15	358.5	306	52.5	65.5	47.25	0.1889362	250.08442	2.1667	1.998×10^{-7}
30	442	366.5	105.5	149	94.95	0.2848327	333.35357	4.4015	3.046×10^{-7}
45	573	399	174	280	156.60	0.3552634	440.79969	5.7406	3.004×10^{-7}
60	665	465	200	372	180.00	0.4103466	438.65356	5.8242	3.063×10^{-7}
75	745	540.5	204.5	452	184.05	0.4506661	403.03410	5.5318	3.166×10^{-7}
90	805	610	195	512	175.50	0.4900077	358.15763	4.7697	3.072×10^{-7}
105	851	677	174	558	156.60	0.5786412	301.94284	3.7425	2.859×10^{-7}
120	881	726	155	588	139.50	0.5371069	259.72483	3.1176	2.769×10^{-7}
135	910.5	783	127.5	617.5	119.75	0.5579178	205.67545	2.7725	3.110×10^{-7}
150	930	830	100	637	90.00	0.5754939	156.38740	2.0873	3.079×10^{-7}
165	946	870	76	653	68.40	0.5901223	115.90817	1.5467	3.079×10^{-7}

 (Average: 3.025×10^{-7}).

during firing and reduction. They observed the formation of fayalite bridge between iron ore particles which melts and covers the iron oxide. In the present case no fayalite was observed in X-ray analysis of fired ore. Wynnyckyj and Fahidy¹⁸⁾ reported that trivalent iron oxide does not form iron silicate under oxidising conditions, which is in confirmation with our observation. Yank and Standish¹⁹⁾ opined that iron ore sintering is basically a liquid phase sintering process due to the formation of low melting ferrites in presence of basic oxides as CaO. Nasr²⁰⁾ and co-workers also reports the formation of calcium ferrites with their studies on Beharia iron ore pellets. X-ray analysis (Figs. 1(b) and 1(c)) does not indicate the presence of ferrites either, in the present case, probably due to low CaO/SiO₂ ratio. The β -CaO·SiO₂ formed in induration of pellets is fairly high melting silicate and formation of liquid phase is not possible under prevailing conditions. In view of above, the present case is a solid state sintering process accompanying mineralogical changes.

The weight loss of the iron ore powder on heating is indicated in Fig. 10. The total weight loss is around 4.2% and mainly occurs below 1173 K (900°C). The decomposition of goethite is expected to be completed around 773 K (500°C) or so⁸⁾ and hence the continued weight loss upto 1173 K (900°C) may be attributed to decomposition of other gangue minerals associated with

Fig. 10. Weight loss of iron oxide on firing.

the ore.

The decomposition of goethite and other gangue minerals, formation of β -CaSiO₃ and probably the sintering of intraparticle pores, especially at higher temperature change the density of the powder. These

Table 5. Variation of thermal diffusivity/conductivity with density/porosity.

Weight of pellet (g)	Size (cm)	Volume (cm ³)	Density (m ³ /kg)	Porosity (%)	α (m ² /s)	K (W/m·s)	Theoretical diameter zero poro.	Ratio of specific volume	Treatment
3.9043	0.6921	1.3886572	2812	35.36	3.062×10^{-7}	0.9015	0.5983956	1.5471820	Fired at 1 233 K (950°C)
3.9043	0.6921	1.3886572	2812	35.36	3.025×10^{-7}	0.8903	0.5983956	1.5471820	Fired at 1 303 K (1 030°C)
5.4500	0.7863	2.0363543	2654	38.48	2.9875×10^{-7}	0.8301	0.6687640	1.6253472	Fired at 1 303 K (1 030°C)
3.9043	0.6839	1.3398812	2914	35.24	3.016×10^{-7}	0.9202	0.5916715	1.5443144	Fired at 1 393 K (1 120°C)
2.9585	0.61535	0.9760119	3031	32.64	3.25×10^{-7}	1.0337	0.5394154	1.4845563	Fired at 1 473 K (1 200°C)
3.2939	0.6360	1.0776056	3057	32.07	2.94×10^{-7}	0.9409	0.5590745	1.4721846	Fired at 1 473 K (1 200°C)
3.2939	0.6294	1.0444036	3154	33.46	2.809×10^{-7}	0.9279	0.5494747	1.5029232	Fired at 1 488 K (1 215°C)
2.9585	0.5854	0.8403236	3521	25.72	2.876×10^{-7}	1.0602	0.5301532	1.3963375	Fired at 1 523 K (1 250°C)
3.5496	0.6283	1.0389380	3416	27.93	2.9517×10^{-7}	1.0557	0.5633402	1.3873592	Fired at 1 523 K (1 250°C)
3.5496	0.6146	0.9724476	3650	24.27	3.025×10^{-7}	1.1560	0.5602061	1.3204875	Fired at 1 548 K (1 275°C)
3.2939	0.6294	1.0444036	3154	33.46	2.7425×10^{-7}	0.9056	0.5494747	1.5029232	Fired at 1 488 K (1 215°C)
2.9505	0.61535	0.9760119	3031	32.64	3.045×10^{-7}	0.9668	0.5394154	1.4045563	Fired at 1 473 K (1 200°C)

Table 6. Variation of thermal diffusivity/conductivity with density/porosity (Pure iron oxide).

Weight of pellet (g)	Size (cm)	Volume (cm ³)	Density (m ³ /kg)	Porosity (%)	α (m ² /s)	K (W/m·s)	Theoretical diameter zero poro.	Ratio of specific volume	Treatment
2.6393	0.5756	0.7988234	3304	30.44	2.756×10^{-7}	0.9534	0.5099983	1.43766	Fired at 1 523 K (1 250°C)
2.6393	0.5756	0.7988234	3304	30.44	2.782×10^{-7}	0.9624	0.5099983	1.43766	Fired at 1 523 K (1 250°C)
3.7530	0.6690	1.2542004	2923	38.46	2.50×10^{-7}	0.7651	0.5734982	1.58739	Fired at 1 473 K (1 200°C)
3.7530	0.6490	1.1450451	3278	30.99	2.649×10^{-7}	0.9074	0.5734982	1.44923	Fired at 1 498 K (1 225°C)
2.6393	0.5672	0.7643585	3453	27.31	2.704×10^{-7}	0.9776	0.5099983	1.37563	Fired at 1 598 K (1 275°C)

True density of Iron Oxide Powder 4 750 kg/m³.

density values were taken as true densities to calculate porosity of pellet after firing at appropriate temperatures. The measured density values are

Temperature	Density (kg/m ³)
1 223–1 303 K	4 350
1 393–1 473 K	4 500
1 388–1 523 K	4 740
1 448 K	4 820

Table 6 indicates the values of thermal diffusivities with pellet density, porosity, and corresponding thermal conductivities alongwith the thermal treatment given. The thermal conductivities are calculated by taking²¹⁾ the true heat capacity value of iron oxide at 973 K (700°C) as 1.047 kJ/kg K.²¹⁾

3.2. Model Fitting

A simple expression for effective thermal conductivity of iron ore pellet to its porosity is useful in solving the heat transfer problems. Many expressions used for iron ore agglomerates are listed by Akiyama⁸⁾ and co-workers. They explained their results by applying unit cell model originally proposed by Luikov. In the present investigation attempts were made to correlate the effective thermal conductivity ' K_e ' and porosity ' e ' by different model equations available. The radiative heat transfer within pore is neglected. The equations tried are

$$(a) \quad K_e = e \cdot K_g + (1 - e)K_s \quad \dots\dots\dots(11)$$

$$(b) \quad K_e = [e/K_g + (1 - e)/K_s]^{-1} \quad \dots\dots\dots(12)$$

$$(c) \quad K_e = K_s^{1-e} \cdot K_g^e \quad \dots\dots\dots(13)$$

$$(d) \quad K_e/K_s = (1 - 2e(P - 1)/(2P + 1))/(1 + e(P - 1)/(2P + 1)) \quad \dots\dots\dots(14)$$

$$(e) \quad K_e/K_s = (e^{2/3} + P(1 - e^{2/3}))/ (e^{2/3} - e + P(1 - e^{2/3} + e)) \quad \dots\dots\dots(15)$$

where, K_s : thermal conductivity of pellet with zero porosity,

K_g : thermal conductivity of gas in pore,

P : K_s/K_g .

Figure 11 indicates the experimental points of thermal conductivities with porosity of the pellets along with calculated values of effective thermal conductivity by Eqs. (14) and (15). The variation of ' K_e ' with porosity computed by Eq. (11) is too low and that by Eq. (13) is too sharp to explain present experimental values. However, it could be noticed from the figure that values computed by Eqs. (14) and (15) fits in satisfactorily for ' K_s ' values of 1.55 to 1.60 W·m⁻¹·s⁻¹ for Eqs. (14) and (15), respectively. The thermal conductivity of air for these calculations were taken²²⁾ as 0.06 W·m⁻¹·s⁻¹. Equation (14) is a better fit out of the two equations. It could also be observed that the present experimental values of effective thermal conductivities increases more sharply with the decrease in porosity than those predicted by these models. This aspect motivated us to analyse the results further by using basic sintering equation available in literature.

The process of sintering of fine powders were widely investigated in powder metallurgy. Various mechanisms were proposed and activation energies calculated.^{23,24)} The sintering behaviour of iron oxide in specific were

reported by Misra,²⁵⁾ Seshadri²⁶⁾ and Wynnycykj.¹⁸⁾ The representation of densification of pellet with parameters which approach '1' on sintering to theoretical density were used to interpret sintering kinetics. Use of volume ratios by Tikkanen²⁷⁾ to explain sintering of metal powders and by Wynnycykj¹⁸⁾ for iron ore pellets are reported in literature. Wynnycykj¹⁸⁾ even co-related the crushing strength of pellet to volume shrinkage ratio and to percent theoretical density of pellet. With the same logic, an attempt has been made in present investigation to correlate the thermal conductivity to ratio of volume of pellet to its volume at zero porosity. The results for

iron ore pellets and pure iron oxide pellets are indicated in Fig. 12. The extrapolation of the plot to ratio of '1' will lead to the value of ' K_s '. The log/log plot for same results is indicated in Fig. 13 and the intercept values are calculated by least square method for better accuracy. The values of ' K_s ' thus found for iron ore is $1.81 \text{ W} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$ at 973 K and $1.90 \text{ W} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$ for pure iron oxide pellets. Limited number of points, in case of pure oxide is due to less quantity of synthesised material available. The pellets were hand rolled in this case.

4. Conclusion

- (1) The iron ore from Rajhara mine of India contains goethite alongwith hematite. On firing goethite decompose and on reaction $\beta\text{-CaOSiO}_2$ is formed.
- (2) The decomposition of goethite and other gangue minerals along with formation of CaOSiO_2 changes the

Fig. 11. Variation of thermal conductivity with porosity and model fitting.

Fig. 12. Variation of thermal conductivity with volume ratio.

Fig. 13. Log-log plot between thermal conductivity and volume ratio.

density of powder.

(3) The thermal diffusivity and effective thermal conductivity of iron oxide pellets for radial heat flow can be determined by calculating average heating rate and applying heat balance. The result are comparable to those given in literature.

(4) The decrease in effective thermal conductivity with increase in porosity could be explained satisfactorily by model Eqs. (14) and (15) in the text.

(5) The effective thermal conductivity at zero porosity of the pellet could be determined more accurately by using basic shrinkage parameters and densification.

(6) The value of effective thermal conductivity at zero porosity iron ore pellet is $1.81 \text{ W} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$ and for pure iron oxide pellet is around $1.9 \text{ W} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$.

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