Note

Thermal Conductivity and Diffusivity of Iron Ore Pellet Having Low Porosity

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1. Introduction

The porosity of a pellet is an important property to ascertain its quality.¹⁾ It affects the compressive strength, thermal conductivity and also plays an important role in controlling its swelling during its reduction.²⁾ Akiyama *et al.*^{3,4)} measured the thermal conductivity of iron ore by laser flash method and co-related it to porosity. Kasai and Murayama⁵⁾ reported an increase in thermal conductivity with decrease in porosity for coke pellets. Watts and co-workers^{6,7)} measured the thermal diffusivity of fired and dried hematite pellets for radial heating by measuring the temperature at centre and half-radial distance of a heating pellet and applied transient state conduction equation to get thermal diffusivity. In our laboratory, experiments were conducted to measure thermal conductivity and diffusivity of iron ore pellets with porosity ranging from 24 to 38% by recording centre and surface temperatures of a heating pellet and applying principle of heat balance.⁸⁾ Nishioka⁹⁾ reports that, not only porosity but pore size and their distribution also have an effect on thermal conductivity. He reports two coke samples of same porosity, but with different average pore size, have thermal conductivities with considerable difference, which was indicated by penetration of heat zone. It was explained that pellet with lower average pore size has more solid/pore interface area for same porosity which adds resistance to heat transfer. This effect of solid/pore interface area will be more predominant in small pore size ranges, where increase in specific surface area of pore is more for a similar decrease in pore sizes.

In view of above, an attempt has been made in the present work to prepare pellets with low porosity of around 14 to 23% and measure the effective thermal conductivity for radial heat flow. The results are compared with thermal conductivity of high porosity pellets prepared by same technique and with our earlier results of pelletized pellets.

2. Experimental

2.1. Materials

The iron ore procured from Dalli/Rajhara area of India was crushed and ground to fine size (56% finer to 76 μm). The chemical analysis is indicated in **Table 1**. X-ray analysis of the ore was carried out by scanning it between 5–80° with scan speed of 3–5°/min using Cu-K α radiation.

2.2. Pellet Preparation

It was difficult to prepare pellets with porosity below 20–22% by conventional method. Thus following method was used.

1. Pressure compaction (560–5 600 kg/cm²) of ore powder

to cylinders.

2. Slow heating to 1 173 K and cool.

3. Carving the pellet to spherical shape and drilling a radial hole of 1 mm diameter upto centre.

4. Refiring of pellet between 1 223 to 1 473 K.

A similar technique was used by Sharma and Gupta²⁾ to prepare low porosity pellets in swelling index studies.

2.3. Thermal Diffusivity and Conductivity Studies

The method used is indicated in our earlier work^{8,10)} and was selected for its suitability to spherical geometry and radial heat transfer. The salient features are discussed here for convenience.

In the set-up, pellet is fixed between three chromel–alumel thermocouples with one penetrating the pellet through drilled hole with its bead at the centre. The other two thermocouples are fixed diagonally opposite to the pellet diameter with their beads touching the surface. Care were taken to insulate thermocouple wires and for best contact. Both the outer thermocouples were tied to a thin wall stainless steel tube at its surface and the centre thermocouple penetrated through the centre hole of the tube. This unit is then clamped.

A preheated (973 K) tube furnace is lowered on the pellet and the rise in surface and centre temperatures of the pellet were recorded. The tube furnace design is modified by using stainless steel reflectors above and below the pellet location. The use of reflectors decreases the convective air inspiration from bottom of the furnace and also provides configuration similar to an enclosed chamber and acts as an isothermal reservoir. The pellet was enveloped by keeping a metallic shield on the lower reflector to prevent direct radiation from furnace wall to thermocouple bead. This also decreases the lateral temperature gradient and allows more accurate surface temperature measurements. The surface and centre temperatures of pellet were measured by using strip chart recorder with chart speed of 10cm/min. The pellet configuration and detailed method is given in earlier text.⁸⁾

To evaluate parameter '*n*', discussed later, few experiments were conducted with pellet of pure iron oxide synthesised by precipitation of Fe(OH)₃ from analytical grade FeCl₃ solution with ammonia. The precipitate was washed, dried and fired to get Fe₂O₃. In this case of pure oxide pellet, first the hole was drilled up to half radius and rise of '*T_s*' and '*T_r*' with time was recorded. Subsequently, for same pellet, the hole up to half radius was extended to centre and rise of '*T_s*' and '*T_c*' with heating time was recorded. Two runs were taken to check reproducibility in each case. Pure iron oxide was preferred to ore for the evaluation of parameter '*n*'.

3. Results and Discussion

3.1. Calculation of Average Temperature

The X-ray and thermal analysis of the ore indicates that hematite, goethite, iron oxalate hydrate along with kaolinite and eudialite are its main constituents.⁸⁾ **Figure 1** indicates the rise in surface and centre temperature of a iron oxide pellet with time. Two runs were carried to check reproducibility. Similar type of plots for '*T_s*' and '*T_c*' with time were obtained with pressed iron ore pellets. Attempts were made to correlate the surface temperature (*T_s*) and centre temperature (*T_c*) with time (*t*). Out of the expressions attempted, the expression of the type:

$$(T_s - T_c)/(T_s - T_0) = e^{-kt} \dots\dots\dots (1)$$

Table 1. Chemical analysis of iron ore.

CONSTITUENT	MASS (%)
Fe	63.00
SiO ₂	3.30
CaO	1.00
Al ₂ O ₃	2.02
Loss On Ignition	4.00
	100.00

Table 2. Calculation of thermal diffusivity. (Pellet size $R=0.7122$ cm, porosity: 21.24%)

Time (S)	T _s (K)	T _c (K)	T _s -T _c (K)	0.9(T _s -T _c) (K)	Distance from surface for 0.9(T _s -T _c) drop (Cm)	T _{av} (K)	$\frac{dT}{dr}$ (K/Cm)	$\frac{dT_{av}}{dt}$ (K/S)	$\alpha \times 10^{-7}$ (m ² /s)
15	367	313	54	48.6	0.21627	321.1	224.72	-	
30	485	360	125	112.5	0.32827	389.0	342.71	4.75	3.29
45	583	415	168	151.2	0.38855	463.6	389.14	5.58	3.40
60	672	490	182	163.8	0.45182	556.3	362.53	5.39	3.53
75	736	549	187	168.3	0.48267	625.4	348.69	4.78	3.25
90	790	620	170	153.0	0.51970	699.8	294.40	4.22	3.40
105	830	672	158	142.2	0.53966	752.1	263.50	3.25	2.93
120	856	724	132	118.8	0.56297	797.2	211.02	2.87	3.23
135	882	774	108	97.2	0.58202	838.3	167.00	2.44	3.47
150	905	814	91	81.9	0.59481	870.3	137.69	1.87	3.22
165	921	846	75	67.5	0.60575	894.4	111.43	1.55	3.30
180	938	875	63	56.7	0.61413	916.7	92.33	1.30	3.34
195	952	896	56	50.4	0.61921	933.5	81.39	-	AV.3.305

Fig. 1. Variation of surface, half radial and centre temperature of pellet with time.

Fig. 2. Validity of model equation and evaluation of parameter 'n'.

Fig. 3. Temperature profile and movement of heat front. (Pellet size: $R=0.5759$ cm, porosity: 14.29%)

Fig. 4. Variation of thermal conductivity/diffusivity of pellet with porosity.

was found to be best. ' T_0 ' is the initial temperature of the pellet and ' k ' is the parameter. Similar equations were used by Watt *et al.*^{6,7)} to represent the temperature distribution within heating pellet and by Ray¹¹⁾ in their work. A similar type of expression correlating temperature (T_r) of a volume element at a radial distance ' r ' within pellet of radius ' R ' can be written as

$$(T_s - T_r) / (T_s - T_0) = e^{-k't} \quad (2)$$

Where (k') is another parameter. The correlation between parameter (k) and (k') is taken as

$$k' = k(R/(R-r))^n \quad (3)$$

The validity of above equations was checked and value of ' n ' was evaluated experimentally by using Eqs. (1) and (2).

Figure 1 represents the variation of temperatures with time and Fig. 2 indicate the plot between logarithm of dimensionless temperature indicated in Eqs. (1) and (2) with time. The linearity of the plot confirms the validity of the equation and the ratio between the slopes of these lines (k'/k) gives the value of parameter ' n ' as 0.3. Thus the Eq. (2) could be re-written as:

$$T_r = T_s - (T_s - T_0) \cdot e^{-k(R/(R-r))^{0.3}t} \quad (4)$$

Ray¹¹⁾ reports that the parameter ' k ' is not a constant but may vary with process conditions. In view of this, the temperature ' T_r ' was calculated using instantaneous ' k ' values at any time. The temperature of elements of 1 mm thickness and at radial distance ' r ' equal to ($R-0.05$), ($R-0.15$), ($R-0.25$), were calculated for different time intervals. The

results for one set of experiments with pellet size 0.5759 cm with porosity 14.29% are indicated in Fig. 3.

The average temperature (T_{av}) of pellet, at an instant, is calculated by using an expression¹²⁾

$$T_{av} = \frac{\int_0^R 4\pi r^2 \cdot T_r \cdot dr}{\int_0^R 4\pi r^2 \cdot dr} \dots\dots\dots(5)$$

taking the calculated value of ' T_r ' by Eq (4).

3.2. Calculation of Thermal Diffusivity/Conductivity by Heat Balance

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

Thus:

$$K \cdot A \cdot dT/dr = V \cdot \rho \cdot C \cdot d(T_{av})/dt \dots\dots\dots(6)$$

K - Thermal conductivity ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), V - Volume (m^3), ρ - Density (kg/m^3), C - Heat capacity ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$) and A - Surface area of pellet (m^2).

Rearranging:

$$\frac{dT_{av}}{dt} = \frac{K \cdot A}{(V \cdot \rho \cdot C)} \frac{dT}{dr} \dots\dots\dots(7)$$

$$= \frac{3 \cdot \alpha}{R} \frac{dT}{dr} \dots\dots\dots(8)$$

Table 2 indicates the experimental values of ' T_s ', ' T_c ' and average temperature (T_{av}) with increasing time for 0.7122 cm pellet with porosity 21.24% along with calculations for thermal diffusivity. The (dT_{av}/dt) could easily be evaluated by slope at any instant. Evaluation of (dT/dr) is difficult and requires certain assumption. Figure 3 indicates 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 the present study 90% of temperature fall from ' T_s ' to ' T_c ' is assumed as major change and the depth at which it occurs is calculated by Eq. (4) to evaluate dT/dr and hence ' α '. The thermal conductivity was in turn calculated by taking the heat capacity¹³⁾ as 1.047 kJ/(kg · K).

True density of ore powder increases on heating due to decomposition and other physicochemical changes. The porosity of the pellets was calculated taking corresponding true density for a firing temperature. The variation of thermal conductivity and diffusivity of pellet with porosity is plotted in Fig. 4 respectively. The results indicate that the effective thermal conductivity of the pellet increases with decreasing porosity in the range of 34 to 20%. Earlier workers^{3,5,8)} also report the increase in thermal conductivity with decreasing porosity. Figures 4 and 5 indicate that, both diffusivity and conductivity has a maximum value at around 20–22% porosity and then decreases.

The porosity of a pellet controls thermal conductivity by two aspects:

1. Decrease in porosity increases solid/solid contact area increasing solid state conduction.
2. At same porosity level, decrease in average pore size increases the pore/solid surface area, increasing resistance to heat conduction.

The net change in thermal conductivity with porosity will depend on contribution by above two factors. At high

porosity level and with larger pores, decrease in porosity or pore volume will increase particle to particle contact area and decrease the pore/solid interfacial area. However, after certain pore volume/size the increase in contact area is likely to be less predominant than change in particle pore surface area. The decrease in pore size, at constant porosity, will increase pore/particle interface area with almost no change in contact area. This adds resistance to heat flow decreasing thermal conductivity.

The other reason that could decrease the thermal conductivity is lesser pore radiation due to decrease in their average size. The pore radiation is proportional to its size.⁹⁾ Kasai⁵⁾ calculated the contribution of pore radiation towards effective thermal conductivity for coke pellets and found it to be negligible. In view of this, the contribution towards effective thermal conductivity by factors other than conduction is calculated using Kunni's equation and taking following parameters.

1. Zero porosity conductivity⁸⁾ = $1.8 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
2. Conductivity of air¹⁴⁾ = $0.068 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
3. Emissivity of pellet¹⁰⁾ = 0.76
4. Temperature = 973 K.

It was observed that in porosity range of 5 to 30% and pore size range of 10 to 50 μm , the values calculated are very small to justify the change indicated in Fig. 4, thus eliminating any such possibilities.

4. Conclusions

- (1) Effective thermal conductivity and diffusivity of the pellet decreases gradually with increase in porosity above 20–22% porosity.
- (2) The thermal conductivity/diffusivity attains a maximum value around 20–22% porosity. Further decrease in porosity decreases thermal conductivity/diffusivity considerably (40%).
- (3) The 20 to 22% porosity seems to be the value at which the pores tend to close and isolate causing decrease in their average size.
- (4) Contribution of pore radiation is very less to justify the observed change.
- (5) The decrease in thermal conductivity and diffusivity must hence be attributed to the increase in specific surface area of pores and added resistance to heat conduction.

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