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Short communication

The measurement of porosity for an individual taconite pellet

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ABSTRACT

The knowledge of the variability in the properties of individual taconite pellets as a function of processing conditions may lead to the improvement of the production of iron. An important property is porosity. Pellets with high porosity are desirable for the reduction to iron in the blast furnace. There is a published work describing the measurement of porosity on collections of pellets. Here I describe a method for the determination of the porosity of an individual pellet.

Recent determinations of porosity have used the measurements of the skeletal volume and the envelope volume. Helium pycnometry is the method of choice for the measurement of the skeletal volume, whereas volumetric displacement of dry material is now the preferred method for the envelope volume, requiring collections of pellets. I have adapted a method of silhouettes, developed for single items of fruit, to measure the envelope volume of a single pellet. The porosities of six individual sintered pellets from a facility in North-Eastern Minnesota, USA, range from 33 to 38% with a relative uncertainty of about 1%. Certain pellets have significantly different porosities from each other. The magnitudes are comparable to published porosities on green pellets, ranging from 30 to 36%, and to fired pellets, ranging from 28–38%.

1. Introduction

The increasing demands for iron by the rapidly developing economies of countries such as India and China are stimulating renewed technical and scientific interest into the extraction and beneficiation of iron ore. Additional impetus originates from the concurrent increase in the demand for energy. Small beneficial changes in large-scale commercial processes can lead to significant savings and smaller impacts on the environment. The processing of taconite [1] on the Iron Range of North-Eastern Minnesota in the USA leads, for the most part, to pellets that travel by ship from ports on the western end of Lake Superior to blast furnaces to the east on other Great Lakes. The important properties of the pellets include strength and porosity. The latter is important for the reduction of iron oxide in the blast furnace to be rapid; it is a measure of the open space, or pore volume, within the pellet that is accessible to the reducing gases. The reduction is a heterogeneous reaction that requires first the adsorption of the reducing gas, typically carbon monoxide, on the solid surface of the iron oxide. The larger the pellet's porosity the more surface area there is for the initial adsorption step.

Many have recognized the importance of the measurement of porosity for pellets. Schultz et al. [2] studied the pore and silicate structure of pellets under simulated blast-furnace conditions; they used mercury porosimetry. Janowski et al. [3] also used this method and stereological methods to measure the porosity of reduced hematite. A preferred route to the porosity is to measure the envelope and skeletal volumes because it avoids the use of mercury; this is the approach here. Helium pycnometry is the method of choice for the measurement of the skeletal volume; this is a well-established measurement, there being a number of commercial instruments available [4,5]. The development of a method for the measurement of envelope volumes using the displacement of a dry medium [6] has led to a commercial instrument [7]; this requires a collection of pellets. Forsmo et al. [8] developed procedures for the measurement of the porosity of green pellets using this instrument. They have been able to use these for their studies with green pellets of binding [9], and of oxidation and sintering mechanisms [10].

Potential advantages of measuring porosities on single pellets are the future study of relationships between porosity and other single-pellet properties and the effect of processing conditions on such relationships. Related to this is the shrinkage study of composite pellets during reduction in which Halder and Fruehan [11] essentially estimated the envelope volume of a single pellet by measuring its diameter across diametrically opposite points. Here, I investigate another method for the measurement of the envelope volume of a single pellet, which should take better account of a pellet's irregular shape. I have adapted this from a published method, a method of silhouettes, for single items of fruit [12]. Recently, Turchiuli and Castillo-Castaneda used silhouettes to study the size and structure of dehydrated milk agglomerates [13].

For a single irregular-shaped particle, an optical system records silhouettes at regular angular intervals. Image analysis gives the

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coordinates of the object's perimeter which allows for the calculation of its volume. Here I present data for six sintered taconite pellets. This is a preliminary study designed to judge the efficacy of the method and to see whether there may be advantage in developing the method into a form that is more convenient for routine use.

2. Theory and calculations

2.1. Definition of terms

The terminology follows that given elsewhere [14]. Here the porosity of a single pellet or particle is the final quantity of interest. The porosity, strictly the single-particle porosity, is the ratio of the volume of the open pores in the particle, V_{OP}, to the total volume of the particle, V_E:

$$\varepsilon = V_{OP}/V_E. \quad (1)$$

The envelope volume is the more common term for the total volume of the particle; this is the volume that would be obtained by shrinking a film around the particle in order to contain it completely — see Fig. 1. The envelope volume comprises the open-pore volume and the skeletal volume, V_{SK}:

$$V_E = V_{OP} + V_{SK}. \quad (2)$$

The skeletal volume in turn comprises the volume of the solid material, V_S, and the volume of closed pores, V_{CP}, within the particle:

$$V_{SK} = V_S + V_{CP}. \quad (3)$$

Closed pores are inaccessible non-solid regions within the particle.

2.2. General calculations

For a single pellet the measurement of the skeletal and envelope volumes enables the open-pore volume to be calculated from Eq. (2):

$$V_{OP} = V_E - V_{SK}. \quad (4)$$

The application of Eq. (1) gives the porosity:

$$\varepsilon = (V_E - V_{SK})/V_E = 1 - V_{SK}/V_E. \quad (5)$$

A standard result gives the uncertainty in the porosity [15]:

$$\begin{aligned}\delta\varepsilon &= \left\{(\partial\varepsilon/\partial V_{SK})^2\cdot(\delta V_{SK})^2 + (\partial\varepsilon/\partial V_E)^2\cdot(\delta V_E)^2\right\}^{1/2} \\ &= (V_{SK}/V_E)\cdot\left\{(\delta V_{SK}/V_{SK})^2 + (\delta V_E/V_E)^2\right\}^{1/2}.\end{aligned} \quad (6)$$

It is possible to make many measurements of the skeletal volume, so the Standard Error of the Mean, SEM, is an appropriate measure of its uncertainty, δV_{SK}. In this exploratory work the measurement of the envelope volume was time consuming; the repetition of the measurement for one pellet, Pellet 03, gave a SEM and I chose this to represent the measure of the uncertainty in the envelope volume, δV_E, for Pellet 03 and I chose its relative uncertainty, $\delta V_E / V_E$, to represent the relative uncertainty for each pellet in Eq. (6).

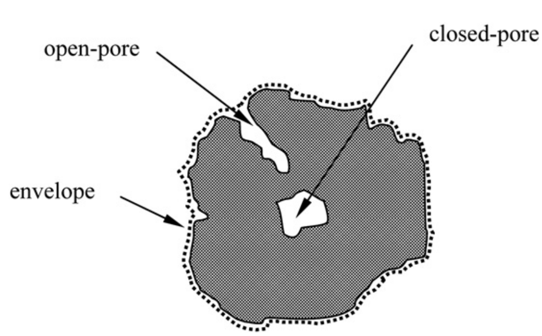

Fig. 1. Schematic diagram of a pellet showing the three types of volume.

The difference in porosities for pellets i and j, enables the comparison of pellets:

$$\Delta\varepsilon_{ij} = |\varepsilon_i - \varepsilon_j|. \quad (7)$$

The corresponding uncertainty in the difference is:

$$\delta\Delta\varepsilon_{ij} = \left\{(\delta\varepsilon_i)^2 + \left(\delta\varepsilon_j\right)^2\right\}^{1/2}. \quad (8)$$

The comparison of the uncertainty in the difference and the difference itself enables conclusions to be drawn regarding the distinction between pellets [15]. The examination of the ratio $\Delta\varepsilon_{ij}/\delta\Delta\varepsilon_{ij}$ is a convenient way to do this; if it is greater than unity then the pellets i and j have different porosities.

2.3. The envelope volume — basic theory

The volume of any object may be calculated [16] from

$$V = {}_a\int^b A(z)\mathrm{d}z \quad (9)$$

where $A(z)$ is the area of a horizontal slice of the object at a height z — see Fig. 2. The vertical extremities of the object are at $z=a$ and at $z=b$. The analysis proceeds by dividing the slice into a series of triangular wedges centered in the axis of rotation, which is parallel to the z-axis; the angle of the triangles' apices at the center of rotation is θ, defined by the regular interval at which silhouettes are recorded. The area of a single triangular wedge i is:

$$A_{\Delta,i} = \tfrac{1}{2}\cdot r_i\cdot r_{i+1}\cdot\sin\theta \quad (10)$$

where r_i and r_{i+1} are successive radii. The approximation for the area of the slice is:

$$A(z)\approx\textstyle\sum_i A_{\Delta,i} \quad (11)$$

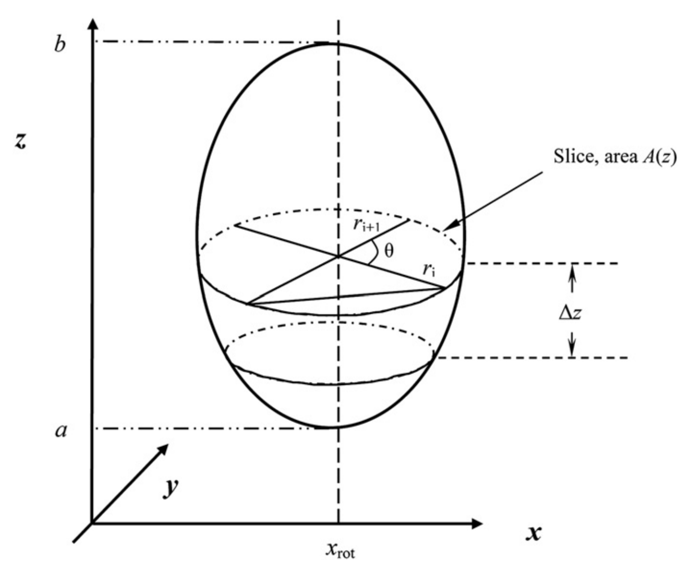

Fig. 2. Schematic view of horizontal slices through a solid.