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Prediction of the granule size distribution of iron ore sinter feeds that contain concentrate and micropellets

A.M. Nyembwe, R.D. Cromarty, A.M. Garbers-Craig *

Centre for Pyrometallurgy, Department of Materials Science and Metallurgical Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

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ABSTRACT

Depletion of high grade lump ore and increased blast furnace productivity with the use of prepared burden has resulted in increased use of iron ore sinter and pellets. There is considerable interest in including fine iron ore concentrate and micropellets into sinter mixes. These materials need to be accommodated in the sinter mix without adversely affecting the permeability of the sinter bed. Addition of fine concentrate and micropellets to a sinter mix will significantly affect the particle size distribution of the granules in the sinter feed. This paper describes the prediction of granule size distribution using the model developed by Litster. The effect of concentrate and micropellet addition on the model accuracy was evaluated by comparing the experimental and predicted Sauter mean diameters of the granules and evaluating the mean absolute percentage error (MAPE). It was confirmed that Litster's model can be applied to the tested sinter mixtures to predict the mean granule size, with a MAPE of less than 10%. The results of the model also provide a scope for comparing mean granule sizes, particle growth and the ratio of finer to nuclei particles as the amounts of concentrate and micropellets increase. The granule size decreased with addition of concentrate while the particle growth and ratio of finer to nuclei particles increased. For sinter mixtures that contain micropellets, the granule size, particle growth and ratio of finer to nuclei particles decreased with an increase in the mass fraction of micropellets.

1. Introduction

Granulation is the first stage in the agglomeration of iron ore for sinter production. Fine iron ores, fluxes, coke breeze and other fine materials (collected dusts, mill scale) are mixed together to form large and bigger agglomerates [1–4]. The primary objective of the granulation process is to produce granules with large mean size and narrow size distribution, which will result in an optimum sinter bed permeability [1–7].

The understanding of the granulation process has recently gained considerable attention in order to predict the properties of granules. In this regard, population balances were used to investigate averaged properties of the whole population rather than the behaviour of each individual particle [8–17]. For instance, the granule size distribution of granular materials was computed by solving the population balances [8–17]. Similarly, models have been developed to predict the size distribution of the agglomerates in the granulation of iron ore for sinter [10–17]. Due to the number of parameters involved and the complexity of the mechanisms, few successful models have been described in the open literature. The models are however scarce in the open literature due to the complexity of mechanisms involved during the process and the huge number of parameters [8–17].

Previous studies reported that the properties of the sinter feed determine the mechanism of granulation as well as the granule size distribution [8–17]. Furui et al. [8] and Vidal et al. [9] reported that the size distribution of the iron ore can be classified into nuclei (coarse particles), intermediate particles and adhering fines. During the granulation process, iron ore granules are formed by the adhering of fine particles on the surface of coarse particles. The intermediate sized particles can act as either nuclei or adhering particles, or may not take part in granulation [8–9]. Similar mechanisms were proposed by Litster et al. [10,11], Waters et al. [12] and Rankin et al. [13]. These authors defined a cut-off size where feed particles can act as nuclei or adhering fines, but they did not consider any particle size as intermediate [10–13]. Litster et al. [7,10,11] and Roller et al. [14] suggested that the size distribution of fines might promote the two-stage mechanism of the granulation process. Initially, finer material adheres onto nuclei particles and form a layer which embeds intermediate particles to form bigger granules. Vantaranama et al. [15] and Kapur et al. [16] reported that granulation occurs through a two-stage mechanism where the intermediates will take part in granulation as long as there is a sufficient amount of adhering fines present in the system. Fines first adhere onto intermediate and coarse particles and intermediate size granules then start to attach onto coarse granules to produce bigger granules. Litster et al. [17] also proposed a two-stage growth mechanism. During the first stage, some

* Corresponding author.
E-mail addresses: alainchmutombo@gmail.com (A.M. Nyembwe), robert.cromarty@up.ac.za (R.D. Cromarty), andrie.garbers-craig@up.ac.za (A.M. Garbers-Craig).

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intermediate particles change roles from nuclei to layering particles. The second stage is slow and can be enhanced by collisions before intermediate particles are incorporated into the adhering layer.

High grade lump ore resources are becoming depleted and the mining of lower grade deposits results in the production of a greater amount of fine concentrate. This fine material is added to sinter feed as received or as micropellets [6–9,17–23]. Their incorporation in the sinter feed affects the mechanism of granulation and the granule size distribution. Most studies on the granulation of iron ore for sinter production agree that granules predominantly form through a layering process. Fine particles have a higher affinity for layering than coarser primary particles, which results in a granule structure that consists of a layer of fine particles around the nuclei particles [6–9,17–23]. Nagano et al. [6] reported that the volume fraction of very fine particles (<0.125 mm) must be low in order to enhance the quality of the granules. Roller [14] stated that fines are necessary for the adhering of larger particles onto the granules already formed. Shatokha et al. [22] showed that concentrate addition causes an increase in microgranules that act as seeds or nuclei. This effect hinders the process of growth of granules. The adhering fines are not enough to adhere onto the nucleus particles, resulting in the production of granules of smaller size. This mechanism deviates from adhering of fines onto coarse particles towards a complex mechanism [22]. The addition of micropellets also causes a decrease in the volume fraction of fines that are expected to adhere onto the nuclei or onto the micropellet surface during the granulation process. In both cases, the number of seeds (coarse particles) onto which the adhering fines are layered, increases to the detriment of the volume fraction of adhering fines. This effect limits the growth of granules, resulting in a reduction of the mean granule size [22]. Similarly, Nyembwe et al. [23] reported that a partial replacement of iron ore fines by concentrate and micropellets results in a complex granulation mechanism. It was found that the incorporation of concentrate and micropellets in sinter feeds produce granules with smaller Sauter mean diameter [23].

Although available models for the granulation of iron ore for sinter production are limited, the model of Litster is widely used in laboratory-scale batch granulation. It describes a population balance based on the adherence of fines onto large particles [10,11]. This model was initially validated for predicting the granule size distribution in granulated mixtures for single sinter feeds. For a broader range of sinter feeds, its validity was verified by the work of Waters et al. [12] and Litster et al. [17]. Good agreement was reached between the predicted and experimental values of the Sauter mean diameter.

This paper presents the validation of Litster's model for iron sinter feeds containing concentrate and micropellets. The mass fractions of concentrate and micropellets were varied from 10% to 40% (with 10% increments). Model predictions were compared to the experimental size distribution and Sauter mean diameter of granules. Particle growth was also investigated to identify the influence of concentrate and micropellet addition on the granulation process.

2. Background to Litster's model

Population balance equations are crucial in the granulation process because they provide a framework for size distribution calculation [8–17]. The development of the population balance model depends on the mechanisms that occur in granulation processes [8–17]. In the case of iron ore granulation the development of the population balance is complex because of the ambiguous behaviour of intermediate particles [8–16]. The particle size distribution of sinter feed is wide and is categorized as nuclei (coarse particles), intermediate particles and adhering fines. The intermediate particles can act as nuclei, adhering or may not take part in the granulation process [8–17].

Litster et al. [10,11] developed a population balance model based on the layering of finer material onto nuclei particles. This model does not take in account the kinetic aspects of the process and predict the final granule size distribution by relating the masses of particles in the feed to the final mass of the granules. Litster et al. [10,11] primarily defined a partition coefficient that represents the probability for particles of a certain size fraction (x) to act as nuclei or seeds. In general, particles that exclusively act as nuclei have a partition coefficient of 1, while those with no probability of being used as nuclei have a partition coefficient of 0. Therefore particles with a partition coefficient of 0 only report to the adhering layer.

For any sinter mixture, Litster et al. (1986) described the partition coefficient as a lognormal distribution function:

$$\alpha(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\ln(x)} \exp\left[-\frac{(t-\ln(x_{0.5})^2}{2\sigma^2}\right] dt \tag{1}$$

where σ is a measure of the spread of size range of intermediate particles and $x_{0.5}$ is the particle size with a partition coefficient of 0.5.

From a mathematical point of view, the population balance equations can determine how changes to input conditions affect the size distribution of the product. In this work, the full description of Litster's model was not given but could be found elsewhere [10–13]. To develop the model, the following assumptions were considered:

(1) Granulation merely occurs by layering of fines onto the surface of larger nuclei particles and the extent of coalescence is minimal.
(2) For each size fraction i, the fraction of particles that act as nuclei can be represented by a partition coefficient.
(3) The effects of the particle shape, density, and chemical composition are assumed to be secondary.
(4) The adhering fine to nuclei ratio (R) is independent of the size of the nuclei particle.
(5) The absorption of moisture by particles is independent of particle size and size distribution.

Litster et al. [10,11] suggested that primary particles which act as nuclei will appear in granules of the same size fraction, or the next larger size fraction due to an increase in size and adherence of fines onto the nuclei particles. It was experimentally established that the partition coefficient or the proportion of particles of a given size i that act as nuclei can be expressed using Eq. (2).

$$\alpha_i = \frac{M_{ii} + M_{ii+1}}{\sum_{j=1}^{n} M_{ij}} \tag{2}$$

where M_{ij} is the mass of particles of size fraction i which are found in granules of size fraction j.

Waters et al. [13] extended the model of Lister to a multicomponent system that is used in real granulation processes. Based on a one-dimensional population balance equation, the granule size of each size fraction was related to the corresponding particle size of sinter feed and the thickness of adhering fines. For a given size fraction (i), the corresponding granule size can be expressed by:

$$x_{gi} = x_i + 2\ \Delta_i \tag{3}$$

where x_{gi}, x_i and Δ_i are the top size of granule size i, the top size of particle size fraction i, and the layer thickness respectively.

The thickness of the adhering layer is related to the mean size and mass ratio of adhering fines to nuclei particles:

$$2\Delta_i = \frac{R_i \bar{x}_i}{K} \varnothing_i \tag{4}$$

where R_i is the mass ratio of the adhering layer to nuclei for granules in size fraction i. x_i is the geometric mean size of the size fraction i. ϕ_i is a lumped parameter, depending on the density of each component in the feed. K is a parameter which relates layer thickness to the mass of