Minerals Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Vertical stirred mill scale-up and simulation: Model validation by industrial samplings results

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ARTICLE INFO

Article history:
Received 3 September 2016
Revised 25 November 2016
Accepted 30 November 2016
Available online xxxx

Keywords:
Vertical stirred mill
Vertimill™
Simulation
Population Balance Model
Iron ore

ABSTRACT

Minas-Rio is an Anglo American property, located in Brazil, which started its operation at the end of 2014. The Minas-Rio regrind circuit is currently the largest Vertimill™ installation in the world with sixteen Metso VTM-1500s installed in closed circuit with hydrocyclones. The grinding efficiency of this circuit was verified through a sampling campaign, and the results showed that the measured specific energy consumption was similar to the predicted specific energy consumption estimated at the engineering design stages of the project. Although essential for plant design, the specific energy consumption for a given product size is not sufficient to predict the performance of the circuit under different operating conditions. A more detailed model and simulations are required to predict performance under different operating conditions, so that the required product specifications can be achieved. A vertical stirred mill model, based on the Population Balance Model (PBM) technique, has recently been developed and validated using extensive data from pilot scale vertical stirred milling tests. This model is the subject of this investigation. Industrial scale data has been generated through a careful sampling campaign at the Minas-Rio plant, and used to further validate the model. PBM ore breakage parameters were obtained from the feed samples using simplified tests carried out in a laboratory scale conventional tubular ball mill and the results are discussed here.

1. Introduction

There are many references showing vertical stirred mills in successful applications in the mining industry. These mills typically operate 30–50% more efficiently than ball mills (Vanderbeek, 1998; Jankovic et al., 2006; Lichter and Davey, 2006; Junior et al., 2011; Rosa et al., 2014; Mazzinghy et al., 2015a,b; Merriam et al., 2015). Vertical stirred mills are typically loaded with smaller media, and part of this extra efficiency would be due to the increased specific surface of the smaller media and, consequently, an increase in the grinding action, especially for smaller particles (Mazzinghy et al., 2015a).

The vertical stirred mills have a screw agitator centrally located in the mill chamber, which promotes the grinding action by stirring the media and circulating it throughout the mill (Morrison et al., 2009). Stirred mills can be divided into two classes: those with low agitator speeds, that also use gravity to promote media movement and apply forces, and those with high agitator speeds, with the speed of the agitator used to effectively fluidize the media (Wills and Finch, 2016; Lichter and Davey, 2006). The subject of this paper is the Vertimill™, which falls into the former category.

2. Modeling

The population balance model concept was first applied for chemical engineering purposes by Hulburt and Katz (1964), and it is used to describe a wide range of particle processes, including agglomeration, flocculation, crystallization, polymerization, and comminution (Verkoeijen et al., 2002). The size-mass balance model that describes the batch grinding process through successive events of particle breakage is given in Eq. (1) (Austin et al., 1984).

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http://dx.doi.org/10.1016/j.mineng.2016.11.018
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Please cite this article in press as: Mazzinghy, D.B., et al. Vertical stirred mill scale-up and simulation: Model validation by industrial samplings results. Miner. Eng. (2016), http://dx.doi.org/10.1016/j.mineng.2016.11.018

$$\frac{dm_i(t)}{dt} = -S_i m_i(t) + \sum_{j=1}^{i-1} b_{ij} S_j m_j(t) \tag{1}$$

where $m_i(t)$ is the mass fraction of particles contained in size class i after grinding time t; b_{ij} represents the size distribution over size-classes i produced by a breakage event involving particles in size-class j; S_i represents the specific rate of breakage of particles in size class i.

2.1. Energy specific selection function

The selection function for each size class, S_i, maintains a proportionality relationship with the power consumed by the grinding action according to Eq. (2) (Herbst and Fuerstenau, 1973).

$$Si = S_i^E \left(\frac{P}{H}\right) \tag{2}$$

where S_i (min^{-1}) is the selection function for each size class, S_i^E (t/kW h) is the energy specific selection function, H (t) is mill hold-up and P (kW) is the net grinding power.

Parameters obtained from simple laboratory batch grinding tests can be used for simulating and scaling-up large industrial mills. The energy specific selection function S_i^E is independent of the dimensions of the mill and may also be modeled using Eq. (3) by Rajamani and Herbst (1984) or using Eq. (4) by Austin et al. (1984).

$$S_i^E = S1^E \exp\left\{\zeta_1 \ln\left(\frac{d_i}{d_1}\right) + \zeta_2 \left[\ln\left(\frac{d_i}{d_1}\right)\right]^2\right\} \tag{3}$$

$$S_i^E = S1^E \left(\frac{d_i}{d_1}\right)^{\alpha} \frac{1}{1 + \left(\frac{d_i}{\mu}\right)^{\Lambda}} \tag{4}$$

where (d_i/d_1) is the dimensionless particle size (usually normalized at 1 mm), the Rajamani and Herbst (1984) parameters are $S1^E$, ζ_1, ζ_2 and the Austin et al. (1984) parameters are $S1^E$, α, μ, Λ. These parameters are characteristic of the material and the grinding conditions.

2.2. Breakage function

The breakage function model can be described by Austin et al. (1984) as showed in Eq. (5) or by the truncated Rosin–Rammler breakage function model developed by King (2012) as showed in Eq. (6):

$$B_{i,j} = \phi \left(\frac{x_{i-1}}{x_j}\right)^{\gamma} + (1-\phi) \cdot \left(\frac{x_{i-1}}{x_j}\right)^{\beta} \tag{5}$$

$$B_{i,j} = 1 - (1 - t_{10})^{\left(\frac{9}{(x_j/x_i)-1}\right)^{\gamma}} \tag{6}$$

B_{ij} is the cumulative breakage function with φ, γ and β Austin's parameters and γ and t_{10} King's parameters. These parameters are characteristic of the ore.

2.3. Classification

The hydrocyclone classification can be described by three different models: Rosin-Rammler, Logistic and Exponential Sum, as show in the Eqs. (7)–(9) (King, 2012).

$$c(d_i) = \alpha + (1-\alpha)\left[1 - \exp\left(-0.693\left(\frac{d_i}{d_{50c}}\right)^{\lambda}\right)\right] \tag{7}$$

$$c(d_i) = \alpha + (1-\alpha)\left(\frac{1}{1 + \left(\frac{d_i}{d_{50c}}\right)^{-\lambda}}\right) \tag{8}$$

$$c(d_i) = \alpha + (1-\alpha)\left(\frac{\exp\left(\lambda \frac{d_i}{d_{50c}}\right) - 1}{\exp\left(\lambda \frac{d_i}{d_{50c}}\right) + \exp(\lambda) - 2}\right) \tag{9}$$

where $c(d_i)$ is the corrected classification function; α is the fraction of feed that short circuits directly to the coarse product; d_i is the particle representative size in size class i (mm); d_{50c} is the median size of the corrected partition function (particle size that has 50% chance of reporting either to the underflow or to the overflow); λ is a parameter that adjusts the sharpness of classification.

3. Model validation

The scale-up and simulation model used here is based on the population balance modeling technique using the Herbst & Fuerstenau scale-up procedure for ball mills, adapted for vertical stirred mills. The model was originally validated with extensive data from pilot scale vertical stirred mill tests (Mazzinghy et al., 2012, 2013, 2014, 2015a). This methodology includes standard batch grinding tests in tubular lab scale mills to obtain the breakage and selection function parameters.

Data from the Minas-Rio regrind circuit has been obtained through a comprehensive sampling campaign around the regrind circuit. The Minas-Rio regrinding circuit is currently the largest Vertimill™ installation in the world and consists of sixteen VTM-1500 mills, grinding in closed circuit with eight hydrocyclone batteries. The Minas-Rio project, an Anglo American property located in Brazil, started operations at the end of 2014. The design production is 24.5 MTPY of Pellet Feed, obtained by processing an itabirite iron ore.

Fig. 1 shows the Minas-Rio regrinding plant and Fig. 2 shows the layout of one of the two banks, containing eight VTM-1500 mills and four hydrocyclone batteries. The grinding efficiency of this plant was recently verified through a sampling campaign and the results showed that the measured specific energy consumption was similar to the predicted specific energy consumption estimated at the engineering design stages of the project (Mazzinghy et al., 2015b).

Table 1 shows the values used for the design, and the data obtained from the sampling campaign (Mazzinghy et al., 2015b).

The specific energies (SE) shown in Table 1 are based on net power. Prony brake calibration data was used to determine the net power for the pilot vertical stirred mills (Metso, 2011). The no-load power draw of one of the VTM-1500 installed at Minas-Rio was measured during the unloading of the ball charge. The no-load power draw measured was equal to 130 kW, which is equivalent to 11.6% of the installed power (130 kW/1119 kW = 11.6%). The measurement of a no-load power in the absence of a torque transducer is traditionally challenging due to changes in motor efficiency at low power draws. A slightly more conservative value of 10% was therefore used as this is in line with vendor estimates based on drive train losses, and reasonably well supported by the measured values (Esteves et al., 2015; Mazzinghy et al., 2015b). Also, the no-load power shall depend on the screw wearing and more investigation is necessary to cover this specific topic.

Although essential for plant design, the specific energy consumption for a given product size, as described by a P_{80} and the Operating Working Index (OWI), is not sufficient to predict the performance of the circuit at different circulating loads, and at the various operating conditions that may be required in order to meet product specifications. These calculations can only be performed through simulation.

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