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Simulating product size distribution of an industrial scale VertiMill® using a time-based population balance model

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ABSTRACT

The paper describes a methodology to simulate product particle size distribution of an industrial scale VertiMill® engaged in regrinding duty. Using survey data, the time-based population balance model has been utilized to simulate mill product particle size distribution. A sub-model relating mill power to particle residence time is developed and applied to the population balance model to predict mill response in different operating conditions. The result showed that the new time-based population balance model applied to the VertiMill® is capable of predicting product particle size distribution with a change in mill power, feed size distribution, mill feed rate, and slurry solids concentration.

1. Introduction

Fine grinding is becoming an indispensable process for the mineral industry due to the increase in the volume of complex and fine-grained ores being mined, and consequently, fine grinding of the ore is required to prepare feed for floatation or leaching processes. The mining industry often needs to grind particles as fine as 7 µm to liberate valuable minerals locked in the gangue minerals (Glencore, 2015). Ball mills have been used previously for fine grinding applications but stirred mills require approximately 30–50% lower energy for coarser fine grinding or ultra-fine grinding (Palaniandy et al., 2015). Grinding particles below 75 µm with the ball mill causes energy costs to rise exponentially, and a P_{80} of 45–40 µm is considered to be the final practical limit of product size from the ball mill (Morrell et al., 1993) beyond which stirred mills are selected in current mineral processing circuit designs to produce fine particles in an energy efficient way (Valery and Jankovic, 2002). Stirred mills have practical advantages in large-scale mineral grinding applications as they are easy to operate, simple in construction, capable of high size reduction ratios and use less energy compared to ball mills in a similar duty (Gao and Frossberg, 1995). Metso VertiMill® and the Nippon Eirich Tower Mill are gravity induced stirred mills that operate at low tip speed (3 m/s) (compared with high-intensity stirred mill such as the IsaMill) and have been well received in various grinding duties i.e. secondary, tertiary and regrind duties in mineral processing circuits (Ntsele and Allen, 2012). These designs use a helical screw on a vertical shaft to stir a column of grinding media usually between 12 and 38 mm in size. Currently, more than 450 units of VertiMill® have been installed worldwide with an aggregated power of more than 300 MW (Allen, 2013).

With the increasing uptake of this fine grinding technology, there has become a greater demand for a practical process model for predicting particle size of the mill product, under different operating conditions for a given feed size distribution. An earlier JKMRC research project focused on fine grinding and flotation developed breakage and power models for Tower mills. Morrell et al. (1993) successfully used the population balance model to represent particle breakage in a Tower mill. Later Duffy (1994) worked on power, and media motion of the Tower mill and Jankovic (1999) worked on power, media motion, breakage and scale-up mechanism of the Tower mill to broaden the understanding of the gravity induced stirred mill operation.

Researchers have been using the population balance technique to model stirred mills for the last two decades, where the first attempt was recorded from Stehr et al. (1987) to compare the grinding performance of the ball mill and horizontal pin stirred mill. A recent inclusion in this list is the VertiMill® model developed by Mazzinghy et al. (2012, 2014), Mazzinghy and Russo, 2014, Mazzinghy et al. (2015a, 2015b), where breakage parameters were developed from a lab scale ball mill and used to predict product size distributions of a pilot scale VertiMill®. However, none of the available model structures can be used to optimize VertiMill® operation using a single set of industrial survey data as those models were concentrated mostly on laboratory or pilot scale mill. Hence, a process model (using residence time based population balance technique) has been developed by integrating individual sub-processes models such as breakage, selection and residence time functions. The model utilizes the VertiMill® power to calculate the particle residence time. The results had shown that the model could predict the mill product size distribution when mill power, feed rate, slurry solids

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concentration and feed size distribution varied. The developed model can successfully be applied to optimize an industrial scale VertiMill® operation using mill survey data.

2. Development of the model structure

The model structured followed the solution of the time-based population balance model proposed by Austin et al. (1984) which can be represented by the following equation:

$$\mathbf{p_i} = \sum_{\mathbf{j}=1}^{\mathbf{i}} \mathbf{d_{ij}}(\tau)\mathbf{f_i},\ n \geqslant \mathbf{i} \geqslant \mathbf{j} \geqslant 1 \tag{1}$$

where, p_i : product size of class i.
$d_{ij}(\tau)$: mill transfer function that indicates the fraction of feed size j transferred to size class i via repeated steps of the breakage process over time τ.
f_i : feed size of class i.

The solution for the transfer function $d_{ij}(\tau)$ function can be shown by following equation:

$$\mathrm{d_{ij}}(\tau) = T\left[\frac{1}{(\mathrm{S_i}\tau + 1)}\right]\mathrm{T}^{-1} \tag{2}$$

For the Eqs. (1) and (2), the below sub-equations are applied.

$$T(i,j) = 0\ \ i < j$$

$$T(i,j) = Sj\ \ i = j$$

$$T(i,j) = \frac{1}{S_i - S_j}\sum_{k=1}^{i-1} b_{ik}S_k T(k,j)\ \ i > j$$

$$T^{-1}(i,j) = 0\ \ i < j$$

$$T^{-1}(i,j) = S_j^{-1}\ \ i = j$$

$$T^{-1}(i,j) = \frac{-\sum_{k=1}^{i-} T(i,k)T^{-1}(k,j)}{S_i}\ \ i > j$$

where,

b_{ij} : Breakage function which denotes the size distribution or progeny of a particle after a single breakage event.
S_i : Selection function or specific rate of breakage in size class i (min^{-1}).
τ : Average residence time of the particles inside the mill (min).

Average residence time, τ for the population balance model is calculated by dividing available volume for the slurry by the volumetric slurry flow rate. Available volume for the slurry is calculated by calculating the grinding media volume and then multiplying by the charge porosity. The residence time is directly dependent on the materials flow rate to the mill.

$$\tau = \frac{\mathrm{v}}{\mathrm{V}} \tag{3}$$

where,

v : Volumetric flow rate of the slurry (m^3/hr).
V : Available volume for slurry flow in the grinding zone (m^3).

Available volume for slurry (V) in the grinding zone can be calculated as follows:

$$V = \left(\frac{\mathbf{m_g}}{\rho_\mathbf{g}}\right) * \left(\frac{\varepsilon}{1-\varepsilon}\right) \tag{4}$$

where,

m_g : Mass of grinding media (kg).
ρ_g : Density of the grinding media (kg/m^3).
ε : Grinding media porosity.

The average porosity value was considered to be 40% of all media sizes as suggested by Gupta and Yan (2006). It should be noted that grinding media porosity changes with grinding media sizes and mill operating conditions. However, due to simplicity in the calculation, the porosity value was kept constant to 40%.

Volumetric flow rate of the slurry can be calculated as follows:v = Volumetric flow rates of the solids + Volumetric flowrate of the water

$$v = \left(\frac{\mathrm{M}}{\mathrm{SG}}\right) + \left(\frac{\mathrm{M}*100}{\%\mathrm{Solids}\left(\frac{\mathrm{w}}{\mathrm{w}}\right)} - \mathrm{M}\right) \tag{5}$$

where,

M : Solids flow rate to the mill (t/hr).
SG : Specific gravity of the solids.

Also, the solids hold-up (H) or content in the mill can be calculated as follows:

$$H = \left(\frac{\mathrm{m_g}}{\rho_\mathrm{g}}\right) * \left(\frac{1}{1-\varepsilon}\right) * \varepsilon * SG * 1000 * \frac{\frac{\%\,\mathrm{Solids}\left(\frac{\mathrm{w}}{\mathrm{w}}\right)}{\mathrm{SG}} * 100}{\frac{\%\,\mathrm{Solids}\left(\frac{\mathrm{w}}{\mathrm{w}}\right)}{\mathrm{SG}} + \left(100 - \%\mathrm{Solids}\left(\frac{\mathrm{w}}{\mathrm{w}}\right)\right)} \tag{6}$$

The model initially takes its feed size distribution in the form of cumulative percent passing and calculates the mill contents at each size fraction from the mill feed rate data. Product size distribution for the given feed is calculated using Eqs. (1) and (2). The predicted product size is compared with actual mill product size data to estimate the selection and breakage function parameters.

2.1. Sub-model for the selection and breakage function

Empirical models proposed by Austin et al. (1984) were used to develop selection and breakage function in the population balance model. The selection function model is shown as below form:

$$\mathrm{S_i} = \mathrm{A}\left(\frac{\mathrm{x_i}}{1000}\right)^{\alpha} * \frac{1}{1 + \left(\frac{\mathrm{x_i}}{\mu}\right)^{\wedge}}\ ,\ \wedge \geqslant 0 \tag{7}$$

where, A, α, μ and Λ are model parameters. A has the unit of min^{-1}, α and Λ are dimensionless, x_i is the particle size in μm and μ is particle size expressed in μm at which dS_i/dx is zero. The selection function parameters in Equation (7) are related to operating data as follows:

A = f (mill conditions, e.g., media size, solid concentration, mill speed, mill filling).
α = f (ore hardness, mineralogy, specific gravity, etc.)
μ = f (mill media size and mill speed).

The breakage function in cumulative form ($B_{i,j}$) is shown as follows:

$$Bi,j = \phi_j\left(\frac{\mathbf{x_{i-1}}}{\mathbf{x_j}}\right)^{\gamma} + (1-\phi_j)\left(\frac{\mathbf{x_{i-1}}}{\mathbf{x_j}}\right)^{\beta},\ 0 \leqslant \phi_j \leqslant 1 \tag{8}$$

where, Φ, γ, and β are the materials characteristics. Mazzinghy et al. (2014) and Mazzinghy et al. (2012) used the Austin breakage function