Original Article

Vertimill™ pilot scale tests simulated by perfect mixing model

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ABSTRACT

Minas-Rio Project, Anglo American property, located in Brazil, considers Vertimill™ to make the particle size distribution adequate to feed slurry pipeline. A pilot test campaign was carried out at Metso’s pilot plant facility located in York city, Pennsylvania State, USA, to provide information to scale up the industrial grinding circuit. The perfect mixing model, normally used to simulate ball mills, was used to compare the direct and reverse circuit configurations. The simulations were based on the appearance function determined from the laboratory tests using a batch tube mill. The combined breakage rate/discharge rate function (v/d) was determined from Vertimill™ feed and product particle size distributions obtained from pilot tests. The residence time was estimated considering the mill hold-up and solids flow rate. The simulation results show that there are no significant differences between direct and reverse circuits for the sample tested.

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1. Introduction

The Vertimill™ is a vertical agitated media mill with a double-helical steel screw agitator located centrally in a vertical cylindrical shell. The screw agitator lifts the media and circulates it throughout the mill. The higher efficiency of the Vertimill™ is due to the higher frequency of lower energy impacts and, by the same token, smaller frequency of higher energy impacts when compared to conventional ball mills [1]. Fig. 1 shows the Vertimill™.

The Minas-Rio Project, located in Conceição do Mato Dentro city, Minas Gerais State, Brazil, predicts the biggest slurry pipeline in the world with 525 km of length. There are 16 Metso Vertimill™ (VTM-1500) to adequate the particle size distribution of the iron ore concentrate to feed the pipeline. Anglo American carries out a Vertimill™ pilot test campaign in Metso’s pilot plant facility located in York city, Pennsylvania State, USA, to determine the specific energy consumption to obtain a product with 88% < 44 μm. The samples were produced in Anglo American pilot plant facilities including crushing, grinding, desliming and flotation to obtain the
Fig. 1 – Vertimill™ (Metso courtesy).

final concentrate that was sent to Metso for Vertimill™ pilot tests.

The main objective of the work was to investigate the differences between direct and reverse circuit and verify if it is possible to perform simulations considering the perfect mixing model. The appearance function was determined from laboratory tests using a batch tube mill and the simulations were performed considering the combined breakage rate/discharge rate function \(r_i/d_i\) obtained from Vertimill™ feed and product particle size distributions obtained from pilot tests.

2. Modeling

2.1. Perfect mixing model

The perfect mixing model can be considered a special case of the population balance model [2–4]. This model has been used to optimize and scale up many different grinding circuits around the world. The model can be written as shown in Eq. (1).

\[
p_i = f_i - \left( \frac{r_i}{d_i} \right) p_i + \sum_{j=1}^{i} a_{ij} \left( \frac{r_i}{d_i} \right) p_j
\]

where:

- \(p_i\) mass flow rate of size fraction i in mill discharge (t/h);
- \(f_i\) mass flow rate of size fraction i in the mill feed (t/h);
- \(r_i\) breakage rate of size fraction i (h\(^{-1}\));
- \(d_i\) discharge rate of size fraction i (h\(^{-1}\));
- \(a_{ij}\) appearance function – mass fraction of the size j that appears at size i fraction after breakage.

The combined breakage rate/discharge rate function \(r_i/d_i\) can be back-calculated by non-linear regression methods using \(f_i\) and \(p_i\) values obtained from pilot or industrial scale circuits. The appearance function \(a_{ij}\) can be determined in laboratory or a standard appearance function can be used.

The function \(r_i/d_i\) could be changed by the mean residence time as shown in Eq. (2) [5].

\[
\left( \frac{r_i}{d_i} \right) = \tau \left( \frac{r_i}{d_i} \right)
\]

The function \(r_i/d_i\) will be independent of solids flow rate, solids concentration and mill volume and dependent on ball load, ball size, stirred speed and stirred design [6].

2.2. Residence time

The mean residence time can be estimated as a function of the volumetric feed rate and the mill hold up as shown in Eq. (3).

\[
\tau = \left( \frac{H}{MV} \right)
\]

where:

- \(\tau\) mean residence time (h);
- \(M\) solids flow rate (t/h);
- \(H\) solids hold up (t).

2.3. Hold up

The hold-up can be calculated considering the mass of the media charge as shown in Eq. (4).

\[
H = \left( \frac{m_b}{\rho_b} \right) \varepsilon \rho_v C_v
\]

where:

- \(H\) solids hold-up (t);
- \(m_b\) mass of balls (t);
- \(\rho_b\) balls density (t/m\(^3\));
- \(\varepsilon\) porosity (%);
- \(\rho_v\) solids density (t/m\(^3\));
- \(C_v\) solids concentration by volume (%).

2.4. Appearance function

The appearance function can be described by a standard function as shown in Table 1 or can be described by truncated
Rosin–Rammler breakage function model [7], defined in Eq. (5):

$$B_{ij} = 1 - (1 - t_{10})^{(r_j/(r_j)_{10})^{-1}}$$

$$B_{ij} \text{ cumulative breakage function; }$$

$$r_j, t_{10} \text{ model parameters characteristic of the ore. }$$

### 3. Experimental

#### 3.1. Vertimill™ pilot tests

Metso’s pilot plant facility located in Pennsylvania State, USA, is equipped with instruments to measure and register the data from the pilot test. The target of the continuous test was to determine the specific energy required to grind the material to eighty-eight percent (88%) passing 44 μm.

The tests were performed in closed circuit with a high frequency screen and in direct and reverse configuration. The screw speed of the Vertimill™ was 87 rpm. Samples from different flows of circuit were collected during the tests for solids concentration and particle size distribution analysis. Table 2 shows the cylpebs size distribution used in the Vertimill™ pilot test.

#### 3.2. Batch tube mill tests

The appearance function was determined using a conventional batch tube mill. Three tests were performed considering different time intervals in wet basis (70% solids concentration by weight). The tests are designed to reach the desired product size distribution specified as a $P_{80}$ value. The batch tests were carried out considering the same cylpebs size distribution using the Vertimill™ pilot test campaign. Table 3 shows the operational variables used in the batch tube mill tests.

### 4. Results and discussion

#### 4.1. Vertimill™ pilot tests results

Table 4 shows the results obtained during the Vertimill™ pilot tests.

The test with reverse configuration presented the target closest to the project target (88% < 44 μm).

#### 4.2. Hold-up and residence time calculations

Table 5 shows hold-up and residence time calculated by Vertimill™ pilot tests through Eqs. (3) and (4).

The residence time calculated for direct and reverse circuit configurations is very closed.

#### 4.3. Appearance function

The appearance function was determined by the interpolation of the particle size distribution curves of each milling test. Fig. 2 shows the particle size distributions curves and the response of the model (Eq. (5)).

Table 6 shows the appearance function determined from a batch tube mill considering $γ = 1.456$ and $t_{10} = 0.010$ as parameters.

Fig. 3 shows the appearance function obtained by Eq. (5).

---

### Table 2 – Media size distribution.

<table>
<thead>
<tr>
<th>Cylpebs (mm)</th>
<th>% Ret.</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.7</td>
<td>52.8</td>
<td>719</td>
</tr>
<tr>
<td>9.0</td>
<td>36.2</td>
<td>492</td>
</tr>
<tr>
<td>6.7</td>
<td>11.0</td>
<td>150</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>1361</td>
</tr>
</tbody>
</table>

### Table 3 – Batch tube mill test.

<table>
<thead>
<tr>
<th>Mill diameter (m)</th>
<th>0.203</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill length (m)</td>
<td>0.254</td>
</tr>
<tr>
<td>Ball charge level</td>
<td>40</td>
</tr>
<tr>
<td>Critical speed (%)</td>
<td>76</td>
</tr>
</tbody>
</table>

### Table 4 – Results from Vertimill™ pilot test campaigns.

<table>
<thead>
<tr>
<th>Circuit configuration</th>
<th>Direct</th>
<th>Reverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{30}$ (μm)</td>
<td>66.6</td>
<td>66.0</td>
</tr>
<tr>
<td>$P_{40}$ (μm)</td>
<td>36.5</td>
<td>38.5</td>
</tr>
<tr>
<td>% &lt;44 μm</td>
<td>90.7</td>
<td>88.5</td>
</tr>
<tr>
<td>Specific Energy (kWh/t)</td>
<td>6.32</td>
<td>5.31</td>
</tr>
</tbody>
</table>

### Table 5 – Residence time calculated by Vertimill™ pilot tests.

<table>
<thead>
<tr>
<th>Circuit configuration</th>
<th>Direct</th>
<th>Reverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media mass (kg)</td>
<td>1361</td>
<td>1361</td>
</tr>
<tr>
<td>Media dens. (t/m³)</td>
<td>7.80</td>
<td>7.80</td>
</tr>
<tr>
<td>Media porosity (%)</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Solids dens. (t/m³)</td>
<td>4.98</td>
<td>4.98</td>
</tr>
<tr>
<td>% Mass conc. (by weight)</td>
<td>57.6</td>
<td>63.1</td>
</tr>
<tr>
<td>Solids feed (t/h)</td>
<td>0.83</td>
<td>0.84</td>
</tr>
<tr>
<td>Media volume (m³)</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Slurry dens. (t/m³)</td>
<td>1.85</td>
<td>2.02</td>
</tr>
<tr>
<td>% Solids conc. (by volume)</td>
<td>21.4</td>
<td>25.6</td>
</tr>
<tr>
<td>Hold-up (t)</td>
<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td>Residence time (min)</td>
<td>5.4</td>
<td>6.3</td>
</tr>
</tbody>
</table>

---

Fig. 2 – Particle size distributions obtained from batch tube mill tests.
### Table 6 – Appearance function from batch tube mill tests.

<table>
<thead>
<tr>
<th>i</th>
<th>Size (µm)</th>
<th>Appearance function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>295</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>208</td>
<td>0.293</td>
</tr>
<tr>
<td>3</td>
<td>147</td>
<td>0.134</td>
</tr>
<tr>
<td>4</td>
<td>104</td>
<td>0.076</td>
</tr>
<tr>
<td>5</td>
<td>74</td>
<td>0.047</td>
</tr>
<tr>
<td>6</td>
<td>53</td>
<td>0.031</td>
</tr>
<tr>
<td>7</td>
<td>44</td>
<td>0.025</td>
</tr>
<tr>
<td>8</td>
<td>37</td>
<td>0.021</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>0.013</td>
</tr>
</tbody>
</table>

#### 4.4. Simulations

Data from mass balance of each test were used to perform simulations using the perfect mixing model. Fig. 4 shows the Vertimill™ feed and product size distributions measured in each of the pilot tests as well as the predicted product from perfect mixing model. The square symbols represent the experimental data and the solid line represents the model response.

The values of the combined breakage rate/discharge rate function \((r_i/d_i)\) were changed in the simulations to check the differences of direct and reverse circuit configurations. Fig. 5 shows the result of simulations considering the direct circuit with \((r_i/d_i)\) from reverse circuit and reverse circuit with \((r_i/d_i)\) from direct circuit.

The results of the simulations show that direct and reverse circuit configurations do not present considered differences.

#### 5. Conclusions

It was possible to predict the particle size distribution of the Vertimill™ product, with good accuracy, by simulations using the perfect mixing model. The results of the simulations show that direct and reverse circuit configurations do not present considered differences. The methodology used in this study can help the process engineers to understand the differences between direct and reverse circuit configurations.

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**Fig. 3** – The appearance function for iron ore tested.

**Fig. 4** – Direct circuit (right) and reverse circuit (left) simulations.

**Fig. 5** – Direct circuit with \((r_i/d_i)\) from reverse circuit (right) and reverse circuit with \((r_i/d_i)\) from direct circuit (left).
Conflicts of interest

The authors declare no conflicts of interest.

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REFERENCES