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Exploring ball size distribution in coal grinding mills

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ABSTRACT

Tube mills use steel balls as grinding media. Due to wear in the abrasive environment it is necessary to charge new balls periodically to maintain a steady balanced ball charge in the mill. The amount and ball size distribution in this charge, as well as the frequency with which new balls are added to the mill, have significant effects on the mill capacity and the milling efficiency. Small balls are effective in grinding fine particles in the load, whereas large balls are required to deal with large particles of coal or stone contaminant. The steady state ball size distribution in the mill depends on the top-up policy.

The effect of the ball size distribution on the milling rate of coal has been measured as a function of ball size distribution. The change in ball size distribution as affected by wear and ball top-up policy has been modelled. From this a best ball top-up policy can be recommended that will ensure a close approximation to the desired steady-state ball size distribution that gives the required PF size distribution for the selected mill demand.

1. Introduction

The expected grinding performance of a mill can be estimated by applying phenomenological grinding kinetic theory that relies on a rate of the process as characterised by the selection function and breakage product distribution known as the breakage function. This approach is now well established and has been discussed extensively by prominent researchers such as Austin et al. [1] and Herbst and Feurstenau [2].

Elaborate batch experiments can be conducted on a sample of the material to obtain relevant parameters that describe the process within the test mill. The parameters can then be applied to other environments by appropriately scaling up to the new milling conditions.

In our approach we used the standard methodology [3] to obtain the selection and breakage function parameters for our batch experiments. We then applied the recommended approach [1,4] to scale-up to a different mill size and different ball size distribution. The procedure is explained in detail in the experimental section.

The ball size distribution (BSD) in a mill is usually not known, as the measurement of the charge size distribution requires dumping the load and laboriously grading the balls into size classes. Fortunately we had one set of data as discussed below. The general non-availability of BSD necessitates the use of ball wear theory to estimate BSD as required. The development of this theory is tackled in the following section, and validated against this set of data.

One BSD data set was made available when a plant dumped the charge and used an in-house developed device to grade the balls. This device comprised two counter-rotating rods with increasing space between them towards the lower end. As balls rolled between these rods they fell through the gap in accordance with their size. The charge graded in this way was used to establish wear parameters [5].

2. Modelling ball wear in the mill

2.1. Ball shrinking theory

A ball once introduced in the mill will on a continuous basis be subject to wear as it interacts with particles, other balls and internal surface of the mill. The rate at which material is removed from a ball is proportional to the surface area of the ball at that moment in time, which can be written mathematically as:

$$-\frac{dV(t)}{dt} \propto 4\pi\ r(t)^2 \quad \text{or} \quad \frac{dV(t)}{dt} = -4k_1\pi\ r(t)^2 \tag{1}$$

where $V(t)$ represents the instantaneous volume of the ball, $r(t)$ is the instantaneous radius of the ball, and k_1 is the constant of proportionality that takes into account the material from which the ball is made. The minus sign indicates that the ball reduces in size as time progresses.

By doing appropriate mathematical treatment with similar assumption used by previous authors [6,7] the ball wear can be represented as follows:

$$r^2\frac{dr}{dt} = -cr^n \qquad n \text{ can be } 1, 2 \text{ or } 3. \tag{2}$$

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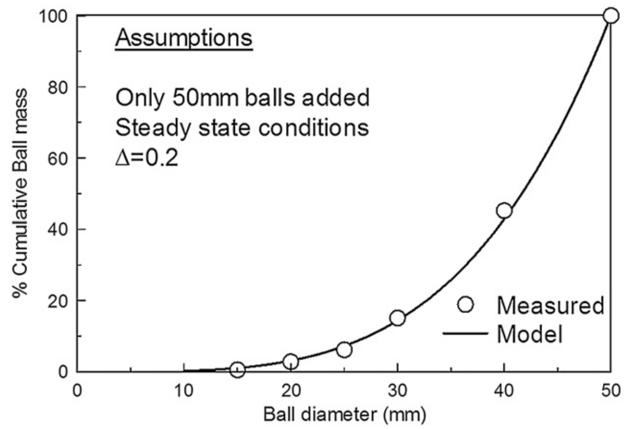

Fig. 1. Model prediction of Matimba steady BSD using $\Delta = 0.2$.

This holds when wear rate is proportional to the diameter, surface area or volume. However, if the power is not a whole number, then wear rate can be considered to be a combination of at least two factors. For a wear rate that is dependent on both surface area and volume, $2 < n < 3$ would be the applicable domain.

Eq. (2) can be simplified as follows:

$$r^{-\Delta}dr = -cdt \quad \text{with} \quad \Delta = n - 2. \tag{3}$$

Eq. (3) can be expressed in terms of diameter and integrated to give:

$$d(t) = \begin{cases} d_0 \exp[-k(t - t_0)] & \text{if } \Delta = 1 \\ \left[d_0^{1-\Delta} - k(1-\Delta)(t - t_0)\right]^{1/(1-\Delta)} & \end{cases}. \tag{4}$$

A Δ value of 0.2 is suggested by Austin et al. [1] for almost all cases of dry milling. This value provides an important starting point as the historical data from Power Stations is usually not of sufficient quality for determining both wear parameters, Δ and k. To determine both parameters we would need to know the initial BSD in the mill, the top-up policy and have an accurate determination of the final BSD when the charge is dumped. It is this latter aspect that is problematic with the Power Station's data. However, if we only have to find k then the final BSD is not needed and the final dump mass of the steel would suffice. This assertion is justified below.

2.2. Steady state simulation

By treating the ball addition rate to maintain the same charge mass as a mass balance problem, Austin and Klimpel [6] have derived the equations that give the steady state BSD when one-ball and two-ball top up sizes are used as given below.

$$\mathrm{P}(d) = \frac{d^{4-\Delta} - d_{\min}^{4-\Delta}}{d_{\max}^{4-\Delta} - d_{\min}^{4-\Delta}} \qquad \text{for a single makeup ball size, } d_{\max}, \tag{5}$$

Table 1
The EQM ball size distribution that was used in the batch tests.

Size class [mm]	Mass [kg]	Mass fraction	Number of balls
44.0–50.0	16.475	0.400	40
37.5–44.0	10.635	0.258	40
31.5–37.5	6.490	0.158	38
26.5–31.5	3.850	0.093	38
20.4–26.5	2.305	0.056	40
15.0–20.4	1.390	0.034	40
Totals	41.205	1.000	236

Table 2
The S-values for the eight prepared samples.

Size (microns)	S-values [min −1]
−26500 + 22400	1.2366
−19000 + 16000	2.0439
−13200 + 9500	2.6860
−6700 + 4700	2.5344
−3350 + 2360	1.7340
−1700 + 1180	0.8297
−850 + 600	0.4465
−300 + 212	0.2622

where P(d) is the mass fraction of balls in the load which are smaller than d. For two makeup ball classes, d_1 and d_2 of mass fraction m_1 and m_2 respectively:

$$\mathrm{P}(d) = \begin{cases} \dfrac{d^{4-\Delta} - d_{\min}^{4-\Delta}}{Kd_{\max}^{4-\Delta} + (1-K)d_2^{4-\Delta} - d_{\min}^{4-\Delta}} & ; \quad d_{\min} \le d < d_2 \\ \dfrac{Kd^{4-\Delta} + (1-K)d_2^{4-\Delta} - d_{\min}^{4-\Delta}}{Kd_{\max}^{4-\Delta} + (1-K)d_2^{4-\Delta} - d_{\min}^{4-\Delta}} & ; \quad d_2 < d \le d_1 = d_{\max} \end{cases}. \tag{6}$$

These equations were incorporated into our simulation software that was written to take the initial steady-state BSD as given by Eqs. (5) or (6), the details of the top-up policy and calculate the BSD at any given time t. This however required an initial estimation of the wear parameter K which was made possible by the availability of the dumped load data. The parameter is calculated as follows:

$$K = \left[1 + \frac{m_2}{m_1}\left(\frac{d_1}{d_2}\right)^3\right]^{-1}. \tag{7}$$

Once the wear parameter value K is known it is possible to use Eq. (4) to numerically simulate the wear of every ball in the mill for any time duration and thus calculate the BSD at any given time provided that the initial BSD and ball top up schedule are known. With the numerical scheme, the BSD can be computed for any specified period of time and for more than two top-up sizes. The top-up size can also be changed at any time and the computation of the BSD can proceed.

Note that the steady-state shape of P(d) is a function only of Δ and the top-up policy (TUP), and not a function of the wear rate k. In order to check the value of Δ we use some steady-state P(d) data collected at Matimba coal mine [5]. It is seen in Fig. 1 below that the value suggested by Austin of $\Delta = 0.2$ [1] works very well.

The ability to estimate BSD for any top-up policy (TUP) enabled us to predict grinding performance of the mill under varied conditions. Our BSD calculations had to be combined with the batch grinding data

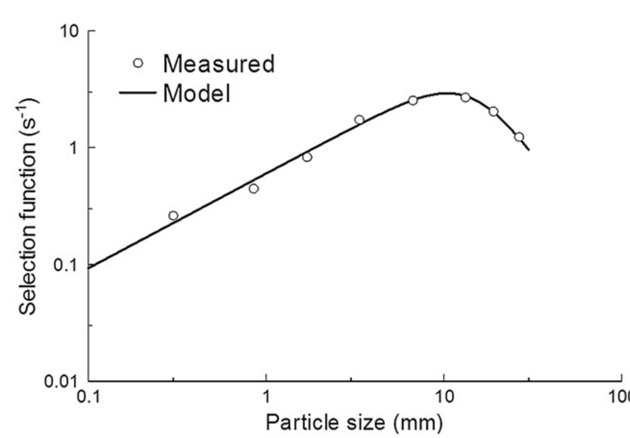

Fig. 2. Selection function for the coal sample ground in 0.55 diameter mill.