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Circulation rate modelling of mill charge using position emission particle tracking

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ABSTRACT

A model linking the circulation rate of charge particles with physical mill parameters (load fraction, shoulder angle and friction) has been developed and tested using experimental data derived from positron emission particle tracking (PEPT). The model parameters are obtained directly from the *in situ* flow field of the PEPT tracer particles. The model formulation, methodology for model parameter correlations and comparison of circulation rate model with direct measurement from PEPT forms the focus of this paper.

1. Introduction

One of the earliest works on charge motion was reported by White (1905), who assumed that particles along the mill periphery move without slip until a gravitational and centrifugal force balance is reached. At this stage particles are projected into parabolic motion, strike the “impact point” and are drawn into the bulk of the charge. His conclusions on regulating water levels in order to generate useful impact work are a valuable contribution to comminution. At the end of the next decade, Davis (1919) formulated a similar mathematical description for a single particle moving along the mill shell without slip. Verification of the theoretical results was achieved by taking end window images of an experimental mill. The agreement between experiment and theory was said to compare well except for the intersecting trajectory paths of cataracting particles observed in experiments. This was argued away as accidental and amplified by a low charge filling. His work clearly highlights the value of mathematical modelling of charge motion while elucidating the shortcomings of simplified assumptions.

Other notable contributions on charge motion analysis has been the development of grinding theories such as the energy distribution theory (Rittinger, 1867; Bond, 1952; Schonert, 1988) and the breakage theory of comminution (Kick, 1885; Powell and McBride, 2006). These dynamical theories would lead one to conclude that for a given feed material and energy input the best comminution device is one which could provide the correct fracture energy to each target product particle size distributions (PSDs), bearing in mind the advantage of power efficiency. Studies on liner designs (Mcler, 1983; Vermeulen, 1985; Vermeulen and Howat, 1988), illustrate the impact of these theories on comminution. Vermeulen and Howat (1988) suggested the charge surging phenomenon commonly encountered in smooth lined rod mills contributes to liner wear, because the large fluctuations in slip induced massive wear on the lining and clearly illustrated the value of using lifter bars.

Qualitative flow phenomena are not only describable from experiments but can also be reproduced through numerical simulations. These simulations are computationally intensive but are becoming more popular as computer processing power has increased. A range of techniques have recently been employed which vary from treating the material being studied as a continuum, with the physics averaged out over all the particles (Charles, 1957), through to treating each particle as a discrete element (Discrete Element Modelling – DEM), Powell and McBride (2006). An essential aspect of DEM simulations is that collision interaction of particles with each other and their environment are detected and modelled using contact force laws. Equations of motion are then solved for the particle motions and for the motion of any boundary objects with which the particles interact (Walton and Braun, 1993; Powell and McBride, 2006). Among the most recent studies undertaken using this technique includes a 142 mm laboratory tumbling mill (Powell and McBride, 2004; Govender, 2005). In these studies, a number of characteristics including charge behaviour, torque and power draw for a range of rotation rates (between 50% and 130% of the critical speed for mills) were analysed.

However, to date there is a notable lack of information on the actual trajectories followed by particles in rotary grinding mills. In particular the speed of circulation of the charge particles relative to the mill rotation, otherwise known as the circulation rate, has

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Nomenclature

a	charge acceleration	N_m	mill speed
C	circulation rate	n_l	number of rolling, cascading or cataracting layers from base of mill
C_r	circulation ratio	r	orbital radius
CoC	centre of circulation	R	mill radius
CoM	centre of mass	v	tangential velocity of mill
D	degree of slip	ω	angular velocity
d_m	mean particle diameter	α	load fraction
F_c	centrifugal force	δ	angle of repose
F_F	frictional force	θ	dynamic angle of repose
F_g	force of gravity	θ_c	critical angle of repose
F_N	normal force caused by friction	ζ	departure shoulder angle
F_r	Fraude number	ε	filling angle
f	filling degree	μ_i	internal friction coefficient
g	acceleration due to gravity	μ_w	wall friction coefficient
k_m	mean charge deflection	μ_k	coefficient of kinetic friction
N_c	critical mill speed		

never been directly investigated and as such is often taken to be unity by many mill models. This apparently is to allow for simple mathematical manipulation of these models.

A comminution device is equipment that converts an input of energy into mechanical motion. This motion is transferred to the content of the device – charge – and the resultant mechanical action applied to the particles leads to their damage and eventual breakage (Powell and McBride, 2006). In this paper, we discuss recent work done on charge motion analysis from an *in situ* perspective using data derived from the novel positron emission particle tracking (PEPT) technique. New descriptions of the transition behaviour between the main forms of motion, as previously investigated by Mellmann (2001), is presented and used in formulating a mathematical model of circulation rate which is well supported by PEPT data.

2. Experimental work

The data used in this research is derived from the experimental program conducted by the Centre for Minerals Research (University of Cape Town) at the PEPT centre of the University of Birmingham (UB). The data derived from the particle tracking system spans a wide range of dry and wet milling configurations and a number of experiments have been conducted over a period of 3 years. Traditional autogenous and semi-autogenous mills were employed mostly in closed circuits and a detailed summary of these experiments is presented herein.

The experimental rig, Fig. 1, consisted of a mill constructed from High Density Polyethylene (HDPE), a DC drive with step-down gear box, torque sensor and a reticulating pump for wet experiments that re-circulated the slurry. The details of the mill are as follows: internal length of 270 mm, internal diameter 300 mm, number of lifters 20, and discharge grate open area ~30%. The mill shell, the lifters and the pulp lifters are manufactured from HDPE which has a specific density of 0.95. HDPE is chosen specifically for this type of experiment because of its low gamma ray attenuation. The grate and the mill cover are manufactured from clear acrylic, so that the discharge dynamics of the mill can be observed using video and photographic cameras. Milling configurations spanned six lifter profiles, five loads between 12.5% and 50% and five speeds between 55% and 100% of critical. The effective grinding length (EGL) is the same as the internal length of the mill for all loads since the mill is flat ended.

3. Charge motion at low speeds – the centre of circulation (CoC) model

The centre of circulation (CoC) is a unique point about which the entire charge appears to circulate as distinguished from the mill centre. The path of the particles in the *en-masse* region form concentric rings of decreasing radii that converge on the CoC. If the circulation plane of the mill is divided into families of horizontal, vertical and radial control surfaces, a cumulative count of particles passing through any point along these control surfaces would yield a local maximum when the particles pass through the CoC (Powell and McBride, 2004). According to Powell and Nurick (1996), the radial and angular positions of the CoC are determined by the instantaneous charge position which in turn is influenced by the mill rotational speed. The initial radial and angular locations of the CoC are observed when the first layer of balls roll down the charge surface. There is a notable initial outward shift of the CoC as more underlying layers enter rolling motion with a corresponding drop in its angular location. At higher speeds, however, this trend is reversed, the CoC tends towards the mill centre and its angular position climbs rapidly towards 90°. A mathematical model, given in Eq. (1), describes the radial displacement of the CoC at low speeds.

$$r_{CoC} = n_l d_m + R\sqrt{1-\alpha} \qquad (1)$$

According to Watanabe (1999), the radial position of the charge surface for a mill at rest is given by $R\sqrt{1-\alpha}$. For a mean particle diameter d_m, n_l would represent the number of particle layers leaving the base of the mill and entering rolling, cascading or cataracting motion. This phenomenon is illustrated in Fig. 2a. For a given maximum radial location of the CoC (Fig. 2a) the outward shift of the CoC ($r_{CoC(max)} - r_{CoC(initial)}$) increase with mill load fraction indicating the possible use of the CoC model for an analysis of charge slippage – which is out of scope of this paper.

In comminution the angle of repose is commonly employed in describing the torque exerted by the charge, and consequently the power drawn. Powell and McBride (2004) have presented the most user-independent definition for the repose angle by noting that "the tangent to the equilibrium surface at the CoC is perpendicular to the radial line passing through the CoC. This condition is uniquely defined because the equilibrium surface has a different curvature to the mill shell, so only one point on the surface can have a tangent perpendicular to a radial line".