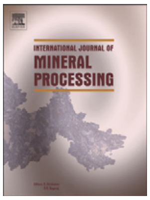
International Journal of Mineral Processing 149 (2016) 94–103

Contents lists available at ScienceDirect

International Journal of Mineral Processing

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



Development of a novel methodology to determine mill power draw

Lawrence Sidney Bbosa [a,*], Indresan Govender [b], Aubrey Mainza [a]

[a] Centre for Minerals Research, Department of Chemical Engineering, University of Cape Town, South Africa
[b] Department of Chemical Engineering, University of KwaZulu-Natal, South Africa

ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form 25 October 2015
Accepted 15 February 2016
Available online 20 February 2016

Keywords:
Power draw
PEPT
DEM

ABSTRACT

This paper presents an approach that has been developed to calculate the power draw of each size within a distribution of charge in a tumbling mill. Positron Emission Particle Tracking (PEPT) and the Discrete Element Method (DEM) are used to test the methodology. Experiments are conducted using dry spherical glass bead charge in a laboratory scale tumbling mill, which is mounted with a torque transducer and tachometer to provide measurements of mill power. Particle tracking information from PEPT is used to reconstruct the motion of glass beads and infer the overall charge behaviour, while DEM is employed to simulate particle motion and interaction, with collision mechanics calculated using the Hertz–Mindlin contact model. For both sets of data, the product of torque and average angular velocities in discrete cells are accumulated to obtain mill power. This method is found to be within statistical agreement with measured power for all cases investigated.

1. Introduction

In comminution circuits, the power draw of tumbling mills is an important design and operating variable. The net power draw of a tumbling mill refers to the energy expended per unit time in causing motion of the contents, or charge (Austin et al., 1987). This quantity is determined as a product of the torque exerted by the charge on the external shell and the specified mill rotational speed (Arbiter and Harris, 1982).

Many methods have been proposed to predict the power draw of tumbling mills (Hogg and Fuerstenau, 1972; Arbiter and Harris, 1982; Morell, 1992; Moys, 1993). In the last several decades, advancement in measurement and computational tools has enabled more detailed study of the mechanisms that govern charge motion behaviour. This has provided the opportunity to develop mechanistic models which describe the power draw in terms of the variables that influence charge motion (Govender and Powell, 2006).

The Discrete Element Method (DEM) is one such means of analysing the internal dynamics of tumbling mill motion (Agrawala et al., 1997; van Nierop et al., 2001). With this computational technique, the motion of individual bodies is calculated using Newton's laws while the body interactions are simulated using a set of equations referred to as the contact model (Cundall and Strack, 1979). To verify that the energy environment is represented correctly, the net power draw from DEM simulations can be determined and compared to experiments (Mishra and Rajamani, 1992, Cleary, 1998).

Positron Emission Particle Tracking (PEPT) is a technique that has been utilized to analyse charge motion in rotating drums (Parker et al., 1997). The premise of the method involves obtaining the position of a radio-labelled particle at discrete time intervals in the field of view of the Positron Emission Tomography (PET) equipment. Using PEPT, the trajectory of a single particle in a stochastic system such as a tumbling mill can be obtained and used to ascertain the bulk motion properties of the charge body. The unique value of this aspect is that data from PEPT can be used to calculate the average kinematic properties of each size class within a charge distribution. Similar to DEM simulation data, calculated power draw from PEPT data can be validated by comparison with the net power draw from measurement (Bbosa et al., 2012). The average kinematic properties of charge motion in a tumbling mill from PEPT experiments can then be compared against similar properties from DEM simulations of identical systems (Yang et al., 2003). This offers a unique quantitative method of verifying the results of DEM simulations which considers the charge motion characteristics in addition to validating the energy environment against power draw measurement.

In this paper, experiments using PEPT and computational simulations *via* DEM are used to study the charge motion of glass beads of different size classes in a laboratory scale tumbling mill. A novel methodology is then developed to calculate the power draw which is tested against data from both techniques and found to be consistent with measurement.

2. Background

2.1. Summary of charge motion characteristics

The power drawn by a rotating mill has a direct correlation with the type of charge motion produced by the regime in which it operates (Wills and Napier Munn, 2006). The charge motion, and consequently

---

* Corresponding author.
E-mail address: lawrence.bbosa@uct.ac.za (L.S. Bbosa).

http://dx.doi.org/10.1016/j.minpro.2016.02.009
0301-7516/

power draw has been demonstrated to be influenced by mill operating variables such as lifter height and speed, as well as charge parameters such as size and volumetric filling (Powell and Nurick, 1996).

Mellmann (2001) aptly summarized the different types of charge motion that occur with increasing speed in a rotating mill. As shown in Fig. 1, charge motion is largely divided into three basic types, which can be further divided into seven subtypes according to the Froude number. Differences in appearance and an indication of the resistance to flow that characterizes each regime are highlighted.

The type of motion that is desired in comminuting mills is a combination of the cascading and cataracting regimes, as this motion largely encourages the mixing and grinding of charge. At lower speeds, such as rolling, while mixing may occur, the charge does not generate much motion, which severely reduces the amount of size reduction that is generated *via* impact. At higher speeds, at which centrifuging occurs, the charge mainly clings to the periphery of the mill which leads to little in the way of grinding and mixing. Additionally, at speeds close to the centrifuging value, the trajectory of falling material begins to impact against the mill shell rather than the charge which is damaging to the internal surface. Due to the undesirable consequences of running a tumbling mill in these regimes, it is of great importance to ensure that the operating conditions create the desired collision environment.

Several descriptors of charge motion have been introduced to characterize the degree of mixing and impact in tumbling mills. These features are evident when motion is captured using techniques such as videographic filming (Venugopal and Rajamani, 2001), X-ray imaging (Govender et al., 2004) and DEM (Powell and McBride, 2004). The work by Powell and McBride, illustrated in Fig. 2, provides a summary of the main features that are customarily used to describe motion in tumbling mills. In this diagram, the particle trajectory in the cascading and cataracting regime was visualized in a two-dimensional plane along the transverse mill face and used to define several descriptors for the bulk motion.

The head is defined as the highest vertical position attained by the charge. The departure shoulder is defined as the uppermost point at which the charge departs from the mill shell. Powell and McBride defined two distinct toe regions in their work. The bulk toe is located at the point at which the cascading charge collides against the mill shell while the impact toe is the point at which the cataracting charge collides with the shell. A flow region known as the equilibrium surface is also defined: a region of zero velocity which separates the ascending charge from the descending charge. Along this surface, the point about which the charge in the mill rotates is termed the centre of circulation. The free surface is the curve that delineates the bulk rising and cascading charge from the cataracting material in free flight.

2.2. Power draw models

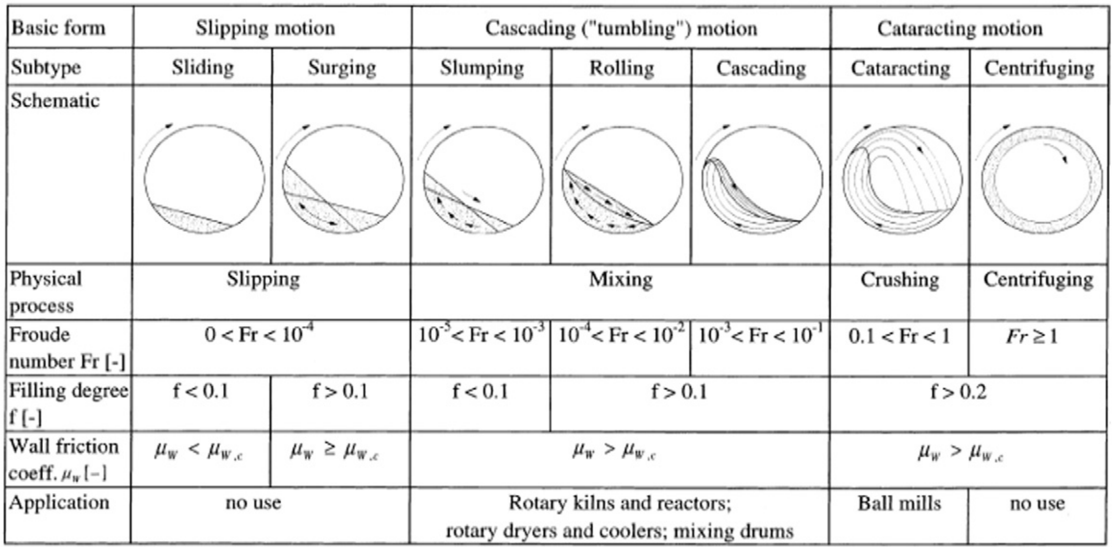
Numerous methodologies have been proposed for calculating mill power in terms of charge motion (Hogg and Fuerstenau, 1972; Arbiter and Harris, 1982, Liddel and Moys, 1988, Moys, 1993, Austin, 1990, Mishra and Rajamani, 1992, Morell, 1992; Cleary, 2001). Of these, several significant features are highlighted which are of pertinence to the current paper.

Hogg and Fuerstenau (1972) applied a simplified description of charge shape, shown in Fig. 3, in which particles moved in the bulk region along fixed concentric paths with the rotating mill. At the free surface the particles were then proposed to descend by rolling down to the base of the mill, whereupon the cycle would recommence. This model incorporated the equilibrium surface, which was described as a path separating the rising charge from the falling material.

Arbiter and Harris (1982) modified the charge motion model by Hogg and Fuerstenau to obtain a power model based on the principle of a lever arm (see Fig. 4). For their method, the total charge was approximated to have a fixed mass which formed a torque about the mill centre rotating with the rotational speed of the mill. The mill power draw was the product of the torque and rotational speed. The function obtained was similar to that suggested in Hogg and Fuerstenau's model. This was because the derivation using torque and rotational speed amounted to a calculation of the work done against gravity or gain of potential energy.

Morell developed a power draw model based on empirical data from several industrial mills, which is among the most highly regarded in comminution research (Napier-Munn et al., 1999). In his work, the region of the mill charge which drew power was represented using an annular ring as depicted in Fig. 5. This represented the rising bulk charge of the mill, neglecting cascading and cataracting material.

With the development of the Discrete Element Method (DEM) in application to tumbling mills, Mishra and Rajamani (1992) used the technique to analyse charge motion and develop a methodology to derive the power draw. A linear spring and dashpot contact model was used to calculate interaction forces and energy losses between colliding bodies, and total energy losses to collisions were calculated. Assuming steady state, this was equated to the energy supplied by the mill, which could then be divided by the simulation time to calculate mill power.



Basic form	Slipping motion		Cascading ("tumbling") motion			Cataracting motion	
Subtype	Sliding	Surging	Slumping	Rolling	Cascading	Cataracting	Centrifuging
Schematic							
Physical process	Slipping		Mixing			Crushing	Centrifuging
Froude number Fr [-]	$0 < Fr < 10^{-4}$		$10^{-5} < Fr < 10^{-3}$	$10^{-4} < Fr < 10^{-2}$	$10^{-3} < Fr < 10^{-1}$	$0.1 < Fr < 1$	$Fr \geq 1$
Filling degree f [-]	$f < 0.1$	$f > 0.1$	$f < 0.1$	$f > 0.1$		$f > 0.2$	
Wall friction coeff. μ_w [-]	$\mu_w < \mu_{w,c}$	$\mu_w \geq \mu_{w,c}$	$\mu_w > \mu_{w,c}$			$\mu_w > \mu_{w,c}$	
Application	no use		Rotary kilns and reactors; rotary dryers and coolers; mixing drums			Ball mills	no use

Fig. 1. Transverse motion of solids in rotating cylinders (from Mellmann, 2001).