Minerals Engineering 92 (2016) 86–109

Contents lists available at ScienceDirect

Minerals Engineering

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

Using DEM to understand scale-up for a HICOM® mill

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ARTICLE INFO

Article history:
Received 28 October 2015
Revised 6 February 2016
Accepted 2 March 2016
Available online 8 March 2016

Keywords:
DEM
HICOM mill
Comminution
Scale-up
Scaling laws

ABSTRACT

Scale-up is a process of developing a larger version of a processing machine based on the performance of a smaller machine. For mills, scale-up is made difficult by the different rates at which different physical processes occurring within the machine change with the increasing size. Discrete Element Method (DEM) modelling can now be performed at a range of scales and can be used to help understand scale-up issues for mills. This paper explores the ways in which DEM can be used to assist in the scale-up process for a mill using the HICOM mill as a case study. By choosing speeds at each mill size that have the same charge distribution and structure a scale-up relationship is developed which allows prediction of the power draw with increasing mill size. Similar scale-up relationships are developed for the specific power intensity and the most common collision energy occurring within the charge. The peak loads on the liner and at the nutation point of the mill are key inputs to mechanical design. Their variation with increasing physical size is also explored. Finally, the change in wear behaviour with increasing scale is also determined. This scale-up process can be applied to any form of mill.

1. Introduction

Comminution is an important process in industries ranging from mineral processing to ceramics and pigment preparation to pharmaceuticals. It involves the systematic reduction in the particle size of a feed material to produce a finer product material. In mineral processing, there are moderate quality requirement but the volumes of materials to be comminuted are huge. In contrast, industries such as ceramics and pharmaceuticals have high quality requirements but low volumes. These different needs have led to the development of many different types of mills, all of which have different operational behaviours and different responses to variations in feed and varying ability to change product specification. For mineral processing, comminution is dominated by large tumbling mills, such as Autogenous Grinding (AG) mills, Semi-Autogenous Grinding (SAG) mills, and ball mills. For cement and clinker grinding, ball mills and High Pressure Grinding Rolls (HPGR) are typically used. For finer grinding, tower mills, Vertimills and roller mills or grinding tables are more common. For very fine grinding, stirred mills (such as the Isamill and the Netzche mill) and high intensity agitated mills such as the centrifugal mill and the HICOM are used.

In trying to understand and optimally design such a broad range of mills, historically trial and error experimental development processes have been used. Difficulty in measuring any internal flow or breakage processes due to the opaque and highly damaging flow environment means that the information available to the design process is highly limited. This has led to a slow rate of evolution of these machines, with long generation times and high capital requirements since each concept needs to be designed mechanically, built and then tested. Often mechanical design issues dominate over process efficiency considerations. The Discrete Element Method (DEM) provides a way to simulate the flow of materials, their breakage, classification and transport in comminution devices. This has been used extensively for simulating tumbling mills (Mishra and Rajamani, 1992, 1994; Rajamani and Mishra, 1996; Cleary, 1998, 2001a, 2001b, 2001c, 2009b; Cleary and Sawley, 2002; Cleary et al., 2008; Djordjevic, 2003, 2005; Herbst and Nordell, 2001; Morrison and Cleary, 2004, 2008; Kalala et al., 2005a, 2005b, 2008; Weerasekara et al., 2011; Powell et al., 2011; Delaney et al., 2013) and special issues SAG2006 (Allan et al., 2006), DEM2007 (Cleary and Morrison, 2008) and SAG 2011 (Major et al., 2011).

DEM modelling of tower and stirred mills has been more recent (Yang et al., 2006; Sinnott et al., 2006; Cleary et al., 2006b, 2008; Jayasundara et al., 2008, 2009). Transport and discharge of feed and product particles are usually important aspects of mill performance but they are rarely included in DEM models. Cleary (2006) examined the axial transport and discharge of coarse rock and in a dry ball mill. Coarse particle flow through the grate of a dry SAG mill into the pulp chamber was simulated by Cleary (2004). For

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http://dx.doi.org/10.1016/j.mineng.2016.03.004

wet mill applications a combined SPH-DEM method was proposed by Cleary et al. (2006a) for predicting the distribution and transport of slurry in SAG mills and extended to three dimensions by Cleary and Morrison (2012). Rajamani et al. (2011) and Lichter et al. (2011) also explored flow in the pulp chamber of a SAG mill.

The centrifugal mill is a long established high intensity mill (Hoyer, 1984, 1985) which is a precursor of the HICOM mill. Inoue and Okaya (1996) and Cleary and Hoyer (2000) used DEM to model such a mill and demonstrated strong predictive accuracy by comparing to high speed photographs through the Perspex bottom of an experimental mill and to power draw measurements. More recently, Cho et al. (2006) and Lee et al. (2010) have used DEM to further study this type of mill.

The HICOM mill uses roughly light bulb shaped grinding chamber which is inclined at an angle (the nutation angle). This angled axis of the mill is then rotated around the vertical which produces a novel nutation motion. The key consequence of this design is that the centrifugal force generated by the motion varies with distance below the nutation point (as the distance of the chamber from the vertical increases). Particles are added through a central feed opening at the top of the mill. Ground product discharges through ports at various locations on the sides of the grinding chamber (see Owen and Cleary, 2014 for details of port discharge). The wear life cycle of the HICOM liner has also been studied using DEM by Cleary et al. (2010) and Cleary and Owen (2015). More extensive details of the HICOM mill will be given in the following section.

The current status of DEM as a tool for understanding comminution is summarised in a recent review article by Weerasekara et al. (2013). With the DEM method now in principle able to make predictions of all the key elements of the comminution process, there are three key ways in which such a model can be used

1. Understanding performance of a specific machine (either an existing one for optimisation or a design of a new machine). This is the most commonly usage mode for DEM with the bulk of published work to date (see references above) for this purpose.
2. Comparing the relative performance of two or more machine to help users make more informed choices of which machine to use in which circumstances. This was used by Sinnott et al. (2006) and Cleary et al. (2006a, 2006b) to compare a tower mill and a similar duty pin mill. It has also more recently been used by Morrison et al. (2009) to compare a ball and a tower mill.
3. To understand scale-up of a mill through a range of sizes with the aim of producing the same products but with increasing production rates with increasing mill size.

To date, scale-up of mills has been performed using scaling relationships supported by experimental measurement, for example see Herbst and Fuerstenau (1980) and Hoyer (1992). A key challenge in scale-up is that different aspect of the process typically scale up at different rates, so the flow pattern, the collision energy ranges and the particle breakage they produce and the feed and product transport all vary at different rates with the mill scale, see Harris and Arbiter (1983). Wear behaviour is also likely to be scale dependent. Typically, the flow processes responsible for transport of fine particles and slurry scales more slowly than the collision processes that create particle breakage. This mismatch of the scaling of the transport and breakage processes mean that their relative performance varies with increasing mill size. This is often the largest single problem in successfully scaling up a mill. This is complicated by mechanical engineering design issues where the integrity of the mill structure and of the drive and gearing mechanisms can place serious restrictions on the required physical changes to the mill as its size increases. Design changes, driven by mechanical and construction demands, can often have both unexpected and undesirable consequences for process efficiency.

The use of DEM in the scale-up process should ideally provide increased information on the process implications of design options in advance of constructing expensive prototypes. To date, little DEM based modelling has been reported on the problem of machine scale-up, see Iwasaki et al. (2010) with this based on trial-and-error and general experience. Mio et al. (2004) used experiments and DEM simulations to study scale-up over a narrow range of a planetary ball mill by varying the diameter of the pots (from 40 mm to 101 mm) and the radius of revolution (from 70 mm to 120 mm). Cleary and Sinnott (2008) used DEM for a preliminary exploration of aspects of scale-up for a V-blender for mixing of particulates. They scaled the V-blender from laboratory size (1.86 l) by two orders of magnitude to production size (186 l). More recently, de Carvalho and Tavares (2013) used DEM to predict breakage rates for the scale-up of laboratory sized ball mills to pilot scale by varying particle and ball diameters, mill speeds and mill diameters (from 0.3 m to 1.8 m).

In this paper, we explore the use of DEM in evaluating the scale-up of one specific mill type through several geometric sizes. The mill chosen was the HICOM high intensity agitated mill. The aim here is to explore in general the degree to which DEM can help in understanding machine scale-up issues and to provide some specific information relating to the scale-up of the HICOM mill itself. Specifically, we consider how scale dependent changes to the shape of the grinding chamber affects performance and how best to choose the mill speed at the larger scale to give similar flow and stress conditions to those of the smaller mill.

2. The HICOM mill and the scale-up process

The HICOM mill is a high intensity fine grinding mill with multiple peripheral discharge ports. Fig. 1 shows two diagrams of the HICOM mill. On the left is a representation of the overall mill with a section removed from the front so that the inside of the grinding chamber can be viewed. On the right is a simplified representation of the key aspects of the mill the structure. At the top is the nutation point through which the angled grinding chamber axis passes and which acts as a fixed point. The mill chamber rotates around the nutation axis which is typically vertical. The HICOM mill grinding chamber is a cylindrically symmetric vessel that is smaller in diameter at the top, increasing to a maximum diameter at around 1/3 from the bottom and then decreasing on approach to the closed bottom. There is a relatively narrow cylindrical neck at the top through which feed material enters. The liner has vertical lifters running from the neck to the base to lock into the charge and to increase the efficiency of the transfer of energy from the mill. Discharge ports in the form of circular openings are located between some of the ribs of the mill liner and can be at a range of heights. These allow fine ground particles and/or optional large liberated ore particles or media to discharge. Typically such a mill will be operated in closed circuit with media being separated from the discharge stream and returned to the mill or fine grates can be placed over the ports to retain media while permitting finer particles to exit. For the current scale-up study we will not consider discharge so the ports are closed and therefore not shown in Fig. 1.

The grinding chamber inclination (nutation angle) used here is 4.75° from the vertical. This is the value typically used for the HICOM mill. As a result of the nutation inclination and the rotation of the chamber around the nutation axis, this causes the chamber to move with a nutating motion around the mechanical joint which is located above the top of neck of the grinding chamber. This joint is the nutation point which remains stationary, while all other points on the chamber below describe circles around the vertical