TOWARDS A BETTER UNDERSTANDING OF STIRRED MILLING TECHNOLOGIES - ESTIMATING POWER CONSUMPTION AND ENERGY USE

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ABSTRACT

Stirred mill technology dates back to 1928 where the idea to use "an agitator and spherical grinding media" was presented. The year 1948 saw the successful application of DuPont's "sand mill" for pigment grinding. Subsequent years have led to the development of different types of stirred mills spanning a number of industries that require fine and ultrafine grinding.

In the context of the mining industry, smaller grain size and other mineralogical characteristics have motivated the need to grind finer. In order to address this need, the interest in stirred milling technologies has grown over the last 20 years as can be illustrated by the large body of literature published over this same period of time. The typical observation reported in the literature is that in certain circumstances stirred milling is significantly more efficient than ball milling.

Despite these developments, the tumbling mills are continuing to be used in fine and ultrafine grinding applications. The main reason for this, as communicated at the Canadian Mineral Processors roundtable discussion in 2013, is that the comfort level in understanding stirred milling technologies is not at the level of that of tumbling mills.

The aim of this paper is to contribute to increasing the general comfort level with stirred milling technologies by developing a better understanding of how power and energy is affected by stirred mill impellor design and mill operation. This will be accomplished by first completing an overview of the power models found in the literature followed by a general description of DEM and CFD stirred mill models as well as the insights that can be drawn from them. Finally, a generic stirred mill power model will be presented and applied to different stirred mill types in order to develop some insights into the differences between different mill types. The paper will close with a discussion on some of the challenges that these models have and how future research might contribute to overcoming them.

KEYWORDS

Stirred mills, comminution, modelling, validation

INTRODUCTION

Stirred mill technology dates back to 1928 where the idea to use "an agitator and spherical grinding media" was presented (Stehr, 1988). The year 1948 saw the successful application of Du Pont's "sand mill" for pigment grinding. Subsequent years have led to the development of different types of stirred mills spanning a number of industries that require fine and ultrafine grinding.

In the context of the mining industry, smaller grain size and other mineralogical characteristics have motivated the need to grind finer. In order to address this need, the interest in stirred milling technologies has grown over the last 20 years as can be illustrated by the large body of literature published over this same period of time. The typical observation reported in the literature is that in certain circumstances stirred milling is significantly more efficient than ball milling.

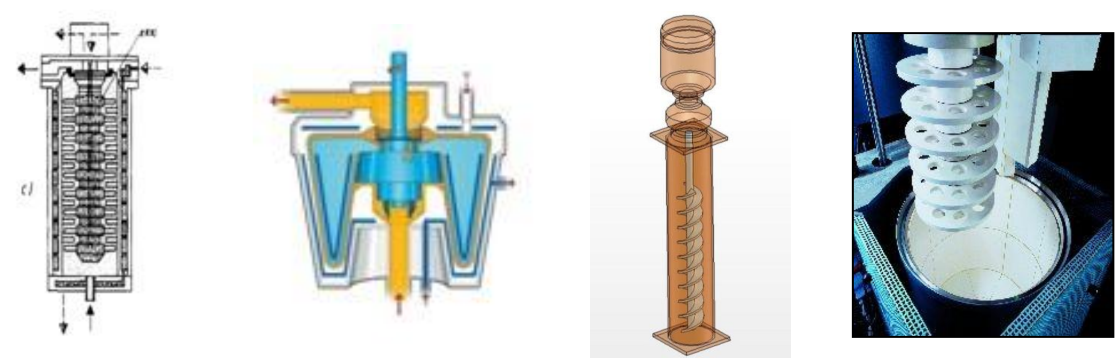
As a case in point, the VERTIMILL® grinding mill has been cited in a couple of papers (Nesset et al., 2006; Mazzinghy et al., 2012) as being some 35% to 40% more efficient than ball mills for fine grinding with the same ore and size distribution.

Despite these developments, the tumbling mills are continuing to be used in fine and ultrafine grinding applications. The main reason for this, as communicated at the Canadian Mineral Processors roundtable discussion in 2013, is that the comfort level in understanding stirred milling technologies is not at the level of that of tumbling mills.

The aim of this paper is to contribute to increasing the general comfort level with stirred milling technologies by developing a better understanding of how power and energy is affected by stirred mill impellor design and mill operation. This will be accomplished by first completing an overview of the power models found in the literature followed by a general description of DEM and CFD stirred mill models as well as the insights that can be drawn from them. Finally, a generic stirred mill power model will be presented and applied to different stirred mill types in order to develop some insights into the differences between different mill types. The paper will close with a discussion on some of the challenges that these models have and how future research might contribute to overcoming them.

BACKGROUND

Since the first stirred mills were introduced a number of stirred mill configurations have been introduced and commercialised mainly to the clays, pigments and pharmaceutical world. Some of these mills are illustrated in figure 1. Almost all of these stirred mills can be described as a concentric impellor of some geometry inside a circular or near circular chamber. The only exceptions noted are the MaxxMill series of mills (see fig. 1d) where the impellor is off-set from the center of the chamber in order to provide room for air sweep ducting.



a) counter pin mill (Stehr, 1988) *b) CoBall® annular gap mill (FrymaKoruna, 2013)* *c) screw agitated mill (Sinnott et al., 2006)* *d) MaxxMill® (Nessatti, Hessling, 2003)*

Figure 1 - Examples of different stirred milling technologies

The broader adoption of stirred milling technologies in the industrial mineral applications versus poly-metallic mineral processing for the mining industry has been driven by a number of reasons such as: greater need for finer grinding, product contamination limits leading to the use of inert grinding media, smaller capacity, batch operation and low availability and more stable processes as determined by feed material being consistent with respect to both mechanical and chemical properties.

In the context of the mining industry, smaller grain size and other mineralogical characteristics have motivated the need to grind finer which has motivated the evolution of industrial mineral stirred mills to be adapted to the poly-metallic mineral applications. To illustrate this point, the VERTIMILL® (fig 2a) was introduced to the mining industry some 35 years ago followed by the SMD (fig 2b) and the IsaMill™ (fig 2c) some 20 years later. The FLSmidth VXPmill™ (formerly the Deswik mill) (fig 2d) saw its inception into the mining industry some 5 years ago followed by the most recent entry from Outotec with the HigMill™ (fig 2e) joining the mining effort last year.

a) Metso VERTIMILL® Grinding Mill (VertiMill, 2013) | *b) Metso SMD (SMD, 2013)* | *c) IsaMill™ (IsaMill, 2013)* | *d) FLSmidth VXPmill™ (VXPmill, 2013)* | *e) Outotec HigMill™ (HigMill, 2013)*

Figure 2 Typical stirred mills found in the mining industry

It should be note that this evolution from industrial mineral to poly-metallic mineral applications was accomplished by considering not only mechanical design but also practical operational ranges, manufacture optimizations and limitation, and economic considerations. In many cases, stirred mills are simply scaled up by holding key variables constant and correlating operation performance between machines, power models and, where available, DEM simulation results. Additionally, stirred milling power draw is significantly affected by the mass of the media in the mill and the machines are designed with flexibility such that media can be added as required to achieve the desire mill power consumption.

OVERVIEW OF POWER MODELS

Predicting the performance of any of these mills starts with modelling power consumption and energy use. Jankovic (1998) completed quite a broad literature search finding a number of stirred mill power models which include empirical models (Novosad, 1964, 1965, Jenczewski, 1972, Herbst and Sepulveda, 1978, Duffy, 1994, Gao et al. 1996), adiminsional models (Weit and Schwedes, 1987) and mechanistic models (Tuzun, 1993) into which his own work fits.

It should be understood that all of these models have been developed using data sets related to the different mills tested. As a result, these models are valid, at the very least, for the mills and associate operating conditions tested. Having stated this, it is also important to understand that none of these models provide the precision needed to predict stirred mill power with confidence in the scale of mills currently being designed and manufactured.

Table 1 illustrates the different variables used in many of these models. The only commonality between these models is the use of impellor speed as one of the model variables. Mill diameter is also shared by most models, but not all. This is followed by either media depth (or volume) and slurry density. Only Jankovic's model uses 14 of the 18 variables listed in Table 1.

On the other hand, operational experience of the Vertimill has shown that a number of other variables not included in these models affect power draw. These missing variables may explain why outside of the mills and conditions tested, these models lack the precision needed for the scale of mill currently being manufactured and developed. Missing variables include media size distribution, media shape, particle size, rock density, media wear, impellor wear, liner wear and gravity. To complete the list one can also add variables describing mill shape, number of pins and disks and thickness of disks.

Table 1 – Variable Used in Published Stirred Mill Power Models

	Novosad (1964, 1965)	Jenczewski (1972)	Herbst, Sepulveda (1978)	Weit, Schwedes (1987)	Tuzun (1993)	Duffy (1994)	Gao (1996)	Jankovic (1999)
Impellor speed	x	x	x	x	x	x	x	x
Mill diameter	x	x	x	x	x			x
Slurry density	x			x	x		x	x
Media depth	x		x		x	x		x
Impellor diameter	x	x				x		x
Charge density	x				x	x		x
Media density			x				x	x
Media top size			x			x		x
Shaft diameter	x			x				x
Number of screw Helixes						x		x
Friction								x
Media Mass		x						x
Screw pitch								x
Length of impellor				x				
Screw thickness								x
Thickness of pins	x							
Viscosity				x				
Disperant							x	

STIRRED MILL DEM SIMULATIONS

The advent of the discrete element method (DEM) and its introduction to the modelling of mineral processes opened the door to exploring in yet greater detail the dynamics of these systems. This has been successfully demonstrated through modelling of SAG mill charge motion (fig. 3), liner wear (fig. 4) and crusher dynamics (fig. 5). Further, the introduction of computation fluid dynamics (CFD) as well spherical particle hydrodynamics (SPH) led to the modelling of flotation cell behaviour (fig 6).

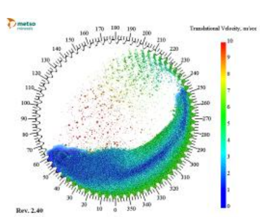


Figure 3 - SAG mill DEM/CFD simulation (*Herbst, 2004*)

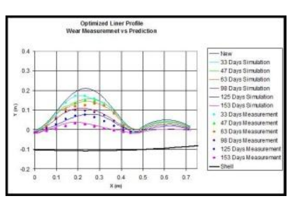


Figure 4-Liner wear DEM simulation (*TD, 2013*)

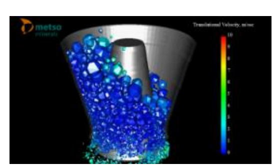


Figure 5 - Crusher DEM simulation (*Murariu, Jacobson,2013*)

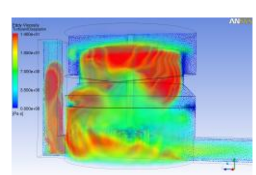


Figure 6 - CFD simulation of flotation cell (*RCS 300, 2012*)

In the context of fine and ultrafine grinding applications, the use of DEM, CFD and SPH to model stirred mill dynamics holds the promise of determining how all possible variables affect the design and performance of different stirred milling technologies. In the case of the VertiMill and SMD mill (see figure 7 and 8), DEM/CFD/SPH models aim to predict power consumption, mill wear (auger and liner), optimise auger geometry and predict overall grinding performance.

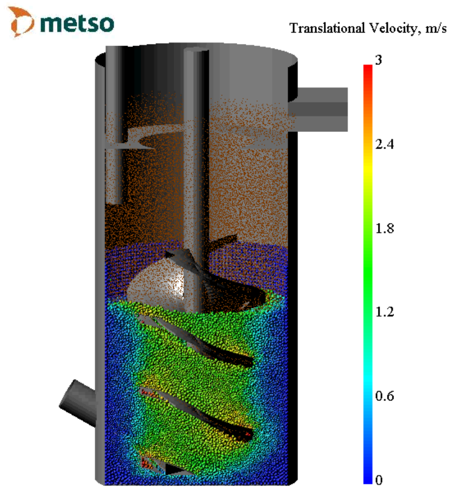


Figure 7 - Typical VertiMill DEM simulation

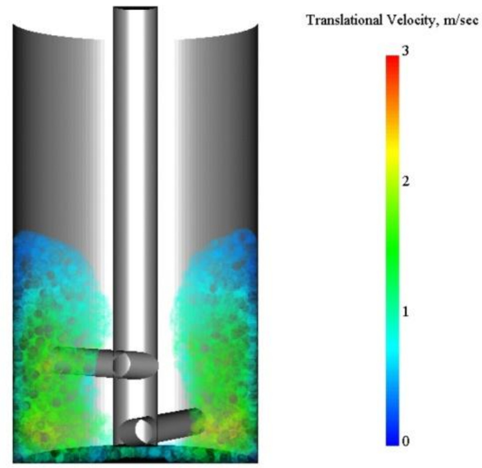
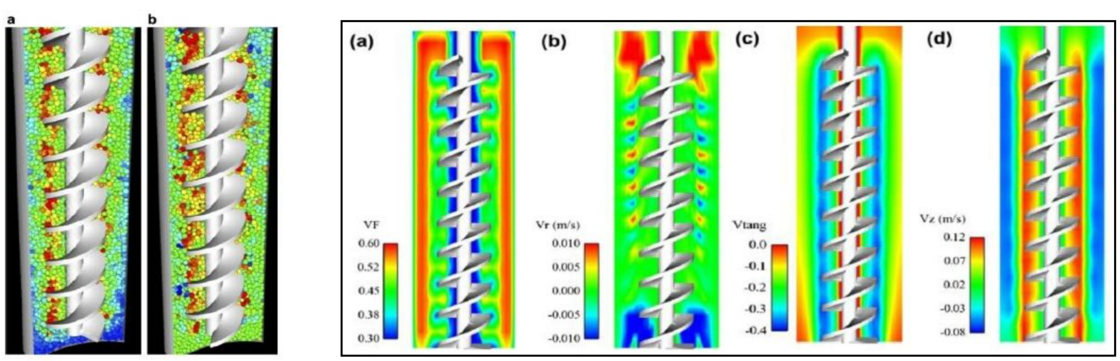


Figure 8 - Lab scale SMD mill SPH simulation

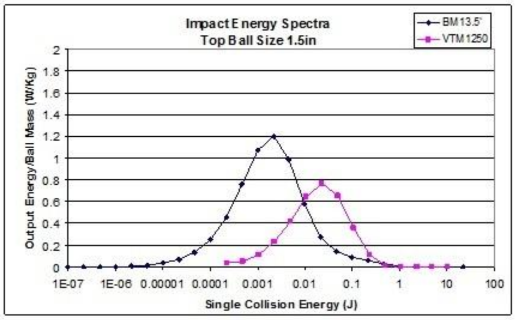
Similar type studies are being completed by other groups such as the work of Sinnot et al. (2006) (see fig 9). In figure 9a, one can see how the particles having the greatest kinetic energy (red particles) are found at the auger tip or edge which is similar to what is illustrated in the VertiMill simulation (figure 7). Further CFD simulations provide insights into the slurry movement as illustrated in Figure 9b. Particularly, figure 9b-c illustrates how the maximum tangential velocity is found the auger tip or edge while in figure 9b-d shows how the vertical flow changes from a vertical movement around the auger edge and a downward movement at the mill chamber walls.



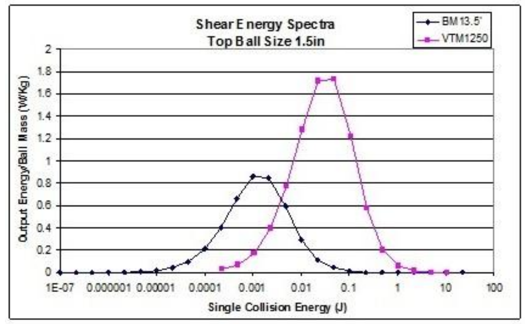
a) DEM simulation results *b) CFD simulation results*

Figure 9 - Screw agitated mill mill DEM and CFD simulation results (Sinnott et al., 2006)

By using these models, it is possible to investigate different dimensions to stirred mill performance such as understanding what drives the increased efficiency of a stirred mill such as the VertiMill as compared to a ball mill. Figure 10 sheds some light onto this question by comparing impact and shear energy spectra for a typical ball mill and a VertiMill of similar power. Essentially what is seen is the impact energy spectrum for the ball mill is greater than that for the VertiMill indicating that much more energy is dissipated in impact type events in the ball mill than in a VertiMill. However, with respect to the shear energy spectrum, the VertiMill illustrates much more energy being found in shear type events than what is found in a ball mill. This difference of how the energy is use or rather distributed between impact and shearing events in a ball mill versus a VertiMill might be one of the reasons for the differences in grinding efficiency reported in the literature (Nesset et al., 2006; Mazzinghy et al., 2012).



a) comparing ball mill and VertiMill impact energy spectra



b) comparing ball and VertiMill shear energy spectra

Figure 10 - VertiMill and Ball energy spectra

SHEAR BASED STIRRED MILL POWER MODEL

The greatest benefit of modelling stirred mills using DEM/CFD/SPH techniques is undoubtedly the degree to which a mill can be modelled. However, this benefit comes at a cost which is essentially related to the computing capacity required to run simulations using these models. As a result, it is this cost that might be one of the factors that can be considered as a hindrance to developing a general “comfort level” with the implementation and use of stirred mills in the mining industry. In order to address this “hindrance” to an increased “comfort level” with stirred mill technologies, it is justified to take a step back from the use of DEM/CFD/SPH models and revisit the development of a mechanistic stirred mill power model.

One avenue to addressing this starts by extrapolating from the insight developed from DEM simulations which indicates that shear plays a more important role than impact in stirred milling. Essentially, one could start by making the assumption that shear is the predominant if not only mechanism that determines stirred mill power consumption (Radziszewski, 2013).

As a result of this assumption, one can look to reducing all stirred milling technologies, with the exception of the MaxxMill, to a shaft spinning inside a concentric cylinder. If one accepts this simplistic description then one can make the assumption that a concentric viscometer is an adequate representation of a stirred mill (fig. 11) independent of impellor design. Assuming this analogy to be adequate, one can then propose that the shear stress (τ) experienced by the turning surface is a function of the viscosity (μ) of a fluid found between these two cylinders, the speed of the sliding surface ($u = \omega r$) and the gap (y) distance between these two surfaces:

$$\tau = \mu \frac{u}{y} = \mu \frac{\omega r}{y} \tag{1}$$

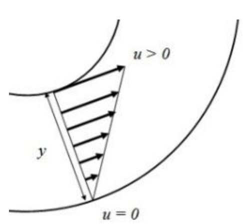


Figure 11 - Shear between concentric cylinders

Knowing the shear stress experienced by the rotating surface, it then becomes possible to determine the torque acting on this cylinder ($T = \tau A r$) and more importantly the power consumed in rotating the cylinder at a given speed. Putting all components together and rearranging, the power consumed by a smaller diameter concentric cylinder can be described by the fluid viscosity, the square of the rotation angular speed and a term coined the "shear volume" (V_τ) which is an agglomeration of all of the previous physical parameters describing all the shear surface pairs created between an impellor and the mill chamber as follows:

$$P_\tau = T\omega = \mu\,\omega^2 A\,\frac{r^2}{y} = \mu\,\omega^2 V_\tau \qquad (2)$$

Confidence in the use of this viscometer stirred mill analogy to describe all concentric type stirred mills can be only determined by applying it to different stirred mills and comparing the predicted power results with that observed. This requires that a viscosity model be determined through a power calibration. This was made possible by using the data set produced by Gao et al. (1996) along with the model described in equation (2) leading to the following viscosity equation:

$$\mu_{est} = k\left(a\omega^{-b}\right)\left(\frac{D_b}{D_{b\,ref}}\right)^c\left(\frac{\rho_m}{\rho_{m\,ref}}\right)^d\left(\frac{\rho_{sl}}{\rho_{sl\,ref}}\right)^e\left(\frac{100-x}{100}\right)^f [\mathrm{Ns/m^2}] \qquad (3)$$

- k: correction factor
- $a\omega^{-b}$: viscosity trend line relationship with rotation speed
- $D_b / D_{b\,ref}$: media diameter correction with respect to a reference media diameter
- $\rho_m / \rho_{m\,ref}$: media density correction with respect to a reference media density
- $\rho_{sl} / \rho_{sl\,ref}$: slurry density correction with respect to a reference slurry density
- $(100-x)/100$: dispersant correction

With the appropriate reference values, constants and exponents (Radziszewski, 2013), it is then possible to apply this relationship to predict the power for Gao's horizontal mill, a Sala pin mill and a screw agitated mill as illustrated in figure 12. It should be noticed that this is a relatively good fit considering the generality of the model structure.

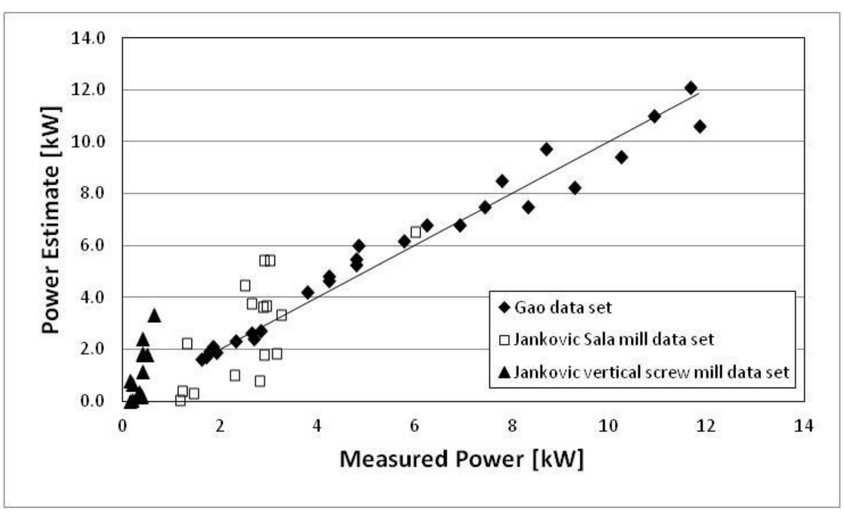


Figure 12 - Stirred mill power comparison

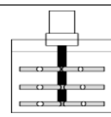
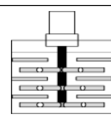
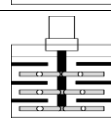
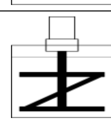
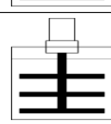
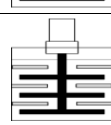
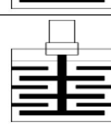
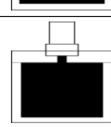
These results, despite the scatter for the Sala mill and the vertical screw mill, illustrate that a shear based model seems to describe quite adequately the power consumption across a range of stirred mills. As a result, it is possible to explore the effect of the stirred mill design space (Radziszewski, 2013) on power consumption using a 1m diameter by 1 m high chamber. For this comparison viscosity is assumed to be the same for all constant speed cases. The results of this comparison is found in Table 2 where the shear volume for different impellor configurations as well as the expect power consumption for low, medium and high speed applications is presented.

Examining this table leads to a few observations for this 1m x 1m mill context:

(i) The pin impellor has the lowest shear volume while the drum has the highest.
(ii) Pin impellor shear volume can be increased by added pins or disks to the chamber wall.
(iii) The auger (single pitch) has three times less shear volume than a 3 disk impellor.
(iv) A disk impellor shear space can be increased by adding pins or disks to the chamber wall.

Lower shear volume can be compensated by higher impellor rotation speeds. So a pin mill having a lower shear volume than an auger can actually have a higher grinding intensity than the auger mill which turns as a lower rotational speed.

Table 2 - Stirred Mill Shear Volume and Power Estimates

Mill Type	Dimensions	Sketch	Shear Volume [m^3]	Shear Power Low Speed (100 rpm) [kW]	Shear Power Med. Speed (500 rpm) [kW]	Shear Power High Speed (1000 rpm) [kW]
3 x 6 Pin Impellor	pin length: 0.4m; pin dia.: 0.1m; shaft dia.: 0.2m		0.114	0.37	0.367	0.989
Pin on Pin	same as 3 x 6 pin impellor plus liner pin length: 0.3 m; thickness: 0.1m		0.150	0.048	0.483	1.301
Pin on Disk	same as 3 x 6 pin impellor plus liner disk inside dia.: 0.4 m; thickness: 0.1m		0.355	0.115	1.143	3.078
Auger	auger dia.: 0.8m; no. of turns: 1		0.466	0.151	1.502	4.044
3 Disk Impellor	disk dia.: 0.8m; disk thickness: 0.1m; shaft dia.: 0.2m		1.618	0.523	5.213	14.037
Disk on Pin	same as 3 disk impellor plus liner pin length: 0.3 m; thickness: 0.1m		2.079	0.672	6.699	18.038
Disk on Disk	same as 3 disk impellor plus liner disk inside dia.: 0.4 m; thickness: 0.1m		2.503	0.809	8.066	21.720
Drum	dia: 0.8m; length.: 0.9m		4.021	1.299	12.957	34.888

Although these results are quite interesting from a comparison point of view, the contribution to a general "comfort level" can really only be accomplished by investigating the use of this shear based model with industrial scale mills.

Therefore, applying this model to Metso's VertiMill database with some adjustments led to the comparison illustrated in figure 13. Further, this model with some adjustments can be used to predict mill power as a function of mill filling as illustrated in figure 14. Although the comparison between predicted and measured is not perfect, the model does show that it quite adequately predicts mill power for the VertiMill.

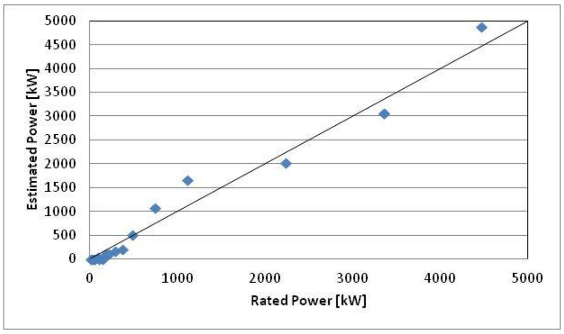


Figure 13 - Comparison between rated and estimated power for various VertiMill sizes

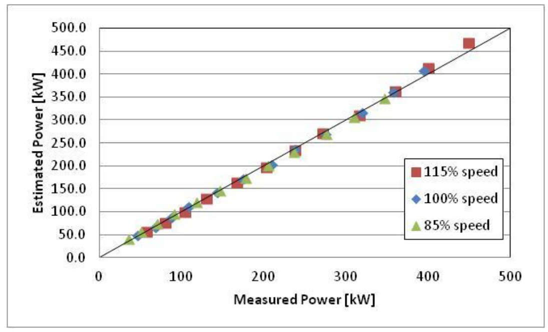


Figure 14 - Comparison between measured and estimated power for a pilot scale VertiMill

DISCUSSION

Starting with stirred mill power models found in the literature, evolving to DEM/CFD/SPH models of the stirred mill and then back to the development of a mechanistic shear based model, the number of variables included in power modelling has evolved somewhat from that presented in Table 1. Illustrated in Table 3, there are 30 variables listed with DEM/CFD/SPH models having the potential to simulate the effects of all of them on stirred mill power. The shear based power model currently uses some 23 variables of the 30 indicated.

Is this sufficient to simulate a stirred mill for design?

Maybe and maybe not.

Maybe, because this shear based model is indeed a function of a large number of design and operating parameters and allows a rather quick indication of how different design parameters affect power consumption.

Maybe not, because many more parameters along with impact type events are not included and those that are included namely viscosity have a very important effect on mill power. The precision required for design probably will not be adequate as compared with DEM/CFD/SPH predictions. Further research is required especially with respect to the effect of viscosity, wear and ore breakage on power.

It should be noted that some of this research is undergoing in collaboration with the JKMRC which is completing a number of industrial surveys as well as the testing of a new Metso stirred mill lab testing apparatus and methodology.

Table 3 – Expanded Variables Used in Stirred Mill Power Models

	Novosad (1964, 1965)	Jenczewski (1972)	Herbst, Sepulveda (1978)	Weit, Schwedes (1987)	Tuzun (1993)	Duffy (1994)	Gao (1996)	Jankovic (1999)	DEM & CFD	Shear based model
Impellor speed	x	x	x	x	x	x	x	x	x	x
Mill diameter	x	x	x	x	x			x	x	x
Slurry density	x			x	x		x	x	x	x
Media depth	x		x		x	x		x	x	x
Impellor diameter	x	x				x		x	x	x
Charge density	x				x	x		x	x	x
Media density			x				x	x	x	x
Media top size			x			x		x	x	x
Shaft diameter	x			x				x	x	x
Number of screw Helixes						x		x	x	x
Friction								x	x	
Media Mass		x						x	x	x
Screw pitch								x	x	x
Length of impellor				x					x	x
Screw thickness								x	x	x
Thickness of pins	x								x	x
Viscosity				x					x	x
Disperant							x		x	x
Mill shape									x	x
Number of pins									x	x
Number of disks									x	x
Thickness of disks									x	x
Media size distribution									x	
Media shape									x	
Particle size									x	
Rock density									x	x
Media wear									x	
Impellor wear									x	
Liner wear									x	
Gravity									x	x

CONCLUSION

Stirred mill technologies being used in the mining industry have evolved from the ones developed for the industrial minerals industry. Power models developed to support this evolution have evolved from empirical models, adimensional models, mechanistic models to DEM/CFD/SPH models of different stirred mills.

Insights developed along the way include the following:

(i) Although stirred mills are in many cases simply scaled-up by holding key variables constant and correlating operation performance between machines, power models and, where available, DEM simulation results, stirred mills are typically designed with flexibility such that media can be added as required to achieve the desire mill power consumption.

(ii) Empirical, adimensional and mechanistic stirred mill power models developed over time are limited in number of variables used which reduce their applicability to predict power in industrial scale mills being designed and developed today.

(iii) DEM/CFD/SPH models of stirred mills hold the potential to simulate the effects of all possible variables affecting mill design and performance.

(iv) DEM simulation results indicate that the difference in impact and shear energy spectra of ball mills as compared to VertiMill may explain the increased efficiency of VertiMill over ball mills.

(v) The cost of DEM/CFD/SPH models may be a hindrance to developing an increased "comfort level" in the implementation and use of stirred milling technologies in the mining industry.

(vi) The development of a simplified shear based stirred mill power model holds the potential to simulate the effects of an increased number of stirred mill variables.
(vii) Initial results for both lab and industrial scale mills indicate that a shear based stirred mill power model predicts mill power quite well for the cases simulated.

It is currently unclear as to the value of this shear based model for stirred mill design purposes especially as compared with the completeness of DEM/CFD/SPH modelling of stirred mills. More research is required and is undergoing.

However, in the context of meeting this paper's objective to "contribute to increasing the general comfort level with stirred milling technologies by developing a better understanding of how power and energy is affected by stirred mill impellor design and mill operation", the use of the shear based stirred mill power model may indeed be warranted.

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