Investigation of High Speed Cone Crushing Using Laboratory Scale Experiments and DEM

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Abstract. Cone crushers are commonly used in secondary and tertiary crushing stages in comminution circuits. A multitude of factors and variables influence the performance in terms of throughput capacity, size reduction, power draw and wear. Crushers are normally installed and operated at a fixed eccentric speed setting. By installing variable frequency drives and real-time optimization algorithms Hulthén and Evertsson have shown that the eccentric speed can be used as a variable to optimize the yield and improve the performance. However, the influence of eccentric speeds above the normal operational range has been scarcely reported on in the literature.

This paper aims at reporting on the result from an exploratory study where experiments and simulations have been used to evaluate cone crusher operation at high eccentric speed levels ranging from 10-40 Hz. A laboratory Morgårdshammar cone crusher has been refurbished for the purpose of the study. A preliminary set of experiments have been performed where results showed that the chamber geometry has a vital importance. The same behaviour as observed in the experiments was also further understood by using DEM simulations leading to the design of a new chamber geometry.

The new chamber design have been evaluated using DEM at four eccentric speeds and two different close side settings. The rock model has been calibrated by single particle breakage experiments and is based on the bonded particle model. The product particle size distribution has been estimated by image analysis of the bonded cluster discharge. The work addresses and shows results relevant to three areas in comminution and engineering research; Simulation driven design, DEM modelling, Cone crusher theory.

Keywords: Cone Crusher, Eccentric speed, DEM, BPM, Simulation, Validation

INTRODUCTION

Cone crushers are typically used in secondary and tertiary comminution stages in minerals processing plants. These crushing stages are normally feeding a milling and grinding circuit consisting of tumbling mills and sometimes other units such as HPGRs and tower mills. The tertiary stage cone crusher product size distribution may typically have a P_{80} ranging between 10-30 mm depending on the circuit design. However, other than the HPGR, compressive comminution units are rarely used to produce finer product size distribution with a P_{80} of less than 10-15 mm.

Slow compressive breakage of individual rock particles, so called single particle breakage (SPB), have been found to be the most energy efficiency mode of breakage (Schönert, 1972). It should therefore be of interest to utilize this mode of breakage as far as possible within the constraints of the machine, circuit and material characteristics.

In a cone crusher the feed material is compressed between the walls of the mantle and concave. The mantle is eccentrically displaced allowing for a nutating motion with an amplitude corresponding to the eccentric throw. The smallest distance between the mantle and concave, termed the Close Side Setting (CSS), is controlled by vertical displacement between the mantle and concave. The CSS determines the maximum size of the particles that can leave the crusher chamber, under the condition that the material is actually compressed and crushed in the CSS region of the chamber. The number of compressions, or breakage zones, is controlled by the eccentric speed of the nutation (Evertsson, 1999).

The performance is hence governed by the chamber design, eccentric throw, CSS and eccentric speed. Hulthén (2010) has developed and implemented real time optimization algorithms that maximize the product yield by finding the optimum operating point of CSS and eccentric speed. Even though the eccentric speed has been used as an optimization variable and its effects on performance have been evaluated previously (Evertsson, 2000), these studies have been made in the normal operating range of 300-600 rpm (5-10 Hz).

In this paper the performance of a laboratory scale cone crusher is investigated at a considerable increase in eccentric speed. This has not been thoroughly evaluated previously in the literature apart from a study performed by Jacobson and Lamminmaki (2013).

Both laboratory experiments and DEM simulations have been used in the research and development process. A secondary objective of the study is show how DEM can be used as an engineering and research tool for investigating a design concept, and in this process, also show how laboratory experiments are used to validate the simulation outcome. The DEM modelling of the cone crusher is based on work by Quist (2015).

Discrete Element Method

The discrete element method, originally proposed by Cundall and Strack (1979), is a numerical approach for simulating particulate matter. A review of how DEM have contributed in the field of comminution research have been completed by Weerasekara et al. (2013). Previous attempts of modelling the cone crusher have been reported by (Cleary and Sinnott, 2015; Delaney et al., 2015; Lichter et al., 2009; Quist, 2015; Quist, 2012). The modelling of a cone crusher and the rock material is complex due to the difficulty of balancing the computational load and the simulation objective. In order to retrieve any valuable results a minimum batch size of feed particles is needed. The optimum model would facilitate simulation of a full scale cone crusher in continuous steady state conditions with particle sizes ranging all the way down to the mineral grain size of the rock particles. At the moment the computational capacity of desktop computers does not facilitate such simulations. The main limitation lies in the total number of particles in the simulation hence this needs to be limited by different means in order to arrive at a feasible solution with computational times which are acceptable.

Several authors have chosen to model the rock particles using the population balance particle replacement model due to the superior computational economy compared to using the bonded particle model. In the population balance replacement model a particle gets replaced by a set of daughter fragment when the particle experience a load greater than an attributed stress constraint. This method have successfully been used by e.g. Cleary (2015) and Lichter (2009).

The disadvantages with the replacement model is that the breakage sequence of a particle is non-continuous in terms of progeny particle kinematics and that only one loading condition is allowed as a failure criteria.

Bonded Particle Model

In this work the bonded particle model (BPM) is used for modelling the rock material (Potyondy and Cundall, 2004). Two different geometrical rock shapes are used that are based on 3D scanning of real rock particles. The shapes are filled with spherical particles with a bi-modal size distribution in order to achieve a high packing density. The spheres, called fraction particles, are bonded together creating a complex network of artificial bonds that are allowed to break independently.

The strength and stiffness micro parameters of the bonds can be manipulated in order to attain the macro properties of the rock material. The BPM model allows for a continuous particle flow route and sequential breakage due to any type of loading condition the particle may be subjected to. The BPM model has been used successfully for modelling compressive crushers (Quist, 2015; Quist, 2010, 2011, 2012) and impact crushers(Schubert and Jeschke, 2005).

Background

In order to investigate the principles of cone crusher operation at higher eccentric speeds a laboratory experimental set up with a crusher, feeder and measurement systems was developed (Johansson, 2015). The crusher was equipped with a frequency drive, online mass flow scale sensor and power draw measurement. A LabVIEW interface was developed in order to control the experiments and facilitate data acquisition. In a first set of surveys the laboratory crusher was operated at high eccentric speeds. The mass flow, power draw and product particle size distribution were investigated at different speed levels. The results showed some improvement in terms of finer particle size distribution, however the results on mass flow rate and power draw was difficult to interpret and relate to established theories. After further tests it was found that the idling power increased dramatically with increased speeds due to issues with the roller bearing assembly design. Further on the results indicated that the chamber design was not suitable for the objective of crushing at high speeds.

To further investigate and gain understanding of the phenomena accruing in the crushing chamber a DEM model was developed. Only a few particles were simulated to decrease the simulation time to a minimum, however the results showed clearly that the particles were prevented to enter the CSS-zone. The liner design can be seen in Figure 1a. The original mantle has a distinct parallel crushing zone in the low end of the chamber. Before this zone a shelf is formed with a nipping angle before the entrance of the CSS zone that is roughly doubled relative to the rest of the chamber. The large nipping angle has a considerable effect for the crusher performance, as the particles are restricted and tend roll and tumble in this pocket area instead of getting crushed. This phenomena could clearly be seen in the first set of DEM simulations.

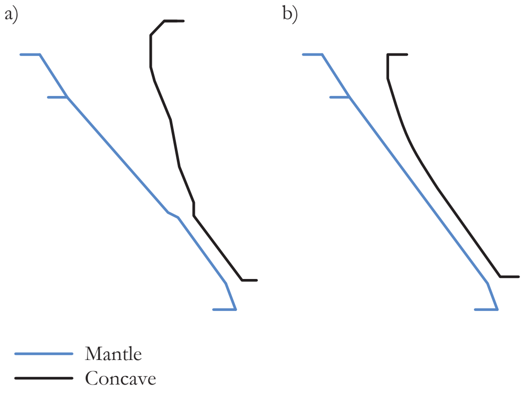

FIGURE 1. Schematic illustration of liner profiles. a) Original liner design. b) New liner design evaluated in this study.

To eliminate the above described problem a new liner design was designed, see Figure 1b. The governing constraining requirements in the design process were: geometrical constraints of the crusher, intended feed size, choke level position which is indirectly controlled by the cross sectional area and the wish to use the full height of the chamber for crushing. In a development perspective the new chamber design can be regarded as a second iteration or prototype.

METHOD

Research Approach

The research is based on an explorative approach trying to evaluate and improve the high speed operation of the laboratory cone crusher. The work is performed in an iterative manner using DEM for identifying and addressing problems which causes and effects are not observable or measurable in the laboratory environment. Solutions and concepts are tested in the simulation environment before parts are sent to manufacturing. The methodology of using DEM in product development is further described by Quist (2015). The approach applied in this study leads to research outcome in three domains; Engineering design methodology, Cone crusher theory and DEM modelling methodology.

Experimental Setup

In Figure 2 the laboratory crusher, Morgårdshammar B90 is shown. Based on drawings and measurements a CAD model was developed which was used in the DEM simulations. The crusher is mounted in a welded frame and the motor is placed in an upright position with the drive shaft downwards. The rig is equipped with an AC- drive and a mass flow instrument all integrated via a graphical interface. The main data which are sampled are: Mass flow, power draw and eccentric speed. The material is fed into the crusher using a vibrating feeder which is placed directly above the crusher.

FIGURE 2. Image of the Morgårdshammar B90 laboratory cone crusher

Material

The material used in the laboratory experiments is a granite rock type from Kållered, Sweden. Characterization of material parameters for this material has previously been done by Quist (2012). The BPM has been calibrated against single particle breakage laboratory experiments. A cylinder is formed with the same packing properties the calibration is performed based on the Brazilian tensile stress test (ASTM, 2008). The properties of stiffness and stress have evaluated using a design of experiments approach where the outcome of a set of simulations are used to minimize the deviation between simulated and experimental strength results. The strength and stiffness parameters can be seen in TABLE 1.

Simulation Plan

The simulation plan consist of 8 simulations with two levels of CSS and four speed levels.

The computational time for a DEM simulation is governed by several factors. In this case the most influential factor is the total number of particles in the simulation. In order to facilitate a feed batch size with a reasonable amount of meta-particles the decision was made to model a 50 degree section of the crusher. The section is created by placing vertical geometry planes limiting the flow of particles in the horizontal direction. The sectioning inevitably leads to some unwanted boundary effects as particles interacts with these walls.

The meta-particles are allowed to settle above the crushing chamber on a temporary plane. When all meta-particles have settled the plane is removed and the particles report as a batch to the crushing chamber resulting in near choke feeding condition.

TABLE 1. Properties used for the BPM model

Parameter:	Value	Unit
Normal stiffness per area	$1.67 \cdot 10^{12}$	N/m^3
Shear stiffness per area	$6.70 \cdot 10^{11}$	N/m^3
Normal bond strength	$3.60 \cdot 10^{7}$	Pa
Shear bond strength	$2.40 \cdot 10^{7}$	Pa
Fraction nominal radius	1.0	mm
Fraction contact radius	1.15	mm
Total number of particles	16540	-
Number of meta-particles	40	-
Total CPU hours	684	CPUh

Post Processing

The discharge mass flow rate, pressure and power draw data have been exported and processed in order to calculate data series average and standard deviations. A set of images are recorded from the discharge region in order to capture the surviving bonded clusters.

The discharge bonded cluster images are further used to estimate the product particle size distribution by image processing in MATLAB. The same type of image analysis algorithms as in optical particle size analysis equipment are applied. The major and minor axis lengths are further used to calculate a fictive ellipsoid volume and particle mass. Each identified particle is then classified and its mass attributed to a specific size class based on the minor axis length. This means that the particle size distribution presented should be regarded as a relative distribution used for comparison as the model is incapable of estimating the unknown particle size distribution of the fines below the fraction particle size.

Since a section of the crusher has been modeled the mass flow, power draw and pressure data series are characterized by peaks with the same frequency as the eccentric speed. As an estimation of the mass flow rate the maximum peak mass flow has been used from each simulation. In the case of the power draw and pressure, enough data was available in the series to record the peak value of each compression. These peak values are further on used to calculate the peak average value and the variance.

SIMULATION RESULTS

The results from the simulations can be reviewed both in terms of the output parameters from the post-processing, but also in regards of the qualitative observations from the simulation animations. These observations include aspects such as particle flow characteristics and breakage event dynamics. In FIGURE 5 images of the breakage process at the same time event are presented. When comparing the breakage of particles for 1 and 3 mm CSS and 10 Hz speed it is clear that the opening of the chamber results in more particles surviving in the 3 mm case. For the 1 mm series it can be seen that no meta-particle clusters survive the breakage process except for a few ones in the 10 Hz case. This also means that it is not possible to extract any data regarding the cluster product size distribution.

There are two main observational findings from simulations. The first is that for 30 and 40 Hz the particles are excited by the mantle very frequently resulting in a bouncing behavior and a lower mass flow rate. The bouncing behavior would most probably be suppressed to some degree if simulating a larger batch of material under choke feed conditions. The second observation is that the lack of compensation for mantle rolling in the geometry dynamics results in an unwanted boundary effect. This can be seen at higher frequencies as particles tends to report to the right boundary wall. This issue can be regarded as a pure modelling inaccuracy and can be suppressed by correcting the mantle geometry dynamics.

The mass flow rate is presented in FIGURE 3. The flow rate is progressively reduced as the speed increases as previously elaborated on. The change in CSS causes a shift in choke level position leading to a relatively constant deviation between the two series.

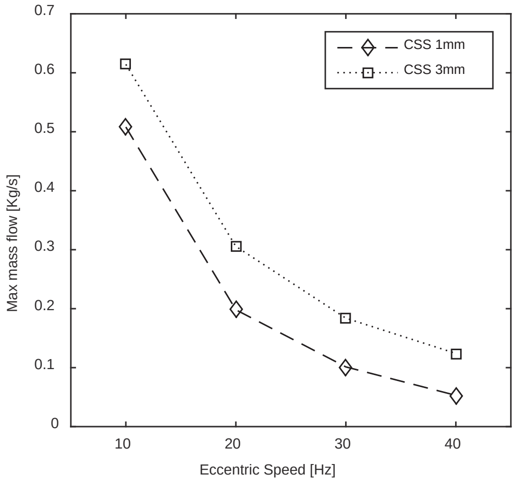

FIGURE 3. Simulated mass flow rate for the eight cases

The estimated power draw is shown in FIGURE 4. The 3 mm series show a 44% reduction between 10 and 40 Hz. In the 1 mm case the trend follows an opposite pattern with a 285% increase from 10 to 40 Hz. The reason to this difference is not fully understood. However, when reviewing the data it was found that the maximum fraction particle size was 15% larger than the CSS. This leads to incorrect compression interactions with false force and torque data contributing to the overall result.

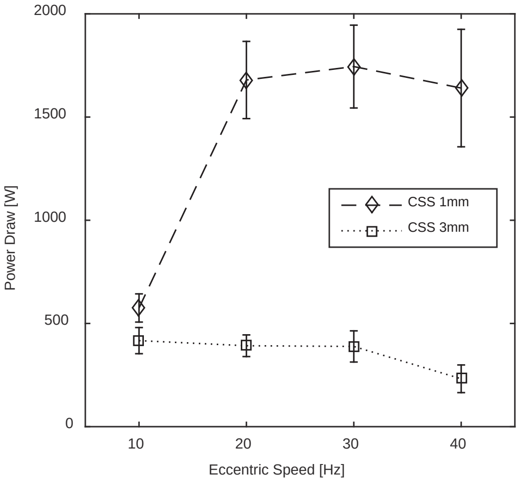

FIGURE 4. Simulated average peak power draw. The error bars corresponds to one symmetrical estimated standard deviation.

In FIGURE 6 the estimated pressure on the mantle is plotted. The 1 mm CSS series displays a significant increase in pressure compared to the 3 mm case. In both cases the pressure drops with increased eccentric speed.

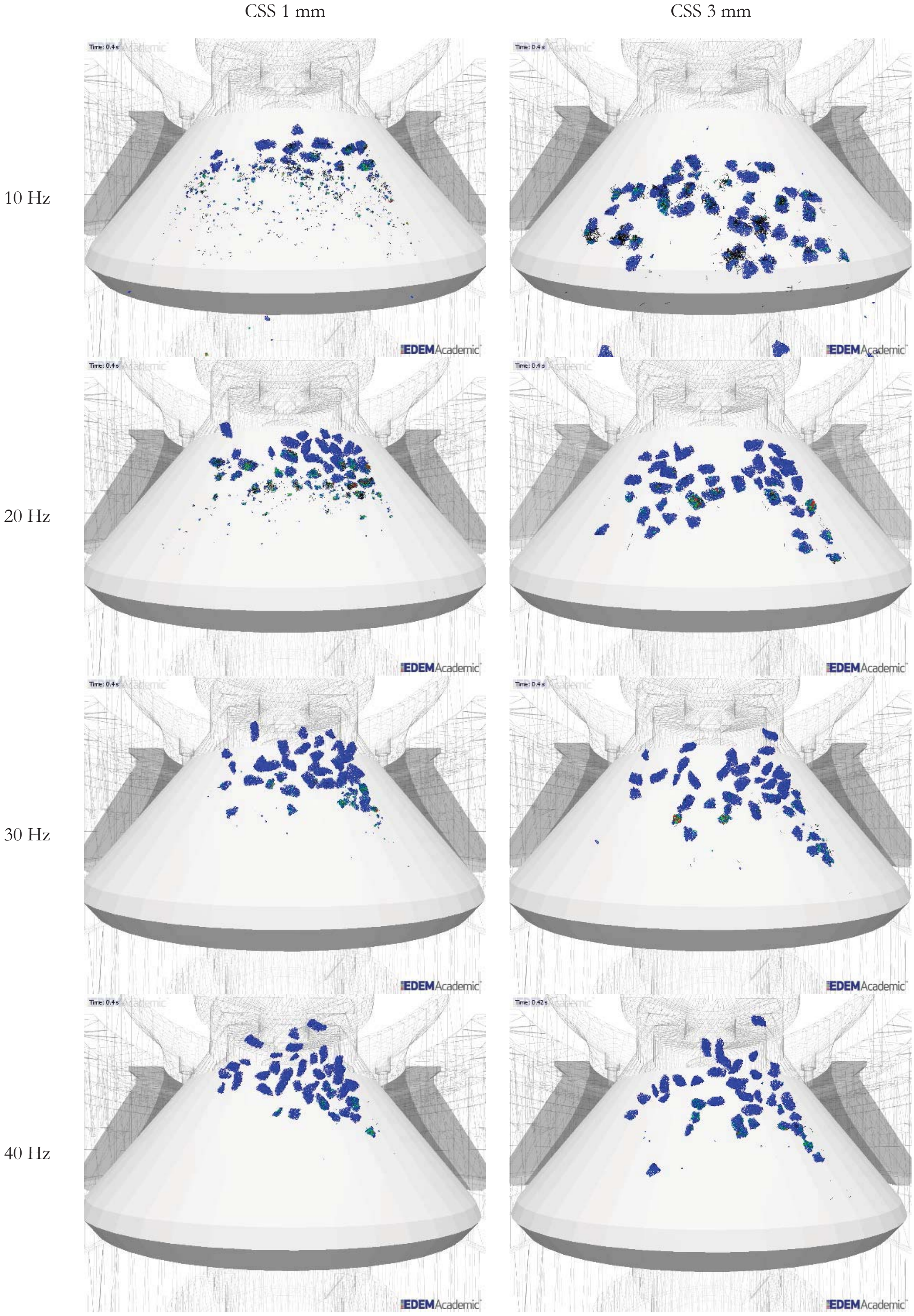

FIGURE 5. Images from the simulation series at 0.4 s with meta-particles represented as intact bonds.

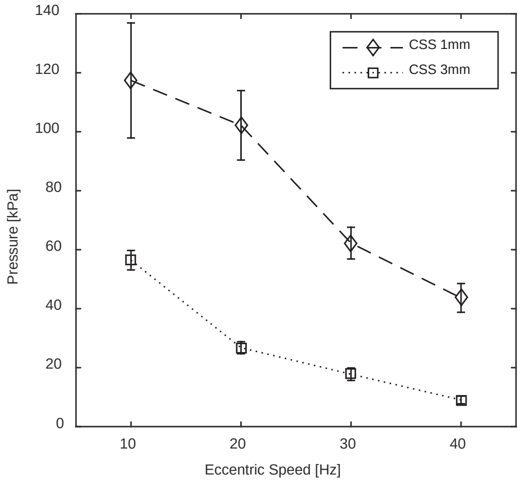

FIGURE 6. Simulated total average peak pressure on the mantle. The error bars corresponds to one symmetrical estimated standard deviation.

IN FIGURE 7 the product cluster size distributions for the 3 mm CSS series are plotted. For the 10 Hz simulation there is enough time between compression events for some particles to fall though the chamber almost undamaged, see FIGURE 5. When the eccentric speed is increased the size distributions becomes similar. It should be noted again that the size distribution presented is the surviving cluster sizes, hence it is limited by the fraction particle size distribution. In order to evaluate what happens below this size limit the fraction size distribution needs to be reduced further.

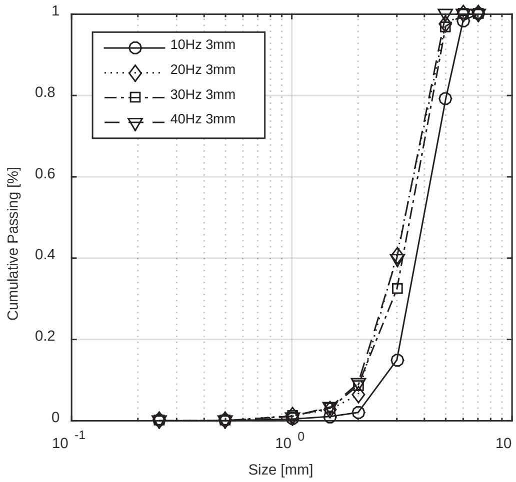

FIGURE 7. Particle size distribution for simulations CSS 3 mm and four speed levels.

In FIGURE 8 the size distribution for the 10 Hz 1 mm and 3 mm cases are compared. The 1 mm case displays a good correspondence in terms of matching the CSS at around P_{70}.

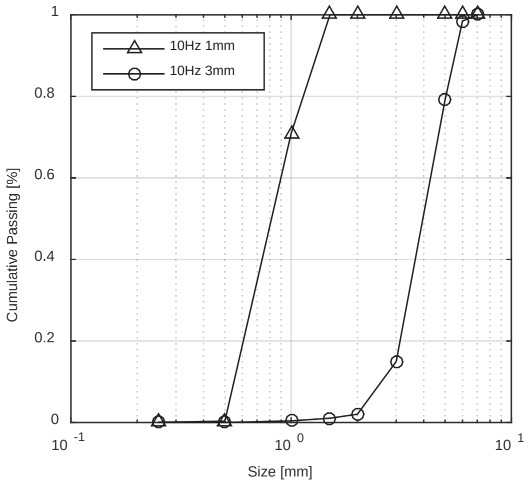

FIGURE 8. Comparison of the product particle size distribution for 10 Hz eccentric speed and two levels of CSS.

The calculated specific energy is displayed in FIGURE 9. The 1 mm series displays a dramatically increasing pattern. It is believed that this is an effect of the poor mass flow due to non-choked conditions and the near CSS size fraction particle problem causing false tangential forces on the mantle, hence potentially an overprediction of the power draw.

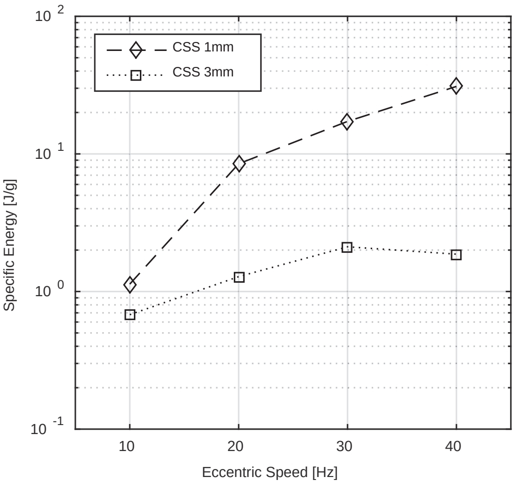

FIGURE 9. Specific energy calculation based on total mass flow rate and predicted average peak power draw

DISCUSSION

The pressure and power draw data series for 1 mm CSS shows an opposite trend in terms of the estimated standard deviation. This needs to be investigated further since there is no apparent reason found. The results suggests that the sectioning boundary walls are influencing the results due to the lack of mantle slip kinematics. The false effect is increasing with increased speed as the particles are subjected to a higher number of breakage events and hence a false tangential force.

In general, design and validation of the functionality of a new design concept can be done either by using physical experiment or virtual experiments. This case emulates a potential situation at R&D departments as they develop novel comminution machines or improvements. In many cases the decision of engaging in physical testing is associated with high risk and costs, which leads to the objective of the simulation study reported in this paper.

In general the particle size distributions fineness depend on CSS and in this case it could especially be seen for the CSS 1mm runs where the clusters are broken down to its smallest building blocks. It would be preferable to simulate with smaller fraction particles in the clusters. This would increase the simulation time. In the best scenario, the majority of fraction particles would leave the chamber still bounded in a cluster.

CONCLUSIONS

The findings from this work makes advances mainly in three areas: Simulation Based Design, DEM methodology and cone crusher theory. In summary, a series of simulations have been performed to test a concept of improvement in a product development perspective which has generated knowledge to base further decisions on. New insight regarding the minimal cluster resolution for using the BPM model together with image analysis has been found. Within cone crusher theory this work predicts that choke feeding is essential for continuous high speed operations and that the chamber geometry has a large impact on the crushing performance and is mainly coupled to mass flow. In general, the results are in line with previously developed analytical models by Eloranta (1995) and Evertsson (2000).

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