

PARTICLE MOTION AND ENERGY DISSIPATION SPECTRA IN A PLANETARY BALL MILL

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Abstract. The charge motion and energy dissipation in a planetary ball mill are investigated using the Discrete Element Method (DEM). In addition to simulations of the grinding media (balls) only, different fill levels of the ground material (fine particles) are considered to examine its effect on the mill charge dynamics. The energy dissipation spectra determined from the DEM simulations provide insights into the comminution processes that occur in the planetary mill, and how they are influenced by the fill level and size distribution of the fine particles.

1 INTRODUCTION

Crushing and grinding are essential processes in a variety of industries, ranging from nanometer fine powder production to large-scale mineral ore comminution. In a laboratory-scale planetary ball mill, a rotating grinding bowl – containing the material to be ground together with metal or ceramic grinding balls – is mounted on a disk counter-rotating at high speed. The resulting planetary motion induces strong centrifugal and Coriolis pseudo-forces yielding high-energy impacts between the material, the balls and the bowl. These particular characteristics make this type of mill suitable for small-scale production of fine powders, metal alloying and laboratory tests for industrial-scale comminution equipment. Understanding the breakage mechanisms occurring in this type of mill is particularly challenging since there is little access to the dynamics of the grinding media and material; indirect experimental observations are generally relied on for breakage studies and process optimization.

In this context, numerical simulations provide an invaluable tool for deeper understanding of the comminution processes occurring in such mills. Particle based methods, such as the Discrete Element Method (DEM) [1-3], have already been successfully employed to investigate a variety of tumbling ball mills [4]. Specific studies include scaling [5], abrasion [6] and liner profile influence [7] in horizontal dry ball mills. The computational resources available nowadays enable the numerical simulation of systems with several million particles, such as for a full-scale cement plant mill [8]. For planetary ball mills, several analytical studies have been performed to understand ball trajectories and impacts [9,10], optimum operational settings [11] and milling energy [12,13]. For this type of mill, DEM has also been

used to determine the best operational parameters, such as speed and rotation-to-revolution ratio [14,15] as well as to study energy scale-up [16] and abrasion [17].

While the aforementioned studies have focused only on the ball charge, it is also important to understand how the presence of the finer ground material modifies the ball motion and impact characteristics. The presence of fine powder has been taken into account by modifying the rolling and sliding friction coefficients of the balls [18], yielding good agreement with experimental data for ball trajectories for a low ratio of fine material to grinding media [19]. However, when this ratio is sufficiently large, the fine particles can have a strong effect on the grinding media trajectories and impact characteristics. This was shown [20] for a laboratory-scale ball mill, where particle motion and collision energy spectra were investigated with the inclusion in the simulations of different quantities of small-size particles.

In the present study, charge dynamics and energy dissipation are investigated by simulating directly the fine particles in addition to the grinding media. Ball trajectories and charge shape and dynamics are analyzed qualitatively for different fill levels of fine particles. Energy dissipation is determined for all particle interactions and energy spectra plotted and examined for several mill fill levels.

2 NUMERICAL SIMULATION

2.1 Discrete Element Method

For the present numerical simulations, a soft-particle DEM approach is employed, for which all particles are treated as spheres with a small overlap occurring during collisions. Collisions are modelled using a linear spring-dashpot contact model [1]. To perform computations in an efficient manner, the detection of collisions is based on the construction of a near-neighbour list at regular time intervals using a multi-grid method [21]. The use of two search grids, with sizes of the order of the grinding balls and the fine particles, enables a high computational efficiency to be attained even for large ratios of particle sizes.

To obtain an acceptable computation time when fine particles are included, a minimal particle diameter must be chosen, considering the total mass of the system. Indeed, for a given mass at constant radius, while the total number of particles scales with r^3 , the integration time-step scales with $r^{-1.5}$. The total computational time, which is almost proportional to the number of particles and inversely proportional to the time-step, therefore scales with $r^{4.5}$. The spring constant of the contact model also influences the time-step. For the particular geometry of the present study, considering the high-speed impacts of heavy grinding balls with fine particles, a normal spring constant of 10^6 Nm^{-1} was selected, keeping the average and maximal overlap at around 0.001% and 5%, respectively. For the present simulations, the minimum time-step was 100 ns, with a maximum computation time of ~ 9 days on a single processor core for a total of $\sim 432,000$ particles.

Collision damping between particles is achieved via a force proportional to their relative velocity, with restitution coefficients of 0.8 for steel balls and mill walls, 0.2 for the fine particles and a Coulomb static frictional limit of 0.5 times the normal force. For each particle collision, the normal and tangential dissipated energies are computed by evaluating the work of the contact forces along the relative path of the two particles. Since the normal force is bounded to be only repulsive, the work of the spring-like component of the force is in

principle non-zero and is therefore also taken into account. In addition, a rolling resistance torque, with a coefficient of 0.2, is considered, although the work of this dissipative force is not computed in the present study.

2.2 Geometry and planetary motion

The planetary mill considered in this work is modelled on the commercially-available Fritsch Pulverisette 6 [22], as shown schematically in Figure 1. The grinding bowl has an inner diameter of 100 mm and is 67 mm high. It rotates at 220 rpm and is mounted on a circular disk with an effective diameter of 121.6 mm counter-rotating at 400 rpm. The grinding media are comprised of 25 steel balls of 20 mm diameter with a density of 7850 kgm^{-3} . For this angular speed, the centrifugal acceleration is around 11 times stronger than gravitation. The planetary motion is modelled by rotating the bowl around its axis and adding a rotating centrifugal pseudo-acceleration to all particles. The mill charge was initialized by first dropping the grinding balls into the bowl with the mill at rest. Fine particles (with a density of 1450 kgm^{-3}) are then poured onto the balls, the initialization procedure concluding when the fine particles are essentially stationary. For the chosen operating conditions, an almost steady flow is observed after 50 – 70 ms. A total simulated time of 200 ms is considered, with collisional data being collected during the last 100 ms.

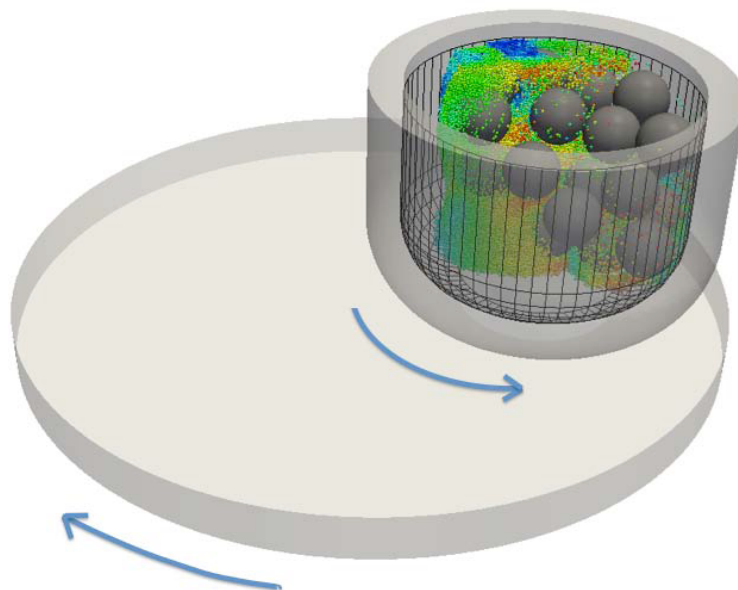


Figure 1: Planetary mill geometry, showing the grinding bowl mounted on a counter-rotating circular disk

3 CHARGE MOTION

Initially, DEM simulations were performed with the ball charge only, which has a total mass of 822 g. To analyse the influence of ground material on the charge dynamics, the addition of four different fine particle charges has been considered: 10 g, 50 g, 100 g and 200 g. The fine particles have diameters ranging from 0.7 to 1 mm, yielding a maximum number of particles of 432,000. With the mill at rest, 100 g of fine particles has approximately the same height as the ball charge, with the particles filling the voids between grinding balls. For the 100 g case, two additional fine particle size distributions, with diameters of 1 – 2 mm and 2 – 4 mm, have been simulated to evaluate the effect of particle size on impact energies. A simulation has also been performed without grinding balls with a charge of 200 g of fine particles, with particle sizes ranging from 1 to 2 mm.

Figure 2 shows images obtained from the different simulations after 200 ms of mill operation. In these images, the bowl is viewed from the top and rotates counter-clockwise, with its orientation being chosen such that the top of the image points towards the centre of

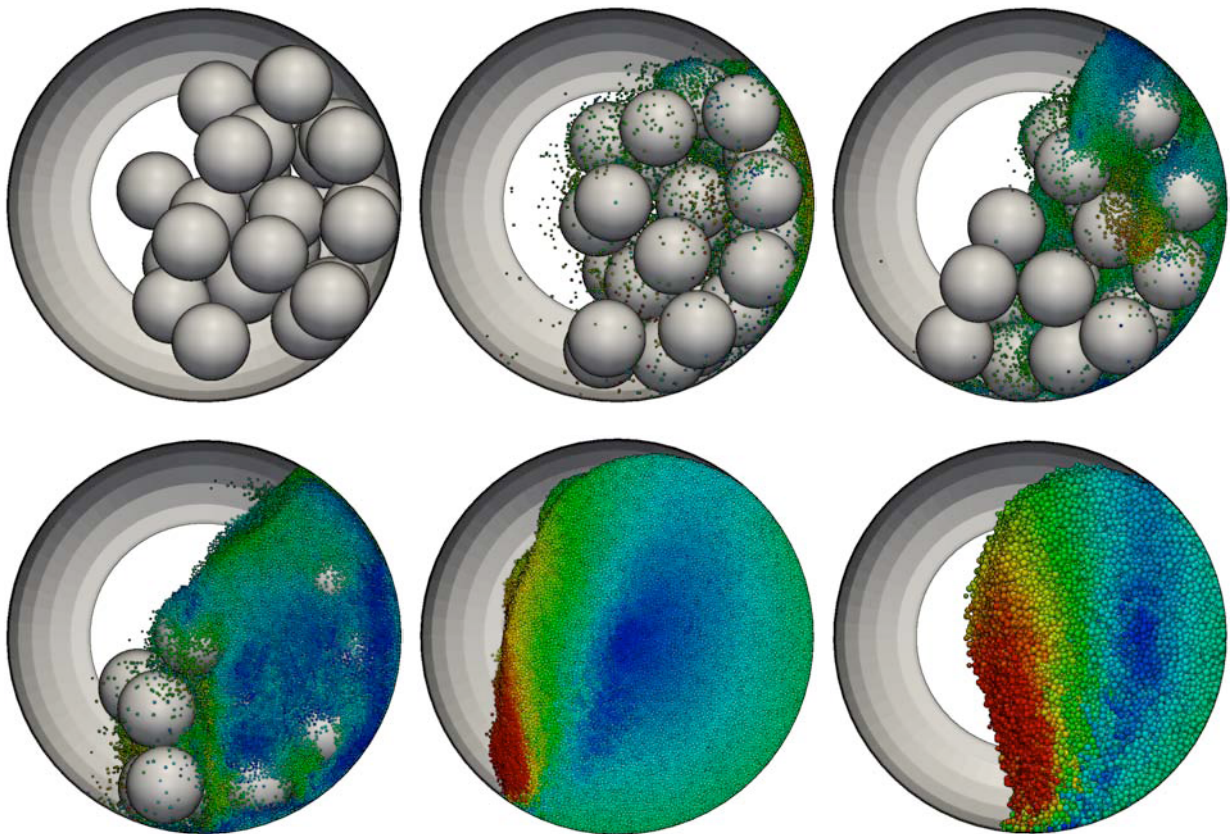


Figure 2: Charge distribution after 200ms of operation.

From left to right: balls only, 10 g fine particles, 50 g fine particles, 100 g fine particles, 200 g fine particles and 200 g fine particles (1-2 mm diameter) without grinding balls.

the circular disk. For this particular orientation, the rotation of the disk generates a constant pseudo-acceleration toward the bottom of the image. Since the bowl rotates at constant speed, particle motion is affected by the Coriolis pseudo-force, with trajectories being bent inwards towards the charge. The fine particles in Figure 2 are coloured according to their velocities, measured in the simulation frame, dark blue corresponding to a static particle to dark red indicating velocities of 3 ms^{-1} and higher.

As in conventional tumbling mills, it can be observed that particles on the outside of the container are lifted toward the top (according to image orientation) of the charge – the shoulder region – and then circulate back toward the bottom – the toe region – with either a rolling or cataracting motion.

Figure 3 presents trajectories of the grinding balls during 50 ms, shown from both top and side views. For the simulation without fine particles, the balls basically follow two characteristic trajectories. The first type of trajectory is traced by balls on the outside of the charge: after following the liner upwards they fall back down, bouncing on other balls and impacting the bowl wall at high velocity. The second type of trajectories appears more random and is traced by particles trapped inside the charge. Due to the large size of the balls compared to container, their axial motion can be seen to be essentially restricted to three layers, with relatively infrequent moving of balls between different layers. As seen from the trajectories, gravitation appears to play a minor role compared to the other forces, producing only slight bending of particle trajectories near the centre of the bowl.

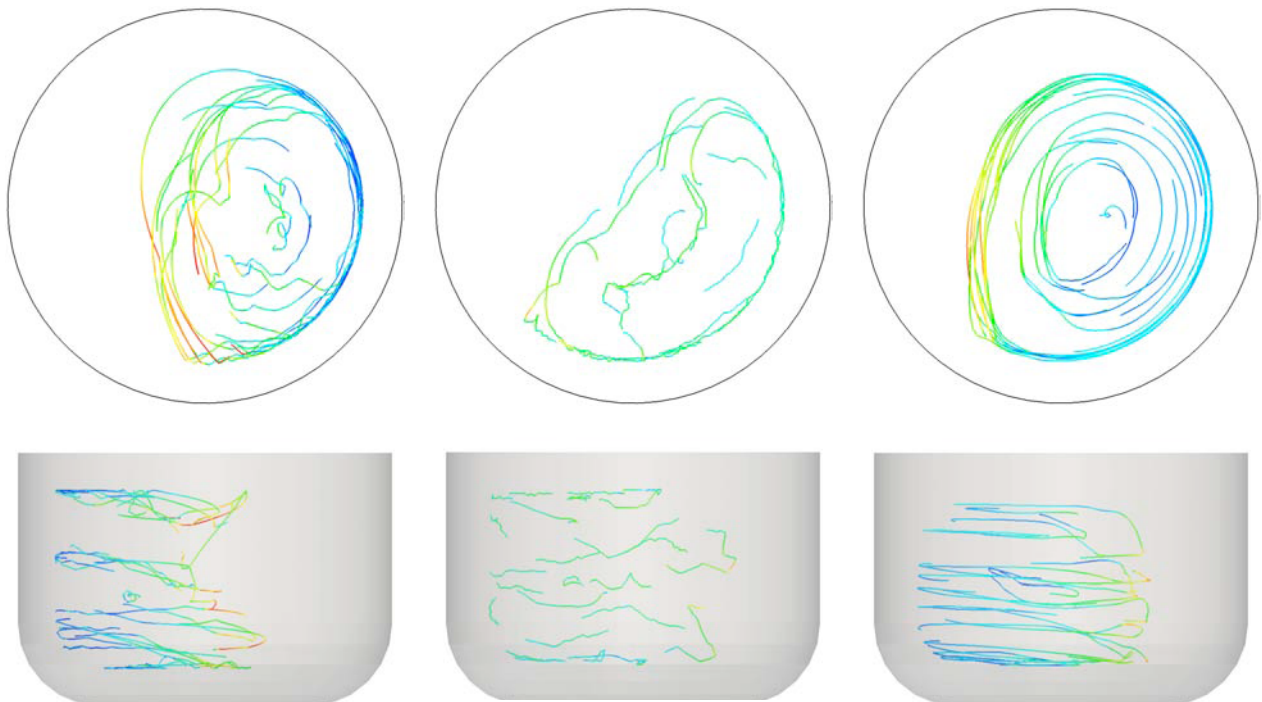


Figure 3: Ball trajectories for 50ms, top and side views.
From left to right: balls only, 100 g fine particles and 200 g fine particles

Figures 2 and 3 indicate that with the addition of 10 g to 100 g of fine particles to the charge, the mobility of the balls is reduced, with ball trajectories becoming shorter and more random. The shoulder and toe regions move clockwise (i.e. lower) for increasing fine particles up to 100 g, while the balls tend to roll on the charge instead of following cataracting paths as is observed without fine particles. Conversely, the fine particles have a much greater mobility, their small size allowing them to percolate through gaps between the balls. These fine particles tend to accumulate in the shoulder region due to their small mass, high mobility and as a result of the Coriolis pseudo-force pushing to the left particles that recirculate toward the toe region. This spatial distribution of fine particles would appear to be deleterious for grinding efficiency as this effect tends to remove fine material from the toe region where the most energetic impacts occur.

For a fine particle charge of 200 g, a completely different situation is observed. The volume occupied by the fine particles is higher than the ball volume, and the balls appear not to interact directly with themselves nor with the bowl wall. Instead the ball charge appears to follow a collective motion with the fine particles resulting in smooth trajectories. It appears that the fine particles lubricate the ball charge, with the result that energy loss is reduced and as a consequence, the shoulder and toe positions are comparable to those in the ball-only situation.

4 ENERGY DISSIPATION

Information regarding the breakage mechanisms active in the planetary ball mill cannot be deduced directly from the determination of the particle motion. As a first approximation, it appears reasonable to link breakage – characterized by a particle dividing into several smaller pieces of roughly equivalent sizes – to normal forces occurring during a head-on impact, while attrition – where small fragments are detached from the original particle surface – results from the influence of tangential shear forces. It is therefore useful to extract physically relevant quantities, such as impact energies, from the DEM simulations by determining the normal and shear forces present during the mill operation.

For each collision occurring between two particles in a simulation, or between a particle and the bowl wall, the work of the normal and tangential interaction forces can be computed, binned according to its logarithm and plotted to give the energy dissipation spectra. For the above-mentioned reasons, normal, tangential (shear) and total energies are depicted separately. Figure 4 shows such spectra obtained for different quantities of fine particles having diameters ranging from 0.7 to 1 mm.

For a mill with grinding balls only, the dissipated power per energy channel can be observed to increase almost linearly, reaches a peak at around 20 mJ and exhibiting a cut-off value at ~ 80 mJ. With the presence of fine particles, a second peak at much lower energies appears. The height of this peak increases with the total mass of fine particles and eventually reaches a energy dissipation level comparable to the high energy peak. At the same time, the normal energy dissipation drops significantly with larger quantities of fine particles, with the greatest energy dissipation resulting from tangential forces rather than normal forces at higher fill levels of fine particles. Indeed, with 200 g of fine particles, there is no energy dissipated due to normal forces in the energy range > 0.1 mJ associated with ball-ball collisions.

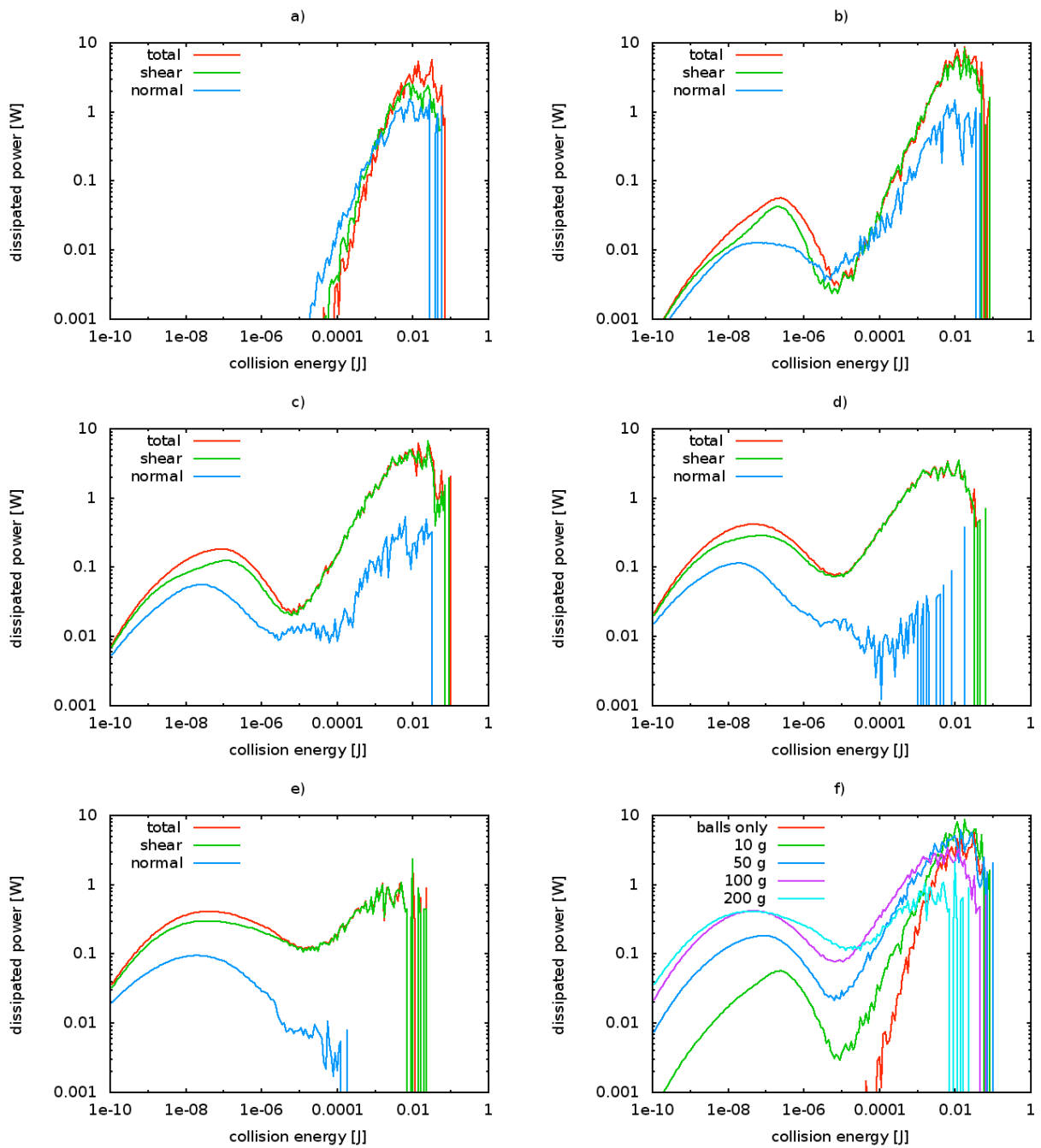


Figure 4: Collision energy spectra for a) ball charge only, b) 10 g fine particles, c) 50 g fine particles, d) 100 g fine particles, e) 200 g fine particles and f) comparative plot for total energy dissipation

Figure 5 shows modal energy dissipation for all possible types of pairwise interactions, for charges with 100 g and 200 g of fine particles. All curves involving fine particles have a characteristic shape with two energy dissipation peaks, with the peak values depending on the

type of collision. As expected, for the larger fine particle charge, ball-ball and ball-liner direct collisions completely vanish, the balls being apparently shielded by the surrounding fine particles.

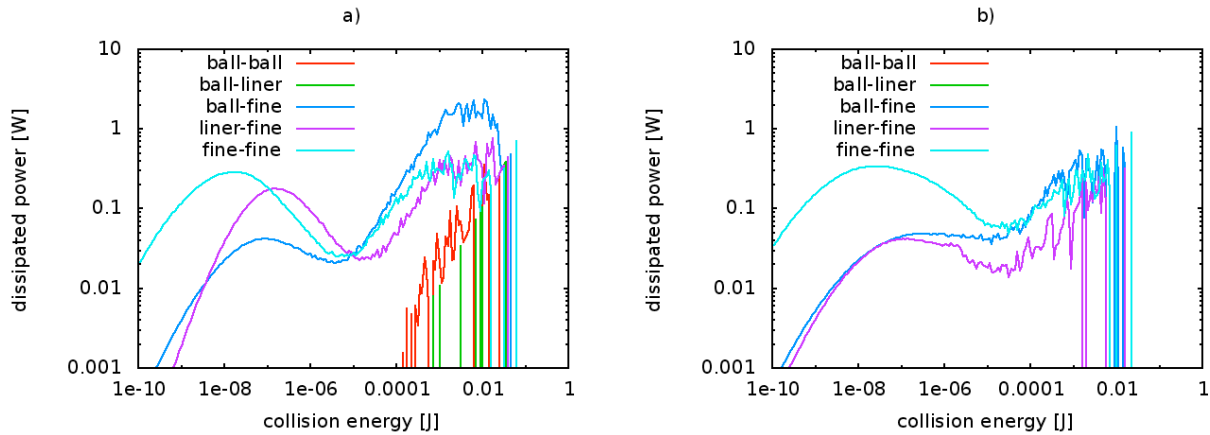


Figure 5: Energy dissipation modes for a) 100 g of fine particles and b) 200 g of fine particles

The effect of the size of fine particles on the numerical simulation results is two-fold. Firstly, as seen in Figure 6(a), the low energy peak due to fine particles is shifted towards higher energies for larger particle size, due to the higher kinetic energy associated with their larger mass. Secondly, fine particle mobility relative to the balls decreases for larger sizes, decreasing the spatial segregation of balls and fine particles seen for the simulation with finer particles. It is therefore important to note that, for the range of fine particles considered in the present study, particle size has an important influence on the mill charge dynamics.

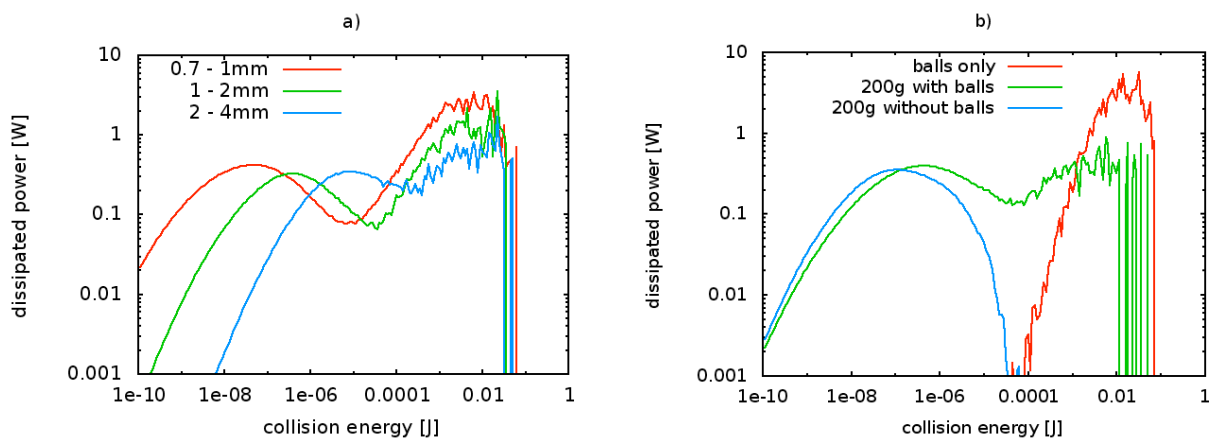


Figure 6: Total energy dissipation for a) different size fine particles and b) different charges types

Figure 6(b) shows total energy dissipation spectra for fine particles of 1 - 2 mm diameter, with and without balls and compared to the case of balls only. Without considering any

charge dynamics or spatial segregation effects, the presence of grinding balls modifies the energy dissipation by shifting the average energy of two-body collisions toward significantly higher energies. In a simplistic breakage model where size reduction occurs when the impact energy is greater than a certain threshold, the presence of the balls has clearly a positive effect on comminution by shifting the spectrum above the threshold. It is noted that these spectra are similar to those presented in [20] for a laboratory-scale tumbling ball mill.

Finally, the dependence of the dissipated power on the total mass of fine particles in the charge and the average fine particle diameter is shown in Figure 7. These plots confirm that the behaviour of the normal and tangential collisional force components of the dissipated power is completely different. As the quantity of fine particles increase, the dissipated power due to normal forces monotonically decreases. However, the dissipated power due to tangential forces initially increases before decreasing with further increase in the quantity of fine particles. In addition, for a fixed charge mass, the dissipated power due to normal collisional forces increases with particle size, while that due to tangential forces decreases.

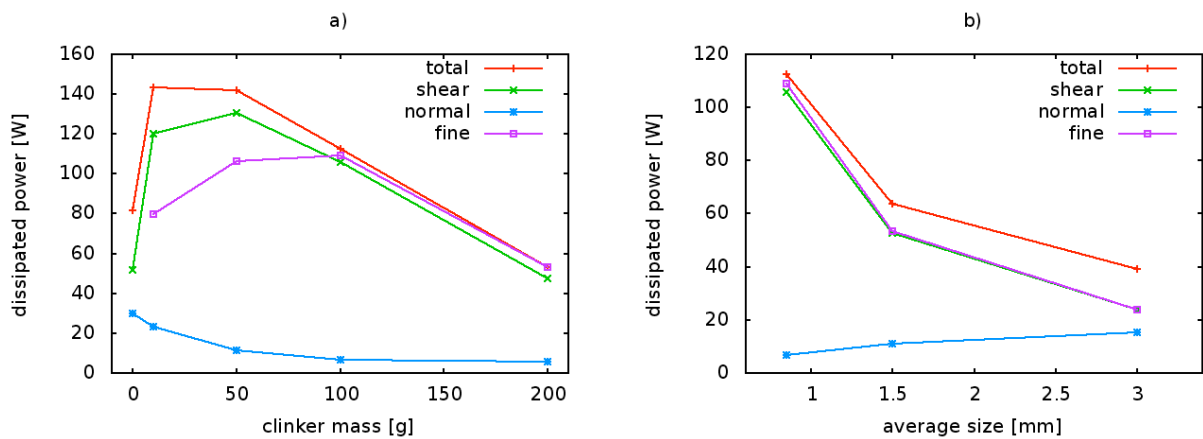


Figure 7: Total energy dissipation as a function of a) total mass of fine particles and b) fine particle diameter

5 CONCLUSIONS

A laboratory-scale planetary ball mill with different fill levels and sizes of fine particles has been numerically simulated using the Discrete Element Method. By performing a qualitative analysis of the ball trajectories, it has been shown that the presence of fine material has a substantial effect on the mill charge dynamics. This observation indicates that care must be taken when assessing comminution in this type of mill based on DEM simulations that consider only the ball charge. Energy dissipation spectra that have been determined from the simulations provide an initial indication of the relative importance of breakage and attrition occurring in such mills under different operating conditions.

Based on the present numerical simulation results, several preliminary comments may be made regarding the optimization of comminution in a planetary ball mill. Firstly, low fill levels of fine material results in poor grinding performance due, in part, to the presence of spatial segregation of the fine particles and balls. The high mobility of the fine particles enables them to be concentrated in a region separated from the toe region where high-energy

impacts occur. Moreover, it may be conjectured that the high ratio of ball-ball and ball-wall energy dissipation in these cases would result in an increased wear rate of the grinding media and bowl inner wall. Secondly, at moderate fill levels, the mobility and velocities of the balls are greatly reduced due to interactions of balls with fine particles, resulting in a decrease in grinding efficiency. Finally, at high fill levels of fine particles, segregation effects are minimal and a collective fluidized motion of the mill charge is observed. In addition, normal impact energy and total average energy dissipations are greatly reduced for higher fill levels of fine particles, indicating a higher attrition to breakage ratio for these operating conditions.

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