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Mineral movement simulation through the grates and pulp lifter in a SAG mill and evaluation for a new grate design using DEM

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Abstract: Nowadays computer simulations have been shown to be powerful tools to understand the performance of systems where we have mathematical models that can capture the physics of the problem. In this paper we attempt to simulate the behavior of the particles that move inside a large-scale mine mill, specifically through the grates and the discharge ducts of the material, when small changes are made in the geometry of the grates. Basically, the continuity, energy and momentum conservation equations are the ones that can solve the behavior of the material in that zone. The discrete element method is used to carry out the simulation, under the hypothesis that the restitution coefficient can substitute for the presence of the fluid inside the mill, and that by changing the angle of inclination of the grate slots the performance can improve the classification that they make and in the total discharge flow. A corollary of this study is that the pulp-lifters have a greater impact than the grates in improving the discharge flow. It was possible to quantify phenomena like flow-back and carry-over, effects that are not evaluable experimentally, in this way showing the usefulness of this simulation. The application of the DOE method has allowed to back up statistically the results and indicate that the slot angle increases the mill's outlet flow.

Keywords: grate, SAG-Mill, DEM-Simulation, flow-back, carry-over

1. Introduction

Size reduction of ores has an important role in the process of obtaining various metals. For example, for copper the ore must be separated from the mineral and must reach sizes smaller than 50 μm, and this size reduction process takes place in successive stages and in different processes (blasting, crushing, and grinding), in each of which there are different devices whose purpose is to decrease the mineral's size. The most important devices nowadays are certainly the mills, which have been studied computationally by various authors, (Panjipour and Barani 2018; Sinnot et al., 2017; Cleary and Morrison 2016; Gutierrez and Guichou 2014; Powell et al., 2006; Rajamani et al., 2000). The most commonly used method is that of the discrete element (DEM). Two interesting papers have been published (Morrison and Cleary 2008) and (Weerasekara et al., 2013), who attempt to simulate a virtual machine for size reduction and describe how the DEM has contributed to the development of the knowledge of the comminution process. Several other studies have been made to know the performance of the mills, which go from fully experimental studies based on laboratory mills (Xialei Bian et al., 2017) with the construction of a small scale mill and the evaluation of its power and flow, (Rezaeizadeh et al., 2010) who study the wear of the lifter in a mill under normal operating conditions, with their main results indicating that there is maximum wear at medium rotation speed (75%) and filling level (21%), and on the other hand, Latchireddi et al. (2003) study the unloading mechanism, concluding that the grates play a preponderant role in the good performance of mill. Govender et al. (2013) studied the behavior of the movement of the load using Positron Emission Particle Tracking (PEPT) and compared the results with DEM simulations. Only the computer simulations have also been developed (Delaney et al. 2013), reviewing fracture criteria to determine the fragmentation, concluding that an adequate

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criterion for a SAG mill is that of accumulated damage (Cleary et al., 2016 and Djordjevic et al., 2004) are other examples. There also is pseudo-experimental work based on phenomenologic models that fit curves to validate the models, as shown by Yahyaei (2010). Those papers in general conclude that the results capture the overall behavior of the granular material inside the devices. Notwithstanding the above, some specific aspects that act simultaneously have not yet been modeled in large scale mills: size reduction (fragmentation), the direct presence of fluid, the fluid's property changes, and the geometric changes caused by wear. These are research works and they have been carried out on a small scale.

There are many factors in this area that support the development of these types of studies, with economic aspects related to production, reliability, availability, and safety levels, etc., as some of them. As examples, it is mentioned that the benefits due to the production of a mill for large-scale mining reaches US$ 200,000 per hour (US$ 7000 per ton; its reliability must be as high as possible and they must operate 24/7 all year long (increased availability).

Nowadays, SAG mills are the machines that are most frequently found in operation in concentrating plants. Their large sizes allow processing large volumes of materials with flows of the order of 5000 tph. These kinds of equipment have the function of reducing the size of the material to a maximum of 75 mm. Their geometry is cylindrical with a horizontal shaft, and they turn around that shaft. At their ends they have truncated conical covers characterized because one of them is the mineral inlet zone and the other is the outlet zone. The mills have internal structural elements that allow lifting the granular material, and in the periphery of the discharge side there are classifying grates and evacuation ducts that allow the exit of the mill's liquid mixture and the granular material. Internally they also have the grinding media (steel balls) meant to speed up the size reduction process. Fig. 1 shows, as an example, a picture of a 36 feet SAG mill, a geometric model, as well as a section of it.

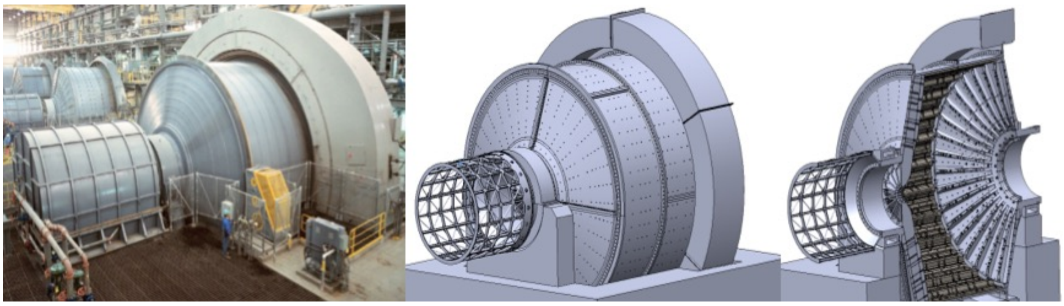

Fig. 1. Picture, geometric model, and section of a SAG mill

Note that nowadays, from the geometric standpoint and an adequate computational support it is possible to "construct" completely any of these kinds of machines virtually.

2. Operational condition

The operating process of SAG mills is evaluated mainly by two factors: a) their ability to reduce the size of the material, and b) their ability to transport the fragmented material out of them. These factors can be measured independently, because a mill can reduce the particle size rapidly, but their removal may be slow, so as an operational result we have a mill with a low production volume. The opposite case, but with the same operational result, is to reduce the size slowly and speed up its discharge, conditions that are completely opposite. Therefore, the ideal is to have a great size reduction in a short time and have the discharge as fast as possible. These conditions can be quantified by means of the more related variables, which are the granulometry and the size and shape of the slots.

The evaluation corresponding to the transport capacity in the zone of the grates and pulp-lifter is presented in detail in this paper, emphasizing the grate's geometry. As will be shown, making a small change in the transverse orientation of the slots we get an interesting change in the performance of the classification compared to those existing currently.

Given the operational characteristics of a mill, we get size reduction by generating relative movements between the elements that will reduce their size and the grinding media, and here we can identify various mechanisms, like simple impact, fatigue, abrasion, wear of edges and points, and breakage of points, and determine which of them is more important or has the largest participation in the process. Notice that the material is changing its shape as its size reduction process takes place, and its kinematic and dynamic behaviors change, there is a substantial increase in the number of particles, making their evaluation difficult. As can be seen, the modelling of something as simple as size reduction in a mill represents a great computational knowledge and development challenge.

In general, the growing application of the discrete element method (DEM) to problems that contain granular materials is related to the potential that computers have developed in their hardware components and of the contact calculations algorithms, they have allowed the incorporate, for example, the fracture of the materials, as well as the incorporation of irregularly shaped granular material. The papers aimed at optimizing the comminution process at a real scale are still scarce. Work like that of Owen and Cleary (2015) is one of them, and it presents a method for predicting the filling level of a mill considering the wear of its linings. Another work like that of Delaney et. al., (2013) develops a model predicting the fracture of the material and its size change over time. It can be concluded that the work found in general tends to study wear and fragmentation aspects, to evaluate and validate the work found in the different existing contact models, indicating their benefits and deficiencies under different operating conditions.

The present work will use the discrete element method (DEM) to determine the kinematics and dynamics of the particles in a 10.9 x 6.1m mill, emphasizing the zone of the grates, which have 0.067 m slots and a total evacuation area of 5.84 m^2. The discharge transport ducts have been included in detail and we will study how they are affected by the normal operating conditions. The performance of the grate is evaluated from the standpoint of the operation of the mill considering three filling levels for the same turning speed, with the purpose of determining if small changes in the inclination of the grate slots can improve the performance of the mill. It must be stated that this geometry is a complete novelty. This latter condition also tries to show the precision and accuracy that a model based on the DEM can have in an application of this kind, and finally we must not forget that the economic impact of one of these mills is so important that an increase of only 1% of its processing level means no less than US$ 20 million per year in benefits if copper ores are processed, so small variations give rise to great economic benefits.

Since the study is centered on the performance of the grates and pulp-lifter, the DEM model can ignore the phenomenon of the fracture of the material without decreasing the validity of the results. This fracturing effect takes place inside the mill's chamber, with the material reaching the grates with the size already defined to face the slot size. As the material goes through the grate, it finds the evacuation chambers, where there is no ore fragmentation. On the other hand, since the mills use water to help in the transport of the fines that are generated in the fragmentation chamber, the present model has considered that the effect produced by the water to the granular material corresponds to a damping, and that to capture that effect, a number of impact experiments have been carried out that allow the determination of the restitution coefficient and relate it to the damping coefficient. These experiments have the characteristic of knowing how the restitution coefficient varies when two solid surfaces hit each other in the presence of water at different levels. The method developed here avoids the use of methods such as SPH and/or CFD that can consider the existence of fluid explicitly, but in turn generate a high computational cost. The computational modeling of a mill represents a large magnitude challenge from the standpoint of its phenomenological as well as computational resource needed to get reliable results. Although we are dealing only with a unit operation whose purpose is to reduce the size of the material, in the equipment used currently it is impossible to have a visualization and quantification of the problem's important variables, transforming the simulation into practically the only road to understand directly the phenomenon and the performance of the equipment. This paper has incorporated the analysis of the results of the simulations, the Design of Experiment (DOE) method, which will be in charge of defining the number of experiments that will be carried out, and the impact that these factors have on the process by considering the filling level of the mill and the slot angle of the grates.

3. Computational method

The discrete element method, DEM, is used to simulate the movement of the granular material inside the mill and the removal of the material. The Lagrangian behavior of each particle present in the mill is determined, allowing to know the position as a function of time of each of the particles, and therefore their trajectory in a given time period. In general terms, the DEM develops five fundamental problems:

a) Position problem. Knowledge of the positions of each particle and the geometries that act as boundary conditions in $t = t_i$.
b) Contact problem. Determine which particles are in contact with one another or with their geometric surroundings.
c) Crashing problem. Determine the interaction forces by means of an impact model.
d) Incorporation of body or other external forces, add own weight, magnetic, sustentation, dragging, etc.
e) Solution of the motion equations. Use of an explicit method to determine the new position in $t = t_i + \Delta t$.
f) Return to point a).

To determine the interaction forces in the crashing problem use is made of a model defined by Thornton et al., (2013). It is considered that the elements have a rigidity (k_n and k_t) and there is an overlapping between the bodies of magnitud □x; to facilitate the calculation they are decomposed into the forces in the normal and tangential directions relative to a normal axis whose direction and sense are determined from the absolute positions $\boldsymbol{r_i}$ and $\boldsymbol{r_j}$ of two particles that come in contact $\hat{\boldsymbol{n}} = (\boldsymbol{r_i} - \boldsymbol{r_j})/|\boldsymbol{r_i} - \boldsymbol{r_j}|$, whose corresponding magnitudes are determined from

$$F_n = -k_n \Delta x + C_n v_n \tag{1}$$

and

$$\vec{F}_t = min\{\mu F_n , \sum k_t \vec{v}_t \Delta t + C_t \vec{v}_t\} \tag{2}$$

Since in every temporal interaction between the bodies events associated with energy loss appear, in the model damping coefficients, are incorporated in the model, a very important aspect, because the present model does not incorporate explicitely the presence of fluid, and it aims to do it by changing the restitution coefficient from experimental measurements of it when liquid is present. The normal damping coefficient C_n is determined from Equation (3), an expression developed by Corkum (1989), where $\boldsymbol{e}$ is the restitution coefficient, m is the reduced mass given by Equation (4), expressed in terms of the mass of each particle m_i:

$$C_n = -\frac{2 \ln(e)\sqrt{k_n m}}{\sqrt{(\ln(e))^2 + \pi^2}} \tag{3}$$

$$m = \frac{m_i m_j}{m_i + m_j} \tag{4}$$

All these forces are added to obtain the resultant for each time pass and each particle. The differential equation of the movement is solved explicitly and the new position of every particle is determined. This cycle is repeated for each pair of particles and time pass. Further details of the method can be found in Mishra and Rajamani (1992). From the computational standpoint, a computer with 8 fifth generation cores and 16-GB memory, with a saving capacity of 500 GB for each simulation was used.

4. Experimental method to restitution coefficient

With the purpose of capturing in the best way the impact phenomenon in the mill in the presence of liquids by means of the DEM and without using methods like CFD and SPH, the restitution coefficient between the different interacting materials is determined, two variables that are present were considered, namely the size of the grinding media (balls) and the amount of liquid that there can be between them. This condition goes from a direct impact between the particles, to impacts between two particles both of which are immersed. These variables have been related to each other considering the liquid level in terms of the diameter of the spheres used.

Other authors like Aguilar-Corona et al. (2011) studied the impact phenomenon in bodies completely immersed in liquid, incorporating the liquid's viscosity in the evaluation of the restitution coefficient, condensing the remaining velocity and diameter variables in the Stokes number. On the other hand, Cruger et al. (2016) studied the restitution coefficient for 1 mm diameter particles that fall on liquid surfaces 0.1 mm thick, dimensions of an order of magnitude smaller than those dealt with here. Since we had no specific bibliographic data on our problem, more appropriate experiments were made to determine the restitution coefficients. The experiments determine how the restitution coefficient of a steel ball that falls from a fixed height of 0.7 m and impacts a steel surface covered with different water levels varies. The 0.7 m height used corresponds to a speed at which the restitution coefficient stops depending on the speed (Marinack Jr. et al., 2011, and Miller et al. 2016). Fig. 2 is a schematic of the method used. The liquid levels used will be 0, D, 1.25 D, 1.5 D, 1.75 D, and 2 D, and the diameters of the balls were 5, 10, and 14 mm. A total of 18 experiments were ran, with each of them repeated at least three times.

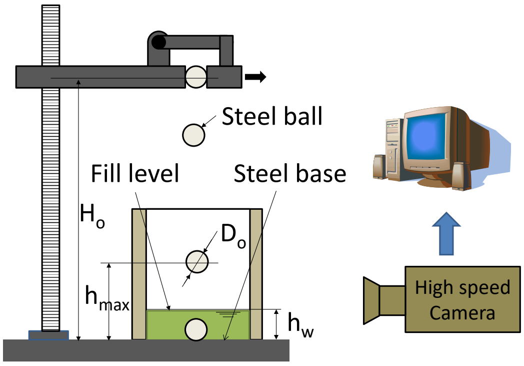

Fig. 2. Schematic of the experiment

The experimental measurement corresponds to the rebounding height h_{max}, which is then used to feed equations (5) and (3), which evaluate the restitution, "e", and the damping, "C_n", coefficients, respectively.

$$e = \sqrt{\frac{h_{max-i}}{h_{max-i+1}}} \tag{5}$$

Fig. 3 shows the results of the experiments as a function of the water level between the base and the ball that impacts it. It is seen that there is a tendency for it to become constant as the liquid level increases, with the maximum deviation range obtained for the restitution coefficient falls within 20% for a water level 1.25 times the diameter of the sphere, and as the water level decreases or increases, the deviation decreases. This condition verifies that the results are consistent with the literature, so we will use an average of those obtained. To determine the coefficients between the ore and the walls or steel balls, or the ore with ore, we will use the model developed by Legendre et al. (2006), which relates the restitution coefficient obtained without liquid (maximum) and as a function of the Stokes number. For our study we have considered the constant viscosity of the liquid, and it will therefore depend only on the speed and the diameter of the particles, which will also be bounded. Equation (6) shows the behavior of the restitution coefficient as a function of the Stokes number, which is given in Equation (7).

$$e = e_{max} Exp\left[-\frac{\beta}{S_t}\right] \tag{6}$$

$$S_t = \frac{(\rho_p + C_{M\infty}\rho)V_\infty d}{9\mu} \tag{7}$$

where ρ_p is the particle's density, ρ is the liquid's density, μ is the fluid's viscosity, d is the particle's diameter, V_∞ is the impact speed, $C_{M\infty}$ = ½, e_{max} is the restitution coefficient in the air, and β is a parameter that includes the viscous effects of the layer's thickness.

Comparing the value obtained in the experiments for a nil liquid height, we get a value that falls within a range given in the literature (Johnson, 1987). In our case a ratio of e/e_{max} = 0.82 was obtained, a proportion that will be used to determine the restitution coefficient of the impact between the other ore and ore bodies, and between the ore particles and the lining. The values used are shown in Table I.

5. Mill model development

For the study the geometry of a real SAG mill of 10.97 x 6.1 m that has 36 steel grates has been considered, as can be seen in general in Fig. 1 and with more details in Fig.s 3, 4, and 5. Fig. 3 shows the main outside measurements used.

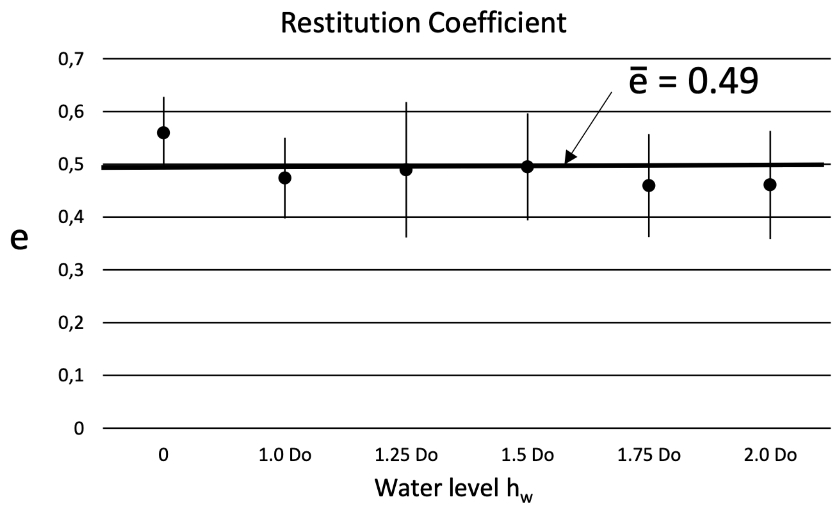

Fig. 3. Restitution coefficient final results

Table 1. Restitution coefficients

Description	Coefficient
Steel - steel	0.49
Ore - steel	0.39
Ore - Ore	0.32

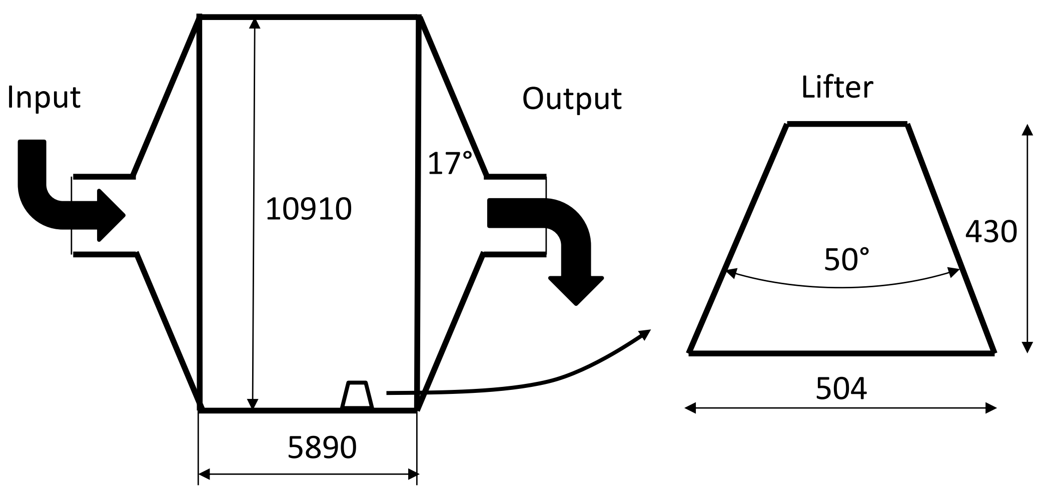

Fig. 3. General dimensions of the mill

Fig. 4. presents a) Cross and longitudinal sections of the mill, showing the internal zone of the outlet; b) a detail of the pulp-lifter; and c) a section of the grate, indicating the variation of the slot angle and the size of the slot. This paper studies the effect caused to the flow entering the grates, the inclination of the slot as seen in Fig. 4c. A small analysis of the material's movement across the slot for an actual grate indicates that when they are in the upper part, the slots allow the material found in the pulp-lifters and is coming down the back wall of the grate, to again enter the grinding chamber of the mill, producing the flow-back. This happens because the gravitational force generates a component in the direction of the slot; now if angle is decreased to 0°, the lack of slant of the slot vanishes the gravitational force component, so the material finds it difficult to enter the grinding chamber. In brief, when the grates are at the top of the mill, they favor flow-back.

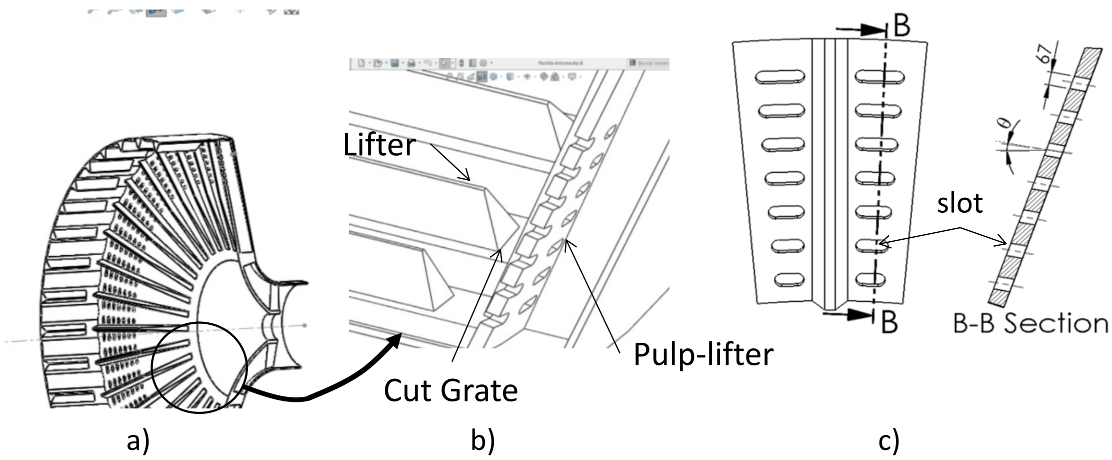

Fig. 4. Details of the geometric model used. a) General inner view of the unloading side; b) sectional view of the grate and pulp-lifter section, showing the evacuation chamber of the particles that succeed in going through the grate; c) a grate and a section across the slots, indicating their inclination angle with respect to to a horizontal shaft and the slot's opening.

Fig. 5 shows a detail of the unloading and the length relations of the pulp-lifter, which in this case was B/A = 0.65. For the calculation by means of DEM, the model considers only the surfaces that come in contact with the particles, and flat surfaces have been generated in the grates with the purpose of having a reference to count the particles that go through the grate. It is also important to mention that in that zone there is a flow that returns and must be reported as such, so the surfaces are defined in the same position, but this time considering a normal vector opposite to the previous one. The particle count is made from the position vector of the particle. Table II presents a summary of the data used in the simulations.

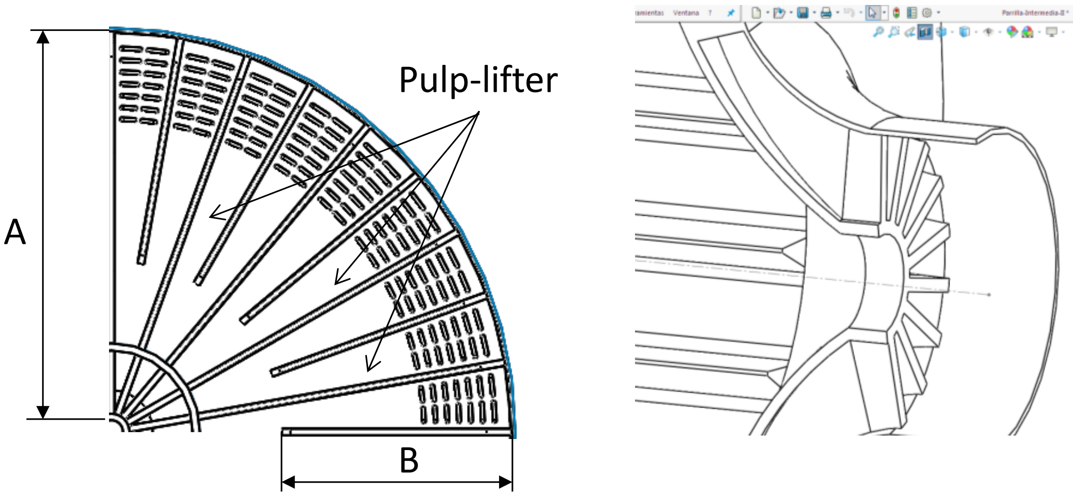

Fig. 5. Details of the geometry of the pulp-lifter and the discharge side

Other important data correspond to the granulometry used for the material and the size of the of ball collars, both of which will remain fixed during the study. Table III shows the distribution of ball sizes considering the volume as a measuring base. The operating conditions for carrying out the simulations and the later analysis of the results can be seen in Table IV. They were obtained from a study based on DOE (©™Minitab-18) from a complete factorial design which considers two factors with an intermediate point; the factors are the filling level and the angle of the grate slot. Five simulations were made, each lasting 75 s. It must be indicated that since, this is a comparative study, it is not necessary for the system to consider only a steady state to make the comparisons.

Table 2. General geometry and operating conditions

Description	Dimensions
Shell inner diameter	10.97 m
Mill length	6.1 m
Number of lifters	36
Liner configuration	High
Lifter base width	504 mm
Lifter height	439 mm
Number of lifters	36
Rotational speed	9.1 rpm
Total discharge area	5.84 m^2
Slot size	0.067 m
Pulp-lifter length ratio	0.65

Table 3. Distribution of ball and ore sizes

Ore size (mm)	Ore PSD (V%)	Ball diameter(mm)	Steel ball PSD (V%)
200	40	163	40
60	20	120	40
40	40	100	20

Table 4. Simulations selected by means of DOE

Simulation	Filling level (%)	Slot angle (°)
1	20	0
2	30	17
3	30	0
4	20	17
5	25	8.5

Finally, the method for each simulation consists in performing the following steps:

a) Filling the mill with ore and balls according to the simulation
b) Finishing the filling with balls and ore in the mill
c) Start turning the mill
d) Start counting the particles that go through the grates
e) The simulation keeps going for 75 s of operation
f) End of the simulation
g) Count the total number of particles that left the mill
h) Count the total number of particles that went through the grates
i) Count the total number of particles that were returned to the grinding chamber
j) Calcultion of the total number of particles that remained in the pulp-lifter

The position of each of the particles present in the mill is obtained as a function of time, so it is possible to follow and draw the trajectory of each them anywhere in the domain, particularly during the path through the grates and the pulp-lifter.

6. Presentation and analysis results

As already mentioned, the operational performance of a SAG mill is measured by its capacity to reduce the size of the ores and by the time it takes to discharge them. A detailed study is made of how the material is transported since it enters the grate and it is removed by discharging.

Fig. 6 shows a schematic of the control volume that is generated. A flow of particles that go through the grate, Q_{input}, a flow that is returned to the chamber, $Q_{flow-back}$, a flow that is retained in the pulp-lifter, $Q_{carry-over}$, and the output flow, Q_{output}, are identified. According to the DEM methodology used in the flow simulation, it is possible to quantify each of these variables, except in this case the $Q_{carry-over}$, which is determined through the continuity equation (8).

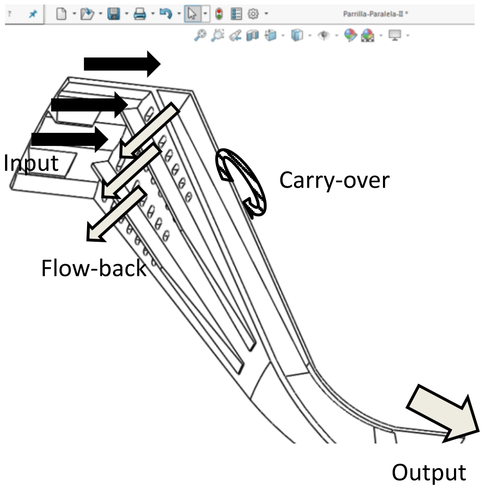

Fig. 6. Section of the grate and pulp-lifter, showing the variables involved.

$$Q_{input} = Q_{carry-over} + Q_{flow-back} + Q_{output} \quad (8)$$

Since there are 36 pulp-lifters, 36 surfaces the size of each grate are considered; they will remain stationary, without movement, and all the particles that go across the surface in the grates zone will be measured. It must be indicated that since on a given surface there is a flow that changes direction, surfaces must be overlapped, but with the opposite normal vector to make a correct evaluation. To calculate the number of particles that cross the surfaces the distance between the surface and a particle is measured by means of the expression $d = (\vec{P}_o - \vec{r}_i) \cdot \hat{n}$, where $\vec{P}_o$ is the position vector of any particle "o", $\vec{r}_i$ is the position vector of a point of the grate's plane, and $\hat{n}$ is a unit vector perpendicular to the plane; if $d < \varepsilon \wedge \vec{V}_p \cdot \hat{n} < 0$, then the particle crosses the plane in the direction in which it was moving, ε represents a small given distance (10^{-5} m), and $\vec{V}_p$ is the velocity vector of the particle that faces the plane. The particle's index "o" is saved, and the process is repeated for every time pass. Notice that the definition of the direction of vector $\hat{n}$ determines the direction in which the particle crosses the plane, and it is calculated from a vectorial product between two edges that have a common origin and form a triangle.

The number of particles leaving the mill is also measured, all in the same time lapse and at the end of every simulation (75 s). Fig. 7 shows for simulation 2 the flow of material that goes through the grate and that which enters the grinding chamber. Th graph is of the radial type, with the radial shaft representing the total percentage of ore that passed through the grate with respect to that which entered the mill for it corresponding filling level. The nil value is found in the periphery and the maximum toward the center.

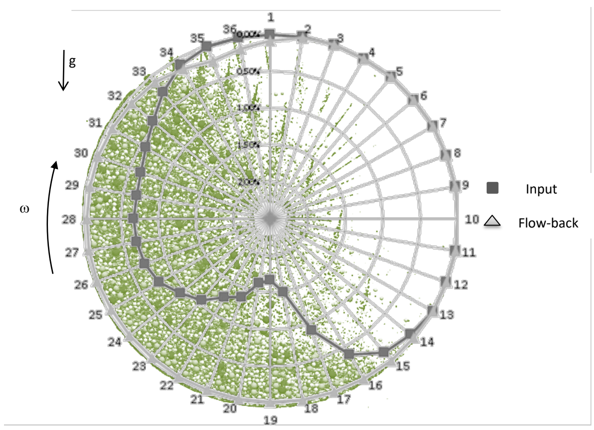

Fig. 7. Amount of material that goes through the grate in both directions

This result corresponds to a typical grate that is currently used in ore processing plants. Fig. 7 shows that the position where the particle flow is highest is that of grate 19, which is the lowest, reaching a maximum of 1.7% of the total amount of ore introduced in the mill. That is the percentage that goes through grate in the 75 s of simulation.

After the position of grate 35, there are practically no particles entering the pulp-lifter, and this condition is maintained until grate 13 is reached, where the entry starts increasing, at first slowly, and between grates 16 and 18 there is a rapid increase. The grate 19 position gets the maximum flow, which is decreased in the following grates until the grate 35 position, where there is practically no flow. Fig. 7 also shows the curve associated with the flow-back. It should be mentioned that its maximum value is 0.24%, which appears at grate 35, and the flow-back is present until grate 2, where it decreases to practically zero up to grate 13, where a slight flow-back begins again, which remains practically constant, with an average magnitude of 0.1% up to grate 32, where it starts increasing. Between grates 34 and 35 there is an equality between the flow that enters through the grate to the pulp-lifter becomes equal to that which returns to the grinding chamber.

On the other hand, Fig. 8 shows the trajectory of a particle of material from the time it is in the grinding chamber until it leaves the mill. First of all, a medium amplitude movement occurs, which increases and ends when the particle enters the grate, and once there the particle goes to the periphery (lowest part) and starts rising due to the push of the pulp-lifter, until it reaches grate 34, where the particle starts falling and changes its trajectory because it comes in contact with the walls of the pulp-lifter. At this point the particle is unable to leave directly through the unloading trunnion and goes to another pulp-lifter. This happens three more times so that later the particle goes to a place on the pulp-lifter closest to the center of the mill, favoring its later exit. Fig. 8 also shows a detail of the particles that are passing through the slots of the grate, which is shown as a section to provide a better view of the process.

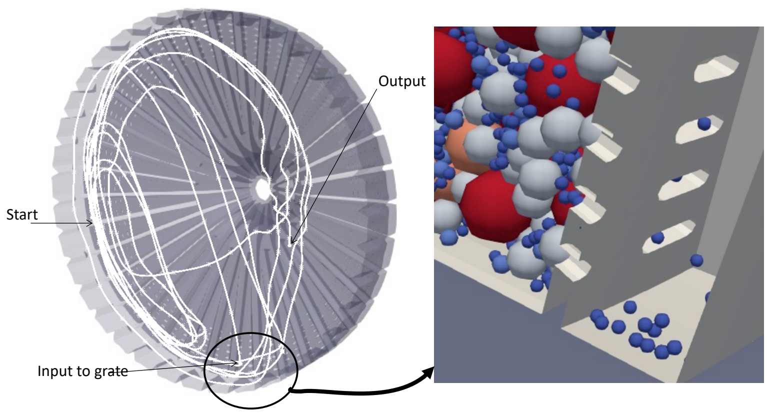

Fig. 8. Trajectory of a particle in the outlet phase, and detail of the passage through the grate

These results may or may not have a direct application or usefulness on the operation of a mill, but they show that the simulation made describes the behavior of the particles which are practically impossible to determine by other methods.

The following results account for the performance of the mill when the grates undergo small geometric changes, a condition aimed to show that the presented model and the method used have sufficient resolution to capture the changes in the performance, and that the incorporated geometric change can improve the performance of the mill. The objective function is whether the mill increases its discharging capacity, and as already shown, the independent variables will be the filling level and the angle of the slots.

Fig. 9 (a) shows comparatively the total flow of material that passed through the grates in 75 s of simulation, considering a grate with 0° and another with 17°, for a 20% filling level. It is seen that a greater amount of material goes through the grates that have the 0° slot, compared to those with a 17° slot. The area between both curves corresponds to increase achieved, and both curves retain the position of their maxima and minima. It is interesting to note that the maximum does not occur in the lowest grate, but in number 22, which is at 30° from the vertical. With respect to the flow-back, it is practically the same for both in the zone between position 4 and 28, and from the latter point on, the grate with the 0º slot has a greater flow-back, and the maximum value reached corresponds to 0.19% in position 36, with the grate with a slot 17º reaching a maximum of 0.14%.

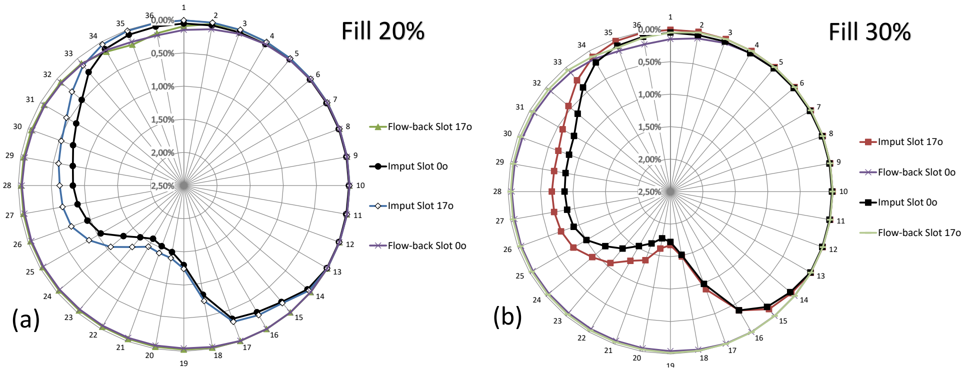

Fig. 9. Total net flow through the grates, (a) 20% fill and (b) 30% fill

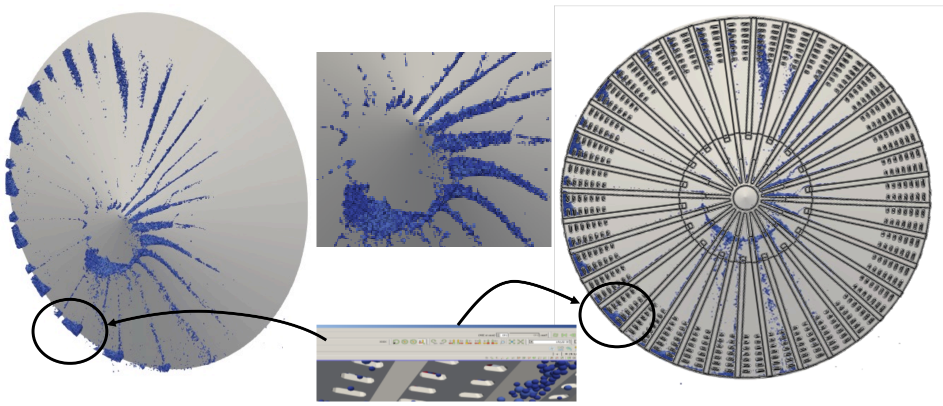

Fig. 10. Position of the particles after 55 s

A qualitatively similar behavior is that presented by the net flow that goes through the grates when the filling level is increased to 30% (Fig. 9 (b)). A slight difference is noted in the maximum flow, which is achieved in grate 20, both in the position and in the magnitude. The small variation of the magnitude indicates that there is a greater net flow as the filling level is increased, in the grates that have a slot angle of 0°.

Fig. 10 shows the equivalent of a photograph of the discharge zone without the cover after 55 s of simulation (some geometries have been eliminated to see the particles better); it is seen that the particles remain at the bottom of the pulp-lifter almost until reaching the vertical (position 34), when they start going down to position 10. From that position the particles start returning on the pulp-lifter. Note that what is important here is having a good unloading cone, since a large number of particles are not capable of reaching the trunnion and accumulate at the outlet.

As seen in the Fig.s, it is possible to visualize the behavior of the granular material that can provide important information to improve the design of the grates, as well as of the pulp-lifter and the discharging cone.

In Fig. 9 it is seen that the angle changes in the slots affect the operating performance, because using grates with 0º of inclination there is 18 % improvement of the flow entering them compared to the 17º grates, which are those used at present. To extend the evaluation of the performance when making the geometric change of the slots' angle, Fig. 11 is shown for all the simulations made. The flows entering the grates, the flow-back, the carry over, and the outlet of material are evaluated. In the Fig. it is seen that 20.3% of the ore that has been introduced into the mill has gone through the grates for a 30% filling level. If we compare the same filling level with a 17º angle, we find that there is a decrease, because it only reaches 16.6%, meaning that there is a net increase of 3.7%. The same trend is also seen for a 20%

filling level. The behavior of the outgoing ore deserves special attention, because even though for a 0º angle it is greater than for the 17º, (8.2% and 7.7%, respectively), it only corresponds to a global improvement of 0.5%. This result indicates that the total improvement of the flow does not depend only on obtaining an improvement of the classification, but also of what happens in the pulp-lifters. This result opens up a new development field of new pulp-lifter geometries that can achieve an improvement of up to 3.3% (Fig. 12), which is the maximum capacity that can be provided by the 0º slot grates, compared to the current 17º. Experimental work like that of S. Latchireddi and S. Morrell (2006) has attempted to develop new pulp-lifter geometries and concepts, which have not yet been accepted massively by mill manufacturers. In Chile, which is the world's largest copper producer, SAG mills with these kinds of innovations have not been implemented yet.

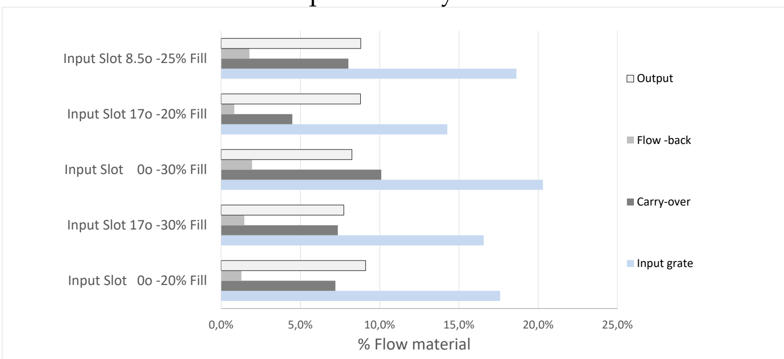

Fig. 11. Flow through Grates and Pulp-Lifter

The DOE analysis of the performance of the grate condenses its results in a graph of absolute normal effects that present the following results (Fig. 13): It must be indicated that the analysis has been made considering a complete factorial design with two factors and an intermediate point; the factors are the slot angle and the filling level; the aim of this analysis is to find out if there is a statistical basis that determines the degree of importance of the factors and their validation. The result indicates that the slot angle factor is more significant than the filling level, and furthermore, in the same Fig. 13 it is seen in the cube graph that the operating condition of 30% filling with a 0º slot angle presents a greater flow percentage than all the rest, indicating that this would be the best operating condition of the mill to get the best processing level.

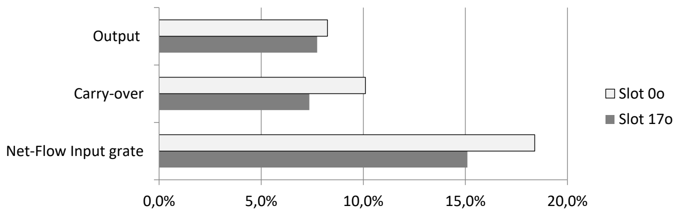

Fig. 12. Flow into Pulp-Lifter with a 30% Fill

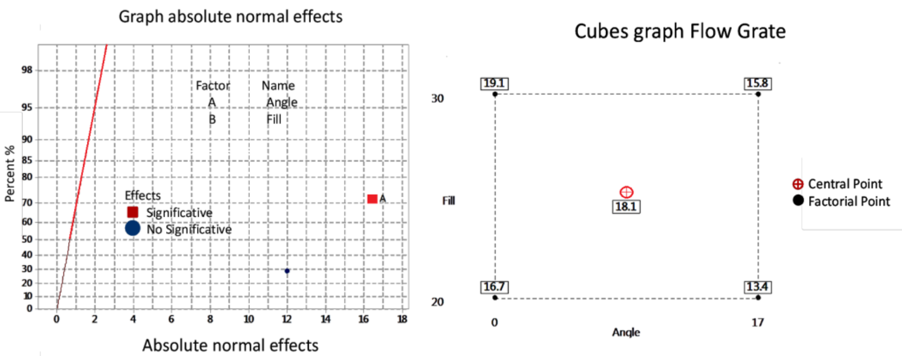

Fig. 13. Absolute normal effects and cubic graph for slot angle and filling level factors

7. Conclusions

It is possible to make simulations with coherent results by incorporating restitution coefficients that consider the presence of liquid between the material and the grinding means, in this way obtaining good quality simulations with an important reduction of the use of computational resources.

The simulations based only on DEM are capable of detecting small performance changes of the particle flow by incorporating small changes in the geometry, without loosing coherence in the results.

Grates that have a slot angle parallel to the mill's axial shaft (0^o) present an increase in the net entering flow of the pulp-lifters, achieving a 3.1% theoretical improvement with respect to the grates that are used at present.

The most important conclusion corresponds to a corollary of the simulation presented here, which indicates that the pulp-lifters are those that have the greatest impact on the outlet flow of the mill. This opens up a large field of study for making simulations with new pulp-lifter geometries and their optimization.

The statistical analysis based on complete factorial DOE, where two slot factors, slot angle and filling level, are considered, both with intermediate point, indicate that the slot angle of the grates is more important than the filling level; it can also be interpreted as meaning that for whatever filling level, the flow through the grates increases as the slot angle decreases.

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