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Increasing drying efficiency by modifying the design of feed chute of the Gol-e-Gohar pelletizing plant ball mill

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Abstract

Pelletizing plant of the Gol-E-Gohar mining and industrial company consists of a burner, a dry ball mill (6.2 m × 13 m), and an air separator. The ball mill consists of a 2 m-long drying and an 11 m-long grinding chambers. The iron ore concentrate is fed to the drying chamber by a feed chute. It was found that when the feed moisture content increased from 1.3% to 3.5%, the throughput decreased by 12% (35 t/h) indicating a low performance of the dryer. Monitoring the wear rate of flights for a period of 12 months showed that the first 0.8 m (59%) length of the dryer length did not experience any wear. To overcome this problem, various feed chute designs with different geometries were simulated by the KMPCDEM© software. With the aim of arriving at a proper material trajectory, where the total length of the dryer is used, a new feed chute was selected. The simulation results indicated that if the height of the feed chute is increased from 1.60 to 2.26 m and the slope is increased from 45 to 48 degrees the material arrives at the first 0.48 m of the drying chamber. In this manner, the unused part of the drying chamber decreases from 59% to 36% of the length. After installation of the new feed chute during a period of three months, the throughput increased by 36 t/h.

1. Introduction

Drying commonly describes the process of thermally removing moisture to yield a solid product. Rotary drying is one of the many drying methods existing in unit operations, which is classified as direct and indirect. This classification is based on the method of heat transfer between hot air and solid particles [1]. In directly heated dryers, hot gas is passed through the drum, which provides enough heat to vaporize the moisture from the showering solid particles [2]. Directly heated rotary dryers have been commonly used across a wide range of industries because of their flexibility in handling a wider range of materials than other types of dryers and their high processing capacity [3]. Rotary dryers are also used to perform heating, chemical reactions, and mixing [4]. These dryers are usually long cylinders rotated axially and slightly inclined (0-5^0) to the horizontal [2, 5]. They are often used in minerals, mineral concentrates, food, metallurgical, chemical, food, fertilizers, pharmaceuticals, cement, sugar, soybean meal, corn meal, and plastic industries to remove the moisture from the granular material and increase its temperature [2, 4, 6-8].

Rotary dryers are especially used for drying iron ores that are being upgrading from the concentration plant, and then sent as a feed to the pellet production circuit for the reduction of the iron. The granular material to be treated is fed at the upstream side and collected at the downstream end. Most of the rotary drums are equipped with longitudinal fins/flights attached to the wall of the drum, which could carry particles and disperse them into hot gas stream to induce heat and mass transfer between particles and hot gas, which

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could then influence the dryer efficiency [9-11]. Particle behavior in the transverse section of the rotary drum is very complicated: as the drum rotates, the particles are lifted by the flight and discharges continually until all the particles in the flight are discharged. With the revolution of the drum, particles packing, slipping, slumping, rolling, cascading, and cataracting, and centrifuging modes are possible if the rotational velocity is large enough [11, 12].
Although the drying process is affected by a large number of factors such as hot gas temperature, hot gas flow rate, feed temperature, throughput, rotational rate, geometrical configuration of the dryer, and flight geometry, filling degree and particle properties [4, 13], the particle behavior plays a major role in controlling the dryer efficiency and the quality of the final product. Therefore, the performance of the drums greatly depends on the gas–solid contact, which is controlled by the flight design [2, 5]. In order to accurately predict the movement of solids and the drying process that occurs within a rotary dryer, it is necessary to understand the behavior of the solid particles within dryer [11]. Previously, we studied [14] the effect of flight design on drying efficiency by testing various flight designs with different geometries with the aim of arriving at a proper veiling profile that maximizes the gas–solid contact. Finally, an optimized flight design was manufactured and installed in the dryer of the Gol-E-Gohar pelletizing plant. The evaluation of plant data showed an increase of 15 t/h in the throughput.
Many researchers believe that the resistance time is undoubtedly the most important parameter because it determines the average time of contact between the wet solids and the drying gas [15, 16]. In the literature, it has been proved that the resistance time of the solids depends on many factors such as the dryer geometry, length, diameter, operating conditions such as feed rate, gas rate, and direction, slope, and rotation rate of the dryer [15]. Another factor affecting the particles residence time is the feed chute design, which determines the falling location of the material. If the feed chute design causes the particles to fall away from the entrance wall of the dryer, the first part of dryer will be inoperative. In other words, in practice, the effective length of the dryer will be shorter than the dryer length. To our best knowledge, the effects of feed chute design and effective dryer length have been discussed in detail in the literature. The proposed method to indicate the effect of feed chute design is based on the predication of particles transportation in the dryer.
The estimation of solids transportation within a rotary dryer has been the subject of several studies. Both the experimental measurements, based on tracer pulse input-response runs, and the development of theoretical models have been reported by Hatzilyberis and Androutsopoulos [17]. The study of motion of solid particles through rotary drums based on experimental measurements is costly and difficult, if not impossible. On the other hand, any model of particle motion must take all mechanisms of transport into account or it will not be realistic. Furthermore, it is very likely that individual particles do not reach the steady state motion. However, the estimation of solid transportation based on theoretical models of the particle transport in rotary dryers has presented many problems [18].
In addition to these methods, the Discrete Element Method (DEM) is a popular method that is able to simulate particulate systems. DEM was first introduced by Cundall in 1979 to model the behavior of soil particles under dynamic load [19]. In 1990, Mishra and Rajamani simulated the charge motion in a laboratory ball mill in two dimensions, which could be considered as the first reported work using DEM in the mineral processing field [20]. In the last decade, DEM has extensively been used to model particle motions in various industrial applications [21-24].
In DEM, every particle has a unique ID and it is described by specific properties (i.e., constant characteristics) such as shape, size, density, Poisson’s ratio, and elasticity modulus or stiffness. By considering these properties of particles and physics laws at any time step, DEM calculates acceleration, velocity, and position of particles, which could be called variable characteristics. The environment where the simulation is performed known as geometry is described by a series of vertexes that are connected to each other with a certain order to build a desired shape. The physical characteristics of geometries and their movements are also defined.
Movements of particles are grouped in two categories: free falling and colliding states. When particles are at free falling state, their positions could be calculated by their velocities and accelerations due to gravity. During the simulation, particles continuously have interactions with each other and geometries. In this situation, in addition to the gravitational

acceleration, there is another acceleration that is originated from the contact force acting on the particles. Computer implementation of DEM follows a cycle of contact detection, force calculation for each particle, and finally, updating the spatial position of the particle until the desired termination time is reached. In-depth presentations of the mathematical formulation and computer implementation can be found elsewhere [25].
This research work was carried out to modify the feed chute design of the Gol-E-Gohar pelletizing plant ball mill dryer to increase the throughput by increasing the dryer effective length. A methodology based on the DEM modeling was proposed to select the best feed chute design for large-scale industrial rotary dryers. The criterion used for selection was the effective length of dryer. The new design with a higher effective length was installed and its performance was compared with the old design.

2. Materials and methods

2.1. The Gol-E-Gohar palletizing plant circuit

Iron ore concentrate is the main product of iron ore processing plants. The processed ores, or concentrate, are in the form of a very fine powder that is physically unsuitable to be used in the blast furnace and must be agglomerated by a pelletizing process. Iron ore pellets are spheres of typically 9-16 mm, which are used as raw materials for blast furnaces [26]. They typically contain 67-72% Fe and various additional materials for adjusting the chemical composition and the metallurgical properties of the pellets. The configuration of iron ore pellets as packed spheres in the blast furnace allows air to flow between the pellets, decreasing the resistance to the air flows up through the layers of material during the smelting. The configuration of iron ore powder in a blast furnace is more tightly-packed and restricts the air flow. This is the reason that iron ore is preferred in the form of pellets rather than in the form of finer particles.
At the Gol-E-Gohar mining and industrial company, a pelletizing plant with a capacity of 600 t/h converts the concentrates of all three processing plants (the magnetite processing plant, the hematite processing plant, and the Polycom iron ore processing plant) to pellets. Typically, the d_{80} and moisture content of the pelletizing plant feed are 400-500 μm and 2–5%, respectively. The first stage in the pelletizing plant is regrinding of the iron ore concentrate to further decrease the particle size, which is usually expressed by the Blaine number (i.e., average particle size deduced from surface area; the higher number indicates lower size). The pelletizing plant, in addition to a pellet production circuit, consists of two parallel dry grinding circuits with the nominal capacity of 300 t/h. Each grinding circuit includes a burner, a pre-drying chamber, and a dry ball mill (6 m × 13 m), which works in a closed circuit with an air separator.
In the grinding circuit, the moisture content of the feed is a crucial parameter because of its effect on the grinding performance and throughput. It is, therefore, important to reduce the moisture content of the feed. Grinding is performed in ball mills consisting of a 2 m-long drying chamber and an 11 m-long grinding chamber.
In the grinding circuit, the iron ore concentrate is fed to each ball mill through a feed chute. In the drying chamber, the moisture content of the feed is reduced by the hot gas generated by a burner located a head of the feed chute (Figure 1-a). The material is subsequently transported into the grinding chamber. The ground material is moved by the air flow created by a blower at the feed end and a suction pump at the end of the line. The residence time is well-correlated with the drying efficiency. In general, a higher residence time of particles in the dryer results in a higher drying efficiency. The materials are then classified by the air separator. The fine materials with the Blaine number above 1900 cm^2/g are sent to the pellet production circuit and the coarse materials are recycled to the ball mills for further grinding.

2.2. Drying chamber and burner

The drying chamber is a cylinder with a diameter of 5.6 m and a length of 2 m. It has been mounted before the grinding chamber of the ball mill and rotates with the ball mills at 75% of the critical speed. The drying chamber consists of 56 flights in two rows with the length of 1.35 m. The main function of flights is to subject the material to the hot gas tunnel in order to decrease the moisture below 0.2%. The dryer is fed by a step feed chute that consists of 3 steps with the angle of 45^o to pass the particles from the transfer chute to the dryer (Figure 1-b).
According to the operating manual of the plant, the dryer should operate normally when the feed moisture is about 5% but due to the low performance of the drying section, the ball mill throughput significantly decreases when the feed moisture becomes more than 2%. The option of increasing temperature to compensate cannot be practiced in the plant because the temperature of

air passing the bag filter must not exceed 100°C. Consequently, the mill throughput is reduced to obtain material with an acceptable moisture content.
The daily sampling results of the grinding circuit showed that there was a correlation between the moisture content of the feed and the throughput of the circuit. In other words, the ball mill throughput is very sensitive to the feed moisture. An increase in the feed moisture from 1.3% to 3.5% decreased the throughput by 35 t/h (12%). It was found that 56% of the operating time, the feed moisture was above 2%. It is, therefore, necessary to improve the performance of the dryer to achieve the nominal mill throughput.

In the period of the annual plant overhaul, visual observations of wear pattern of flights showed that the second row of flights were highly deformed because of the high wear rate, specially in the second half of flights. However, the first row, except in the small part at the right hand side, remained intact (Figure 1-c). This clearly indicates that the phenomenon implies that the first row of flights and a part of the second row with a total length of 80 cm do not participate in the drying process because they have no contact with particles. It was then concluded that the effective length of the dryer was lower than the expected length. This problem originates form an inappropriate design of the feed chute, which directs particles in a way that they collide with the second row of the flights instead of the first row.

Figure 1. a) Schematic view of dryer and feed chute, b) feed chute, and c) worn dryer flights.

2.3. Simulation of movement of particles

In order to simulate the particle movement within the dryer, a 3D DEM-based software called $KMPC_{DEM}^{©}$ was developed. The development of the software started in 2013 at the Kashigar Mineral Processing Research Center (KMPC) in the Mining Engineering Group, Shahid Bahonar University of Kerman, Iran. Full access to the software source codes enabled us to add or modify the algorithms and related relationships, and also to extract the desired simulation data from particles and/or geometries.
The data entry part of the software includes three main sections. The first section includes importing the geometries that had been designed in the SolidWorks software. In the second section, the physical properties of the geometries and their speeds (if it was necessary) were defined. In this section, the users must specify the location of the entering and exiting particles. The particle properties such as the size distribution, physical properties (density, elasticity modulus, Poisson's ratio), and equipment throughput were entered in the third section.

The software also includes the simulation results viewing windows to view the results obtained during the computation process simultaneously in any direction and capture the results. Before running the simulation, the software meshes the geometries and determines the generating rate of the particles based on the throughput and particle size, and then starts the simulation.
In this research work, the dryer along with the detailed features of feed chute was drawn in Solidworks© (2016 version) and the geometry was imported to the $KMPC_{DEM}^{©}$ software. In the simulations, the total dryer throughput was assumed to be 600 t/h, which was the nominal tonnage stated in the plant documentation. The materials enter the dryer by two transfer chutes (the fresh feed and recycled coarse particles), which are located behind the feed chute. The feed rate in each transfer chute is 300 t/h. The detailed operational conditions and material properties that were used in DEM simulations are listed in Table 1.
In these simulations, the mass of each sphere particle with a radius of 5 mm and a density of 5

t/m^3 was approximately 2.61 g. To generate a throughput of 600 t/h, it was necessary to add 63661 particles per second. Simulations were continued until the process reached the steady state. After this period, the number of particles entering the simulation is equal to the number of particles that are exiting from the simulation. The average time of stabilization was approximately 10-12 s. Simulations showed that after reaching the steady state, an average of about 650,000 particles are present in the simulation. All images were captured when the simulations were performed at least for 20 s. In other words, during the twenty seconds of simulation, 1.3 million particles were added and about half of them exited. The required computation time for 1 s of simulation was 3100 s. Thus each simulation required more than 17 h of computation. The workstation specifications used for the simulations are presented in Table 2.

The simulation results were validated by the wear pattern on the flights. In other words, the trajectory of particles obtained from the simulation was compared with the wear pattern on the flights that, in fact, was the trace of particle movement. At the first stage, the original feed chute design was simulated, and the results obtained were validated with the plant flight wear pattern. Several feed chute designs were tested by simulation in order to increase the effective length of the dryer. Finally, with the aim of arriving at a proper design that minimizes the unused part of the dryer (i.e., increases the effective dryer length), a new feed chute design was obtained. A new feed chute was constructed and installed in the dryer and the performance of the dryer was monitored.

Table 1. Operational conditions and material properties.

Parameter	Value
Throughput (t/h)	600
Particle radius (mm)	5
Particle density (t/m^3)	5
Friction coefficient	0.5
Poisson's ratio	0.25
Young's modulus (N/m^2)	2×10^6
Restitution coefficient	0.75
Particle generation rate (Number/s)	63,661
Time step (s)	2×10^5

Table 2. The workstation specifications.

Main Board	Asus X99 E WS
CPU	Intel Xeon E5 2650 v3
GPU	NVidia GTX Titan Xp
RAM	128 GB DDR4 3000 MHz
HDD	1 TB WD 7200 rpm
SSD	240 GB

3. Results and discussion

The DEM simulation results of the existing feed chute design (Figures 2a and 2b) are shown in Figure 2-c. The particles enter the dryer through the two transfer chutes, and the combined stream enters the main feed chute. The feed chute directs and transfers all particles to the dryer. The color of particles indicate the particle speed. Inspection of Figure 2-c indicates that the location of falling material in the drying section is not appropriate because the major part of the length of the dryer is not used. This implies that the residence time of material in the section is not high, which lowers the drying performance. A digital ruler was used to measure the effective length of the dryer to compare the results. Measurements showed that the distance between the particle impact point from the beginning of the dryer was about 80 cm. Considering the length of the flights in one row that was 61 cm, it was found that in addition to the first row, even part (the first 19 cm length) of the second row of flights did not participate in dispersing the material. This is similar to short-circuiting in various process equipment. In fact, only 55 cm of 135 cm of the dryer length (about 41%) actively contributed in the drying task. On the other hand, these results were in good agreement with the industrial observations (Figure 1c), which reconfirmed the accuracy of the results.

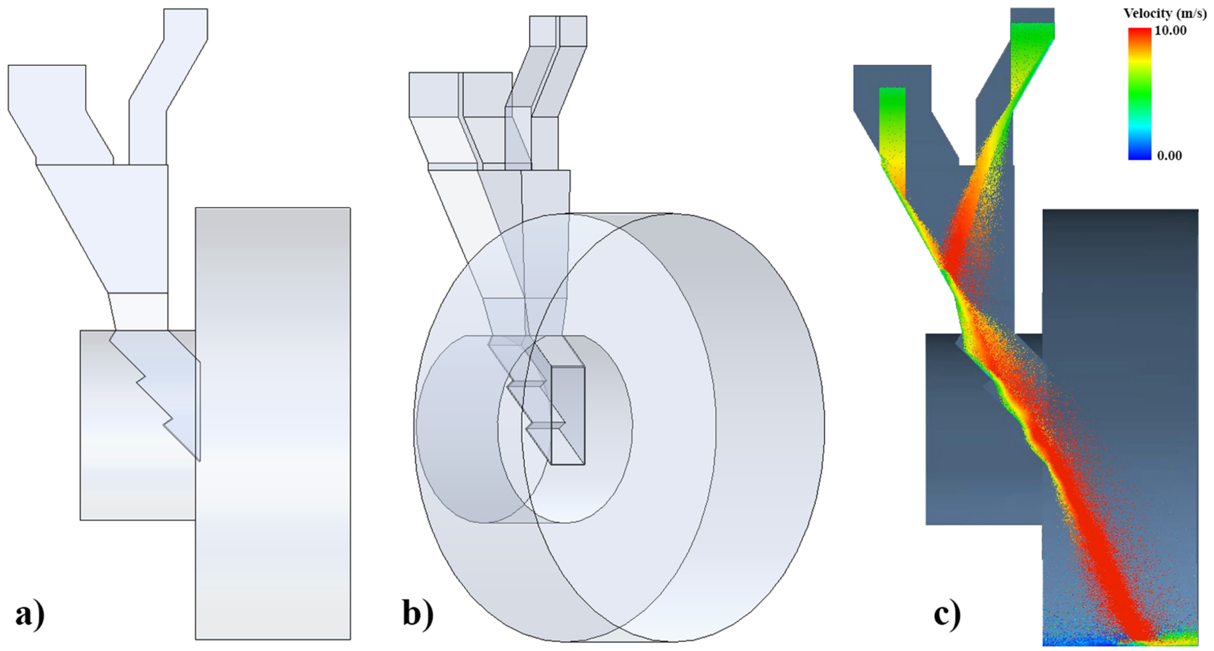

Figure 2. The original feed chute design a) side view, b) perspective view, and c) DEM simulation results.

To overcome this problem, a number of simulations were performed using various designs by the $KMPC_{DEM}^{©}$ software. Finally, it was decided to increase the height of the feed chute from 1.60 m to 2.26 m, increase its step slope from 45 to 48 degrees, and add a new step with the slope of 60 degree at the top of the previous steps to the increase effective length of the dryer (Figures 3a and 3b).

As it can be observed in Figure 3c, the overall falling slope of particles increased, which, in turn, decreased the distance between the entrance wall and the impact point of the falling material. Measurements indicated that the distance decreased from 80 cm to 57 cm, which implied a 23 cm increase in the effective length. This indicated that the active part of the dryer increased from 41% to 58%.

Although the idea was to increase the active part significantly, it was not possible to increase the lowest step slope or to increase the height of the feed chute. Because these modifications could increase the possibility of particle accumulation in the hot gas tunnel. To prevent such an event, a safe distance should be considered from the wall. Furthermore, the impact of the material only on a narrow area increases the wear rate, which could increase the maintenance work and mill shut down periods. It is important to arrive at a design that disperses and spreads the particles in a large area as possible.

To solve the problem of a narrow impact area and to lead the material to an even more backward along the dryer, it was decided to change the slope of the highest step. A design of experiments was used to arrive at 48 degrees. Simulations were performed at various slopes from 60 to 40 degrees by 5 degree intervals. The slope below 40 degrees, due to the adhesion of the material, blocked the feed chute. The longest length of the active part of the dryer and sufficient dispersion occurred when the slope was 45 and 50 degrees. As a result, it was decided to change the slope of the highest step to 48 degrees to make harmony between this step and other three steps (Figures 4a and 4b). The feed chute design was then modified, and the simulation was performed again to observe the effect of modifications on the extent of the impact area (Figure 4c).

According to the simulation results, the particles did not impact a limited area anymore when colliding the flights and spread in a larger area in the dryer. Measurements also showed that the active part of the dryer increased from 41% to 64%, compared to the original design. Finally, this design was selected as the modified design. The key differences between the original design and the modified design parameters are listed in Table 3.

Figures 5a and 5b illustrate the difference between the original and the modified design. The technical drawings were prepared considering the plant operational condition to make the life of flights as long as possible. The feed chute was built based on the technical drawing and installed in one of the mills (Figure 5c).

The daily averages of the throughput from June 2017 to December 2017 are shown in Figure 6.

The vertical line shows the date of replacing the original feed chute with the modified one. It was found that by replacing the feed chute, the average throughput increased by 36 t/h, which was about 12% of the nominal circuit capacity. It was then concluded that the feed chute design played a major role in the drying performance, and also indicated the sensitivity of the ball mill throughput to the feed moisture content.

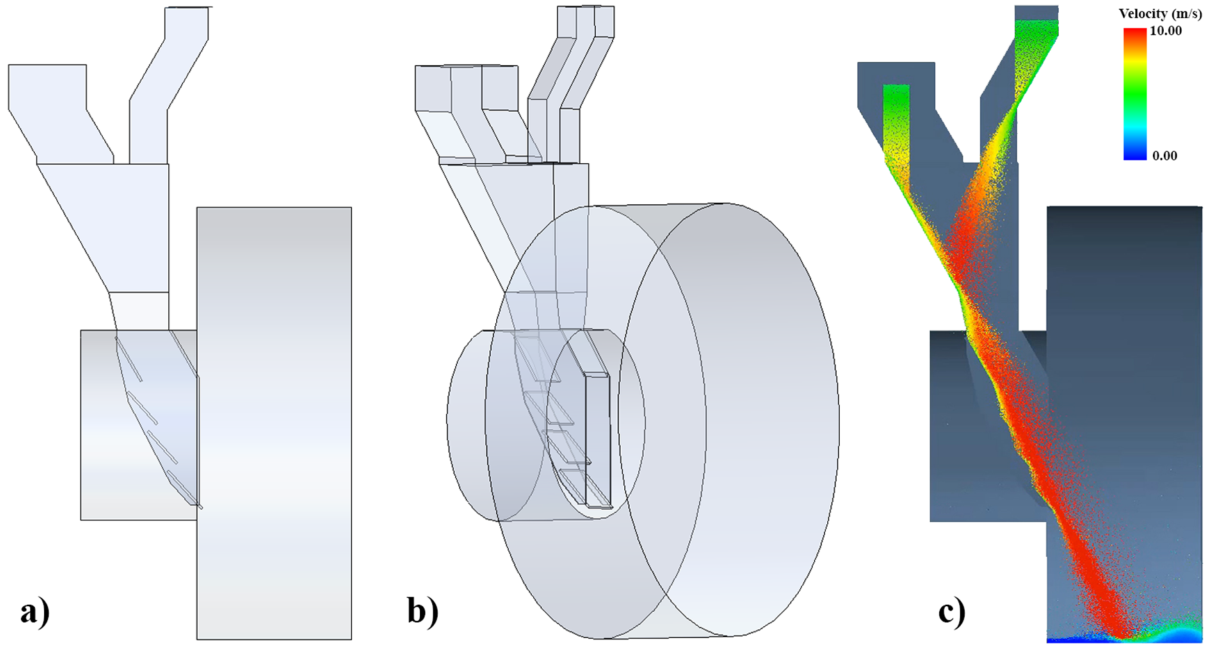

Figure 3. The developing feed chute design a) side view, b) perspective view, and c) DEM simulation results.

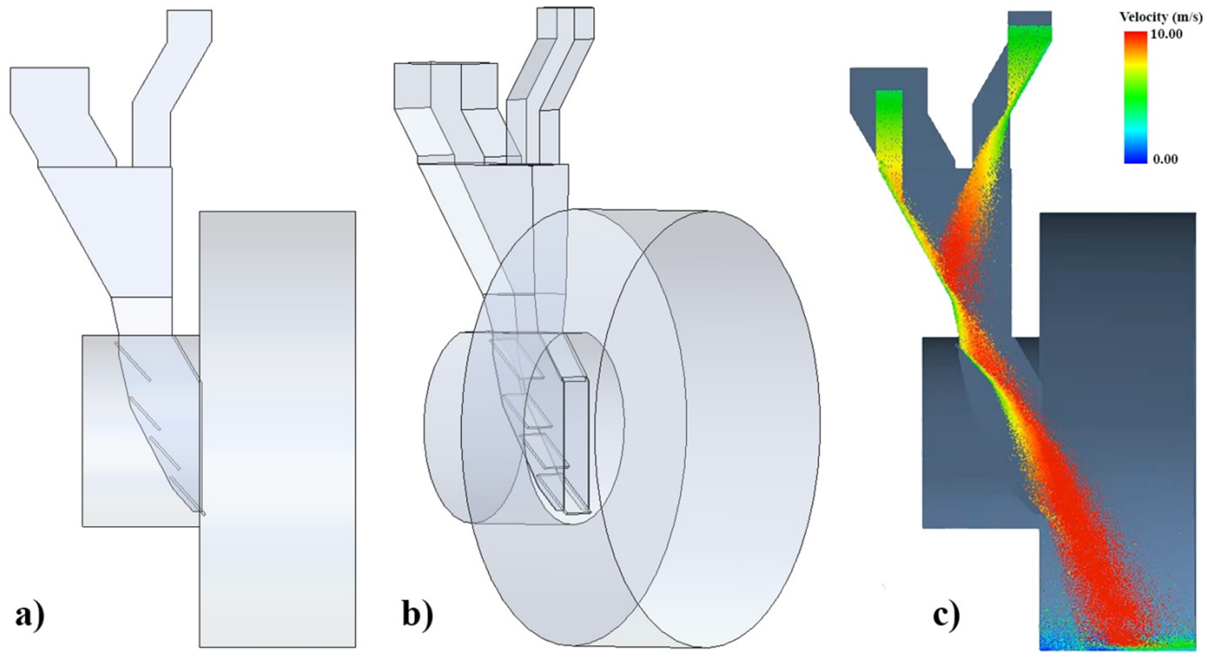

Figure 4. The modified feed chute design a) side view, b) perspective view, and c) DEM simulation results.

Table 3. The key differences between the original design and modified design parameters.

Parameter	Original design	Modified design
Height (cm)	160	226
Number of steps	3	4
Slop of steps (degrees)	45	48
Active part of the dryer (%)	41	64

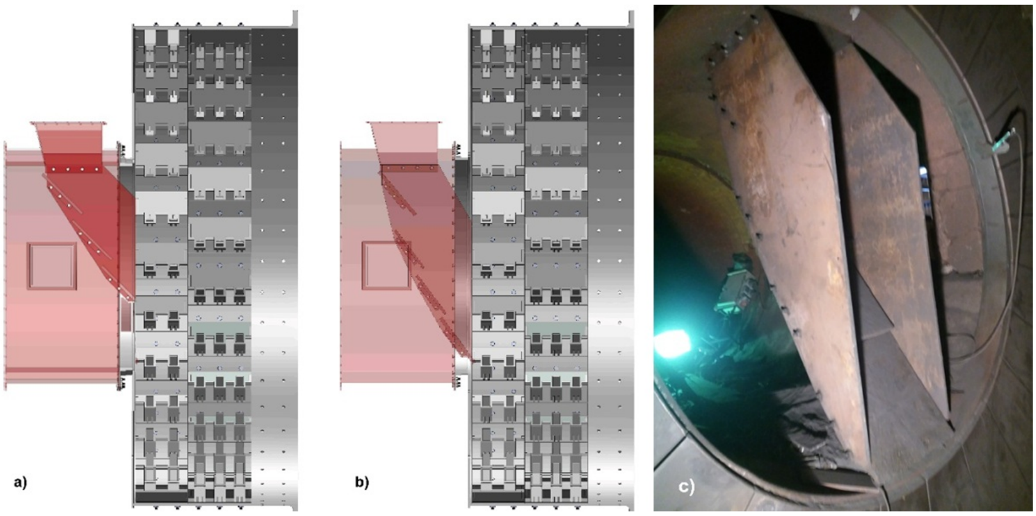

Figure 5. A general view of the feed chute and the dryer a) original design, b) modified design, c) installed feed chute.

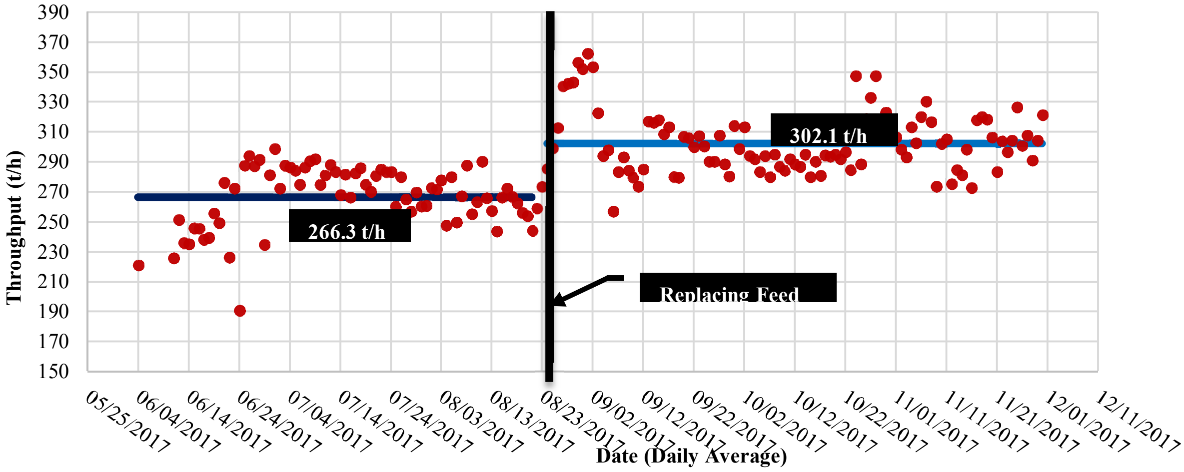

Figure 6. Daily averages of the mill throughput (June 2017 to December 2017).

4. Conclusions

- The numerical modeling of particles falling in the drying section of the ball mills of the Gol-E-Gohar pelletizing plant using the discrete element method (DEM; $KMPC_{DEM}^{©}$ software) indicated that the feed chute design was inappropriate. This meant that the active length of the dryer was 41%.
- Various feed chute designs with different geometries were simulated by the $KMPC_{DEM}^{©}$ software with the aim of minimizing the distance between particle impact location and the entrance wall to increase the effective drying length.
- It was found that to increase the effective length of the dryer, the height and slope of the steps of the feed chute must be increased from 1.60 m to 2.26 m and 45 degrees to 48 degrees, respectively, and a new step at the top of previous steps must be added.
- The simulations indicated that the new feed chute design in comparison with the original one increased the active part of the dryer from 41% to 64%.
- Evaluation of the performance of the new feed chute in a period of seven months in the plant showed an increase of 36 t/h in the throughput.

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افزایش کارآیی خشک کردن با اصلاح طرح سرسره خوراک‌دهی آسیای گلوله‌ای کارخانه گندله‌سازی گل گهر

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چکیده:

کارخانه گندله‌سازی شرکت صنعتی و معدنی گل گهر شامل یک مشعل، آسیای گلوله‌ای (۶/۲ متر در ۱۳ متر) و یک جداکننده هوایی است. آسیای گلوله‌ای شامل یک بخش خشک‌کنی به طول ۲ متر و یک محفظه آسیاکنی به طول ۱۱ متر است. کنسانتره سنگ آهن به محفظه خشک‌کنی توسط یک سرسره خوراک‌دهی باردهی می‌شود. بررسی‌ها نشان داد زمانی که محتوی رطوبت خوراک از ۱/۳ به ۳/۵ درصد افزایش پیدا می‌کند، ظرفیت به میزان ۱۲ درصد (۳۵ تن بر ساعت) کاهش پیدا می‌کند که نشان از کارآیی پایین خشک‌کنی داشت. پایش نرخ سایش بالابرها در طی یک دوره ۱۲ ماهه نشان داد که ۰/۸ متر اول (۵۹ درصد) خشک‌کنی سایش ندارد. برای غلبه بر این مشکل، طرح مختلف سرسره خوراک‌دهی با شکل‌های مختلف با به کارگیری نرم‌افزار $KMPC_{DEM}$© شبیه‌سازی شد. با هدف دستیابی به مسیر مناسب مواد که در آن کل طول خشک‌کن مورد استفاده قرار می‌گیرد یک سرسره خوراک‌دهی جدید انتخاب شد. نتایج شبیه‌سازی نشان داد که اگر ارتفاع سرسره خوراک‌دهی از ۱/۶ به ۲/۲۶ متر و زاویه از ۴۵ به ۴۸ درجه افزایش داده شود، مواد در ابتدای ۰/۴۸ متری محفظه خوراک‌دهی فرود می‌آیند. به این طریق، بخش استفاده نشده محفظه خشک‌کنی از ۵۹ درصد به ۳۶ درصد طول کاهش پیدا کرد. بعد از نصب سرسره خوراک‌دهی جدید، در یک دوره سه ماهه، ظرفیت به میزان ۳۶ تن بر ساعت افزایش پیدا کرد.

کلمات کلیدی: کارخانه گندله‌سازی، خشک‌کن، سرسره خوراک‌دهی، محل ریزش، $KMPC_{DEM}$©.