IJE TRANSACTIONS B: Application Vol. 26, No. 8, (August 2013) 927-932

International Journal of Engineering

Journal Homepage: www.ije.ir

TECHNICAL NOTE

Modeling and Simulation of Modern Industrial Screens using Discrete Element Method

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P A P E R I N F O

Paper history:
Received 14 January 2013
Received in revised form 13 April 2013
Accepted 16 May 2013

Keywords:
Modeling
Simulation
Discrete Element Method
Screen
Banana Screen
DEM

A B S T R A C T

With progress in mineral processing technologies, particle size classification equipment has also been changed to satisfy the needs of modern plants. Accordingly, design, manufacturing and utilization of banana screens in mineral processing plants have led to increased screening efficiency at industrial scale. Banana screen is an important invention which increases screening capacity has occurred in past decade. These screens are made of several screening segments with different slopes. Despite widespread use of banana screens in industry, their control and optimization has been limited due to lack of fundamental knowledge about the screening process. Using numerical simulation is an effective method to overcome such limitations in design and optimization studies. Discrete element method (DEM) is a numerical approach which computes particles interactions and their movements. In this paper, the results of modeling and simulation of particles movement and classification in banana screens using DEM method in PFC3D software environment is presented. Hence, DEM simulation of a three-segment banana screen was done to study the effect of design and operating variables on classification. To validate our DEM simulation, the results obtained in this study were compared with the previous results reported in literature. The comparisons approve the validity this DEM simulation.

doi: *10.5829/idosi.ije.2013.26.08b.14*

1. INTRODUCTION

Screening is one of the oldest particulate material classification methods based on particle size which plays an important role in mineral processing plants [1]. Banana screen is one of the newest types of vibrating screens which consists of several plates connected together with different slopes (see Figure 1). The slope is high at the feed end and it decreases at the end of the screen to produce a layer with a fixed thickness along the screen which leads to increase in screen capacity. Control and optimization of these types of screens is an important task in mineral processing plants which requires basic information about screening process [2].

There are many mathematical models of screening process which are basically phenomenological models. These models have not been derived from first (physical) principles, hence due to the lack of complete understanding of screening operation, some of the parameters involved in these models must be determined experimentally. The lack of complete understanding of screening operation stems from the fact that distribution of particles, which have different sizes, between screen underflow and overflow streams is very complicated. Also, the effect of particles motion in various operational conditions contributes to their final classification. Some proposed models are based on reaction kinetics and statistical theories. For example, first order kinetics is a well-known theory which states that the rate of change in remained mass on the screen is proportional to the remained mass on the screen as function of screening time. Equation (1) represents this relationship mathematically.

$$\frac{\partial W}{\partial t} = -kW \quad (1)$$

where W is remained mass on screen and k is the screening rate constant.

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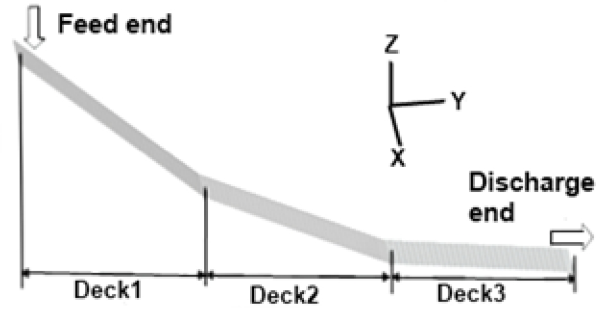

Figure 1. Banana screen with three plates with different slopes

In practice, the behavior of final particles in a system depends on interactions of a particle on another particle and also contact of particle on wall. Therefore, screening process should be understood at particle scale [2]. As tracking and understanding of particles motion at microscopic scale by the laboratory methods is very complicated, so a numerical simulation method such as discrete element method can be used. Li et al. studied the motion of discrete particles on the screen by discrete element method that confirmed the negative effect of particles with a size near to that of the nominal screen aperture size and the positive effect of large particles in the feed stream on screen efficiency which was derived by Standish [3].

Song et al. explained an algorithm about the impact contact of discoid particles [4]. Finally, this method was expanded for screen simulation and Yan-hua and Xin made a three-dimensional simulation of screening process [5].

In this paper, industrial banana screens have been simulated and the effect of various parameters on the screen efficiency has been investigated according to the available information from previous studies.

2. THEORY

The discrete element method was developed by Cundall to solve the geomechanic problems in 1970 [6]. In this method, the contacts among the particles and between particles and the wall which is the screen surface are modeled by the rule of contact forces. In this model a simple numerical plane is used to monitor the motion and response of particles. Translation and swirl for particle i is calculated as:

$$m_i \frac{dv_i}{dt} = \sum_j \left(F_{ij}^{\mathrm{n}} + F_{ij}^{\mathrm{s}}\right) + m_i g \tag{2}$$

$$I_i \frac{d\omega_i}{dt} = \sum_j \left(R_{ij} \times F_{ij}^{\mathrm{s}} - \mu_{\mathrm{r}} R_i \mid F_{ij}^{\mathrm{n}} \mid \hat{\omega}_i\right) \tag{3}$$

where v_i, is transfer speed, ω_i, angular velocity, I_i, moment of inertia of particle i, g, acceleration of gravity, R_{ij}, a vector from center of particle i to contact point with particle j, F_{ij}^{n}, normal force of contact, F_{ij}^{s}, tangential force of contact. Normal and tangential components of contact are calculated as:

$$F_{ij}^{\mathrm{n}} = \left[\frac{2}{3} E \sqrt{\bar{R}} \xi_{\mathrm{n}}^{\frac{3}{2}} - \gamma_{\mathrm{n}} E \sqrt{\bar{R}} \sqrt{\xi_{\mathrm{n}}} \left(v_{ij} . \hat{n}_{ij}\right)\right] \hat{n}_{ij} \tag{4}$$

$$F_{\mathrm{s}} = \mu_{\mathrm{s}} \mid F_{\mathrm{n}} \mid \left[1 - \left(1 - \min\left(\xi_{\mathrm{s}}, \xi_{\mathrm{s,max}}\right) / \xi_{\mathrm{s,max}}\right)^{\frac{3}{2}}\right] \hat{n}_{ij} \tag{5}$$

$$\bar{R} = R_i R_j / \left(R_i + R_j\right) \tag{6}$$

$$\xi_{s,\mathrm{max}} = \mu_s \left[(2 - \tilde{\sigma}) / 2(1 - \tilde{\sigma})\right] \xi_{\mathrm{n}} \tag{7}$$

$$\hat{n}_{ij} = \left(R_i - R_j\right) / \left|R_i - R_j\right| \tag{8}$$

$$E = Y / \left(1 - \tilde{\sigma}^2\right) \tag{9}$$

where R_i and R_j, are radius of particles i and j, Y, Young's modulus, $\tilde{\sigma}$, Poisson's ratio, Y_{n}, simple damping coefficient, μ_{s}, coefficient of friction, ξ_{s}, overall tangential displacement, μ_{r}, coefficient of rolling friction. The action between the particles and wall is calculated according to above equations and the process is dry [2].

3. MATERIALS AND METHODS

In this project, authors used PFC3D (Particle Flow Code in Three Dimension) developed by Itasca Consulting Group, Inc., 1998 to simulate the screening process [7]. At first step of simulation, it is necessary to design and generate the screen surface. In this project, the virtual screen was produced in the software environment according to the details of screen design and geometry explained in [2], which can be seen in Figure 2 by considering X, Y and Z axis in 3D.

The number of the screen surfaces is calculated from the point where the feed enters into screen to the point where particles leave the screen and discharged. The simulated screen is a 1/5th scale model with 3 screening plates. Plates 1, 2, and 3 are considered from 0–33%L, 33–66%L and 66–100% of the screen length, L, respectively [2]. Figure 3 shows the defined balls that act as the feed particles in simulation in different colors. The particle size distribution of the feed (coal) is about 0.45 to 2 mm that is shown from red (the largest particle) to dark blue (the finest particle). Figure 4 shows the screen surface in a close-up view.

The details of the screen geometry and the operating condition can be seen in Table 1 [2].

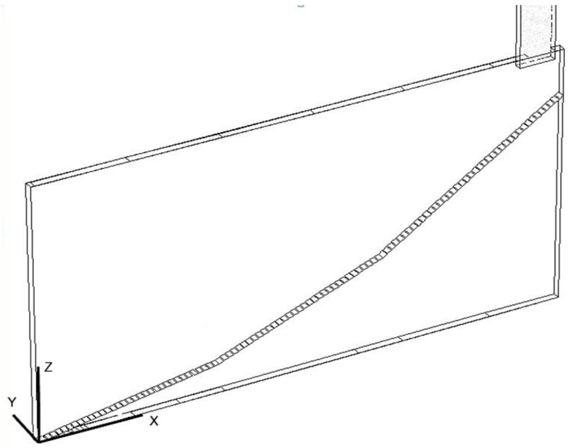

Figure 2. Generated virtual screen in PFC3D software. The feeding part of the screen containing the various balls as the feed particles can be seen at the top right of the figure.

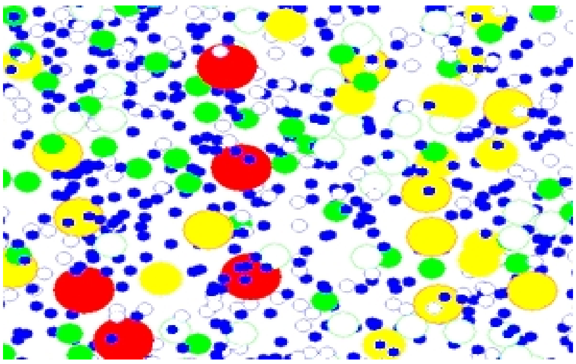

Figure 3. Feed particles with color of red, orange, yellow, light green, dark green and light blue to dark blue showing various range of particle sizes

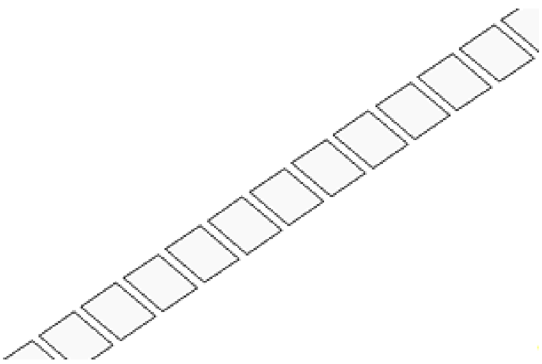

Figure 4. A close-up view of simulated screening surface

TABLE 1. The details of the simulated screen geometry and operating condition

Property	**Value**
Screen width (mm)	9
Screen length (mm)	600
Aperture size (mm)	1
Length of wire (mm)	5
Open area (%)	17
Height of feed downfall (mm)	30
Vibration frequency (Hz)	15 (5 to 25)
Vibration amplitude (mm)	2 (1 to 3)
Particles motion	Linear in slope of 45 degree
Particles density (kg/m^3)	1400
Wall density (kg/m^3)	1050
Damping coefficient among particles	5×10-5
Damping coefficient between particle and wall	5×10-4

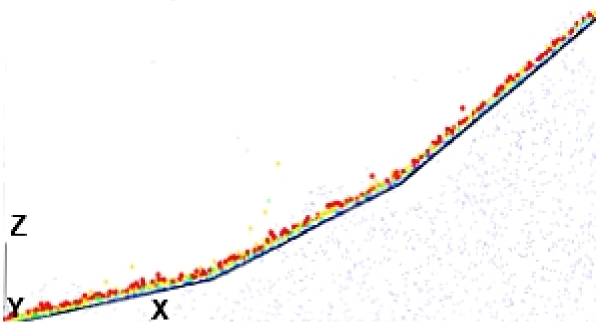

Figure 5. A view of three-plate screen at the end of DEM simulation

With starting the simulation, a composite stream of particles with different sizes conflux with each other and drop down on the vibrating screen which some of them pass through the screen and some of particles discharge from the discharge end [2]. Initial vibration condition was set to a linear motion with a 45 degree angle relative to horizontal level, vibration frequency equal to 15 Hz and vibration amplitude equal to 2 mm.

In Figure 5, large particles remained on the screen surface and fine particles passed through the screen apertures can be observed. It is clear that the separation of fine particles occurs from the beginning of the screen. The partition curve concept is applied to define the screen performance and the effect of various parameters on it. In this paper, the partition curve is calculated as the percent of recovered mass of feed particles in specific size to the screen overflow which is the screen coarse product.

4. RESULTS AND DISCUSSIONS

4. 1. Vibration Amplitude To investigate the screen efficiency, as mentioned earlier, the partition curve was calculated and plotted in which the horizontal axis shows the average diameter of size fraction and the vertical axis shows the ratio of the number of remained particles in screen overflow (stream with large particles) to the total number of particles in the feed for each specified particles size class. According to Figure 6, it is observed that the decrease in amplitude of frequency leads to increase in separation efficiency.

Here, it can be noted that the reduction in amplitude causes reduction of force applied on the particles. So, the particles in a specific time snag more with the screen and have greater chance to pass through the apertures. It is important that for very small vibration amplitudes (less than 1 mm), the particles collect on the screen surface and because of insufficient force to move the particles, a good separation will not occur.

4. 2. Vibration Frequency The effect of changes in screen vibration frequency was investigated and the partition curve for these changes was plotted. According to Figure 7, it can be seen that the reduction of vibration frequency causes an increase in screen efficiency. The effect of reducing vibration frequency is similar to what was observed in reducing vibration amplitude. The low vibration frequency increases the simulation time. A lower screen vibration frequency leads to longer remaining time of particles on the screening surface ; therefore, transmission probability of particles through screen apertures will be increased. It is noted that very low vibration frequencies will decrease the separation efficiency.

4. 3. Slope of Screening Plates The slope of the screen surface is one of the important parameters which affects the screening process. In this project, when studying the effect of slope angle of each plate, the slope of other plates was considered constant. Firstly, according to the conditions defined in [2], the slopes of the first, second and last plates were considered to be 34, 22 and 10 degrees respectively. The results of simulations related to the first, second and third plates in different slopes are shown in Figure 8 to 10.

Considering the screen overflow partition curve, it can be seen that reduction in the slope of each plate improves the separation process. Reduction in the slope of a single deck screen leads to increase in effective size of apertures, decrease in velocity of the particles and increase in probability of particle passing through the screen which results in increased percent passing. However, the way a change in a plate slope angle affects overall screen efficiency is very complicated.

It is notable that the reduction of a plate slope has no effect on the percent passing of particles in previous plates. Change in slope angle of various plates is an effective method to control the particle velocity and percent passing of particles.

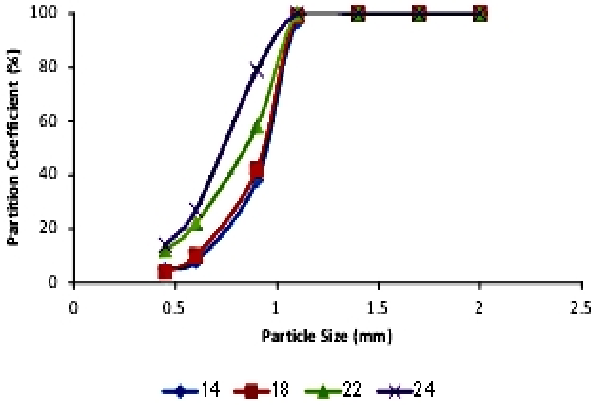

Figure 9. Partition curve of screen overflow with change in the slope of the second plate

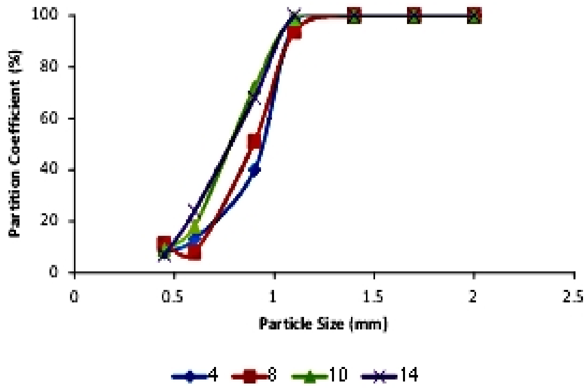

Figure 10. Simulated partition curves for particles recovered to overflow stream for third screening plate at various slopes

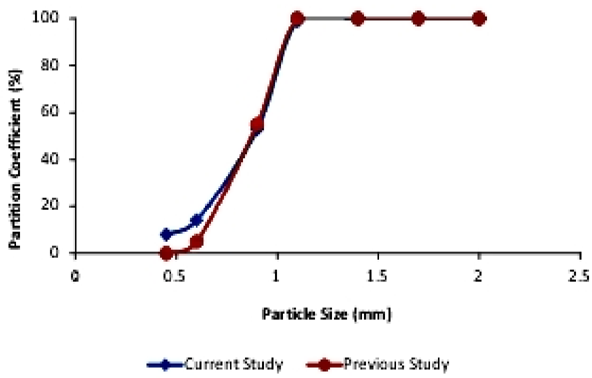

Figure 11. Comparison of simulated partition curve plotted for particles recovered to overflow stream with that of previous studies with vibration amplitude equal to 1.5 mm

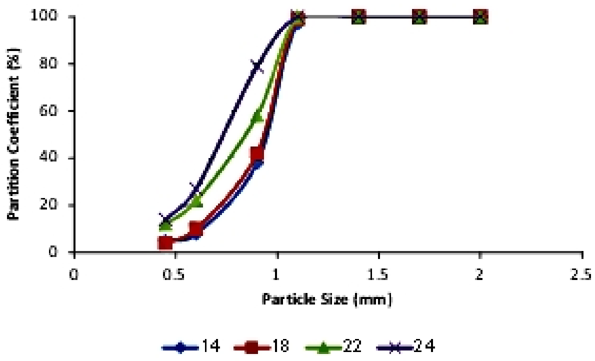

Figure 9. Partition curve of screen overflow with change in the slope of the second plate

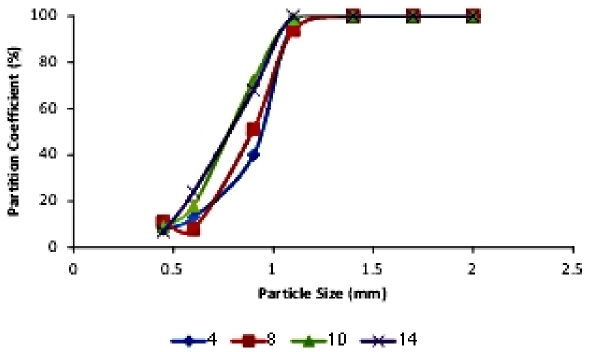

Figure 10. Simulated partition curves for particles recovered to overflow stream for third screening plate at various slopes

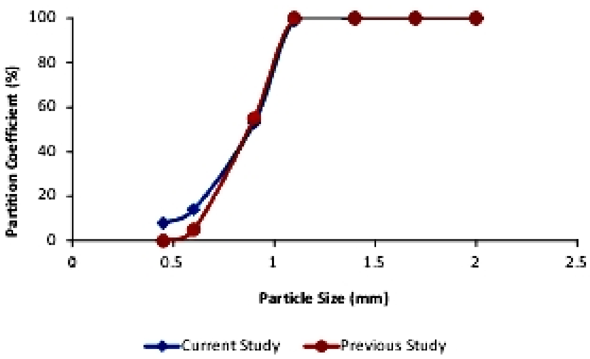

Figure 11. Comparison of simulated partition curve plotted for particles recovered to overflow stream with that of previous studies with vibration amplitude equal to 1.5 mm

4. 4. Validation of Simulation Predictions To evaluate the simulation results of this study, the results obtained from [2], were considered.

Figure 11 shows the results of present simulation and previous studies for vibration amplitude equal to 1.5 mm. It is obvious that all particles larger than the screen aperture (> 1.1 mm) have remained on the screen and both curves are coinciding.

For smaller particle sizes, the curves show a good similarity and the slight difference is due to the diversity in software and the simulation conditions which could not be easily specified due to inaccessible original data and models and algorithms implemented in the proprietary software.

Figure 12 shows the comparison of vibration frequencies. The partition curves associated with current simulation and previous study have been plotted in vibration frequency of 10 Hz.

In overall, the partition curves are in a good agreement while a notable difference can be seen in particles around 0.45 to 0.80 mm in size. The disagreement for fine particle sizes can be attributed to the low vibration frequency which is insufficient to detach fine particles attached to coarse particles and preventing them to pass through the screen aperture.

In Figure 13 the partition curves obtained in both current and previous studies related to first plate of screen in slope angle of 28 degrees are shown. Comparing the plotted curves confirms that the obtained results of both simulations match and the differences are negligible.

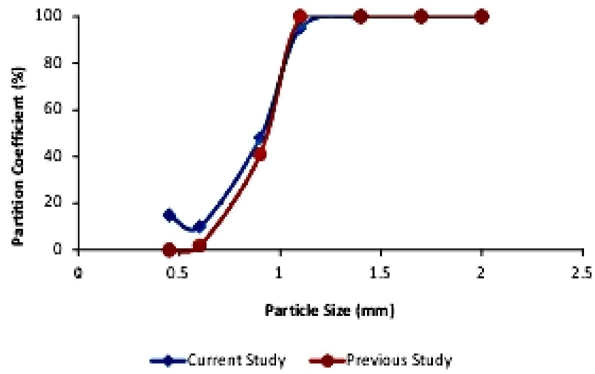

Figure 12. Comparison of simulated partition curve plotted for particles recovered to overflow stream with that of previous study in vibration frequency of 10 Hz

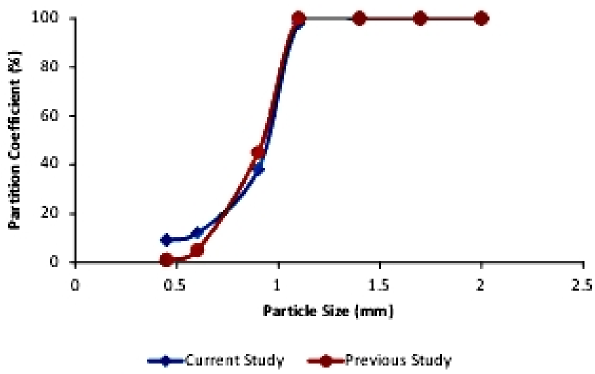

Figure 13. Comparison of simulated partition curve plotted for overflow stream with that of obtained in previous studies for the first plate with a slope of 28 degree

5. CONCLUSION

Two-dimensional modeling by discrete element method is able to predict the performance curve of new screens in details. In this paper, the particle flow on the screen was numerically simulated and the effect of various operation conditions and geometry of banana screen on the screen performance (partition curve) were investigated. The simulation results for the given banana screen showed that reduction in vibration amplitude and frequency improves the screen efficiency because the increasing in vibration frequency leads to increase in infiltration rate, contact rate and return rate. The reduction of slope angle of the plates increases the screen efficiency, because of increasing the effective aperture size, reduced particles velocity and increased time to pass through screen. Percentage of passing particles relates to their velocity in various conditions. An appropriate decrease in particles velocity causes increase in percentage of passing particles, but very low particle velocity can lead to particles aggregation.

The results clearly show that discrete element method can be used for process analysis and optimization in mineral processing.

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چکیده

با پیشرفت فناوری‌های مختلف فراوری مواد معدنی، تجهیزات طبقه‌بندی اندازه‌ی ذرات نیز برای برآورده کردن نیازهای کارخانه‌های جدید تحول پیدا کرده است. در همین راستا، طراحی، ساخت و بهره‌برداری از سرندهای موزی شکل در کارخانه‌های فراوری منجر به پیشرفت و بهبود فرآیند سرند کردن ذرات در مقیاس صنعتی شده است. سرند نوع موزی شکل، یک نوآوری مهم در فرآیند سرندکردن در دهه گذشته به‌شمار می‌آید که باعث افزایش ظرفیت در فرآیندهای طبقه‌بندی اندازه ذره می‌شود. این نوع سرند دارای صفحاتی با شیب‌های متفاوت است. اگرچه این ابداع، استفاده فزاینده‌ای در صنعت داشته است ولی هم‌چنان کنترل و بهینه‌سازی آن محدود است که مربوط به کمبود اطلاعات پایه‌ای در رابطه با فرآیند سرندکردن می‌باشد. به همین دلیل استفاده از شبیه‌سازی‌های عددی، یک روش مؤثر برای انجام چنین مطالعاتی می‌باشد. روش اجزای گسسته یکی از این رویکردهای عددیست که برهم‌کنش‌های بین ذرات و حرکت آنها را محاسبه می‌نماید. در این مقاله، نتایج مدل‌سازی و شبیه‌سازی حرکت و طبقه‌بندی مواد در سرندهای موزی شکل با روش اجزای گسسته برای یک سرند موزی شکل سه صفحه‌ای با هدف مطالعه و بررسی تأثیر شرایط عملیاتی و طراحی (هندسه) سرند بر روی عملکرد طبقه‌بندی انجام شد. به منظور اعتبارسنجی پیش‌بینی‌ها در شبیه‌سازی‌های انجام شده در این تحقیق، نتایج به‌دست‌آمده با نتایج گزارش شده‌ی قبلی در منابع مقایسه شدند که این مقایسه صحت شبیه‌سازی انجام گرفته در این تحقیق را نشان می‌دهد.

doi: *10.5829/idosi.ije.2013.26.08b.14*