Simulation of the ball mill loading movement and study of its operation modes depending on geometrical parameters of the lining

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Abstract. The article analyzes virtual experiments of the lining of a ball-type drum mill depending on a number of factors: the diameter of a mill, the diameter of grinding bodies, the number and height of liner lifters. The numerical experiment was performed using the EDEM software; a parametric model of the mill housing with variable liner lifters was created and imported, studies were performed using the virtual simulation method. A virtual experiment made it possible to study the grinding process without interacting the equipment which eliminates the risk of injury during and allows for more accurate research data. As a result of simulation of virtual experiments, values of the average kinetic energy of grinding bodies and the number of their collisions were determined.

1. Introduction
Experimental studies of construction materials production processes are an important task for Russian researchers. By 2020, the consumer demand for cement will have grown. The growth of energy costs will not have decreased which motivates research institutions to improve energy efficiency of cement production processes. An example of one of the energy-intensive processes is grinding in ball mills, which consumes up to 45% of electricity (per 1 ton of cement). Thus, experimental studies of the grinding process in ball mills and the search for energy-efficient solutions to improve cement production performance are important tasks.

A virtual experiment is a software-hardware complex that allows for conduction experiments without direct contact with the equipment. We are dealing with a laboratory setup with a remote access which includes a real laboratory, a software and hardware system to control the equipment and digitize data, and communication means. In the second variant, all processes are modeled using a computer.

The grinding process inside the rotating drum is complex and multifactorial [1]. Computer simulation and experiments in a virtual environment make it possible to study the influence of the diameter of grinding bodies, the mill diameter, and the geometry of lining plates on the grinding process in a ball mill [2–4].

2. Initial data
The choice of the experiment plan is determined by the research problem and features of the object [5]. The research process has several stages. The information obtained after each stage determines the further strategy of the experiment.
The following factors were taken into account (Figure 1):

- mill diameter, mm ($x_1$);
- grinding body diameter, mm ($x_2$);
- number of the lifters around the circle, pcs. ($x_3$);
- lifter height, mm ($x_4$).

![Figure 1. Diagram of the mill housing.](image)

A central compositional rotatable plan of the full factorial experiment (FFE CCRP $2^4$) was chosen for the study.

When planning, all possible combinations of factors are implemented at all levels chosen for the study. The central compositional rotatable plan (CCRP) has an advantage: its information surface approaches the spherical one, i.e., the accuracy in all directions at the same distance from the center of planning is the same.

In accordance with the chosen plan, the following levels of variation of the experimental factors were established: -1 - minimum; 0 - average; +1 is maximum; -2, +2 - star.

| Factors                           | Notation | Measurement units | -2  | -1  | 0   | 1   | 2   |
|----------------------------------|----------|-------------------|-----|-----|-----|-----|-----|
| Mill diameter, $D$              | $X_1$    | mm                | 2200| 2400| 2600| 2800| 3000|
| Diameter of grinding bodies, $d$| $X_2$    | mm                | 50  | 60  | 70  | 80  | 90  |
| Number of lifters around the circle, $n$ | $X_3$ | pcs.             | 20  | 18  | 16  | 14  | 12  |
| Height of lifters, $h$          | $X_4$    | mm                | 100 | 120 | 140 | 160 | 180 |

Using the data obtained during the performance of the PFC of DCC $2^4$, it is possible to build a regression model

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} b_{ii} x_i^2,$$

where $y$ – state variable; $x_i, x_j$ – levels of factors variation; $b_i$ – linear interaction coefficient; $b_{ij}$ – pair interaction coefficient; $b_{ii}$ – quadratic interaction coefficient.

3. Creation of the virtual experiment in the mill

To study the movement of the grinding load, an electronic-digital model of the mill housing with a parametrically variable composition of the product was created in the “Model Navigator” changing...
values of the varied factors [6], based on the planning matrix and rebuilding the entire node of the digital model (Figure 2): $a$, $b$ – length of lifters and intermediate plates, mm; $D$ – diameter of the mill, mm; $h$ – lifters height, mm; $L$ – mill length, mm; $n$ – number of lifters, pcs.

**Figure 2.** Parametric electronic-digital model of the mill housing.

The calculation was carried out using DEM Solutions EDEM. The platform was designed to simulate and analyze the processing of bulk particles [7]. To simplify the calculation, the simulation was carried out for a mill with a length of 1 m.

For each experiment, the movement of the grinding load was simulated with a rotation interval from 1 to 10 seconds. The simulation stops in 10 seconds, because imitation of the steady-state solution occurs in 4 seconds [8, 9]. The trajectory of grinding bodies depends on many factors (Figure 3).

![Diagram showing the trajectory of grinding bodies](image)

**Figure 3.** The trajectory of movement of grinding bodies at (a) $D = 3000$ mm; $d = 70$ mm; $n = 20$; $h = 140$ mm, (b) $D = 3000$ mm; $d = 80$ mm; $n = 20$; $h = 120$ mm, (c) $D = 3000$ mm; $d = 90$ mm; $n = 18$; $h = 80$ mm.

4. **Results and Discussion**

When conducting experimental studies of the grinding process in a ball drum mill, the output parameters were as follows: the average kinetic energy of balls ($E_k$) and the average number of their collisions ($N_c$). The results of experimental studies are presented in Table 2.
Table 2. Results of the virtual experiment

| No | $X_1$ ($D$, mm) | $X_2$ ($d$, mm) | $X_3$ ($n$, pcs.) | $X_4$ ($h$, mm) | $E_k$ (J) | $N_c$ |
|----|----------------|----------------|------------------|----------------|----------|-------|
| 1  | 2800           | 80             | 14               | 160            | 3.4055   | 2189.94|
| 2  | 2400           | 80             | 14               | 160            | 2.9701   | 1552.72|
| 3  | 2800           | 60             | 14               | 160            | 1.3936   | 5349.1 |
| 4  | 2400           | 60             | 14               | 160            | 1.2129   | 3729.5 |
| 5  | 2800           | 80             | 18               | 160            | 3.4921   | 2230.26|
| 6  | 2400           | 80             | 18               | 160            | 3.0301   | 1603.04|
| 7  | 2800           | 60             | 18               | 160            | 1.4303   | 5478.6 |
| 8  | 2400           | 60             | 18               | 160            | 1.2203   | 3828.02|
| 9  | 2800           | 80             | 18               | 120            | 1.3936   | 5349.1 |
| 10 | 2400           | 80             | 14               | 120            | 2.6876   | 1459.2 |
| 11 | 2800           | 60             | 14               | 120            | 1.2831   | 5182.5 |
| 12 | 2400           | 60             | 14               | 120            | 1.0998   | 3552.54|
| 13 | 2800           | 80             | 18               | 120            | 3.1821   | 2142.18|
| 14 | 2400           | 80             | 18               | 120            | 2.7489   | 1503.8 |
| 15 | 2800           | 60             | 18               | 120            | 1.3095   | 5219.19|
| 16 | 2400           | 60             | 18               | 120            | 1.1249   | 3623.5 |
| 17 | 3000           | 70             | 16               | 140            | 3.8694   | 3847.9 |
| 18 | 2200           | 70             | 16               | 140            | 0.7455   | 1912.1 |
| 19 | 2600           | 90             | 16               | 140            | 4.4296   | 1289.26|
| 20 | 2600           | 50             | 16               | 140            | 0.7281   | 7909.76|
| 21 | 2600           | 70             | 12               | 140            | 1.2752   | 2724.36|
| 22 | 2600           | 70             | 20               | 140            | 2.5805   | 2815.83|
| 23 | 2600           | 70             | 16               | 180            | 2.6982   | 2910.45|
| 24 | 2600           | 70             | 16               | 100            | 1.3284   | 2630.36|
| 25 | 2600           | 70             | 16               | 140            | 2.0522   | 2757.27|

It can be concluded that it is possible to choose a number of lifters and their heights at which the mill diameter and grinding bodies provide the maximum kinetic energy of the balls and their collisions.

5. Conclusion
The article dealt with the calculation of the average kinetic energy of balls ($E_k$) and the average number of their collisions ($N_c$). The following factors were taken into account: mill diameter $D$, diameter of the grinding bodies $d$, number of lifters around the circumference $n$ and height of the lifters $h$. A central compositional rotatable plan of the full factorial experiment (PFE CCRP $2^4$) was used for the study. An electronic-digital model of the mill housing with a parametrically variable composition of the product was created. Using the EDEM software, the movement of a grinding load in a ball drum mill was simulated.

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