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NUMERICAL SIMULATIONS OF THE EXPLOITATION PARAMETERS OF THE ROTARY FEEDER

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Abstract:
The article presents the problems of determining the mass efficiency of a rotary feeder depending on the selection of design parameters of the device, such as outer diameter, number of blades and rotational speed of the rotor. The hitherto theoretical methods of calculating the feeder efficiency were presented, as well as a new method of determining the device operation parameters was proposed. For this purpose, the numerical Discrete Element Method was used, which allowed simulating the transport of limestone powder in a cell feeder with various design variants. The results of the tests showed that the above design parameters affect the instantaneous efficiency of the feeder and thus impact the distribution of the dosed material during the operation of the device. Depending on the design solution, the simulation results gave information on the fill factor of the feeders. The study showed a significant potential of DEM simulation in the design of circular feeders intended for dosing bulk materials.

Key words: *bulk materials, Discrete Element Method, exploitation characteristics rotary feeder*

INTRODUCTION

An indispensable element of economic development is the search for technical solutions allowing to minimise the energy consumption of many devices used in various industries [1]. In recent years, more and more talk about reducing emissions, reducing the carbon footprint, improving energy efficiency, and reducing energy consumption while increasing the efficiency of devices. An example of this is the many works on the grinding of raw materials and determining the impact of selected operating parameters of devices on CO_2 emission rates [2, 3, 4]. The rapid development of numerical methods combined with the increasing computing power of computers means that they modelled complex physical phenomena with high accuracy concerning reality [5, 6, 7, 8]. Virtual prototyping makes it unnecessary to build expensive proper objects and conduct time-consuming experimental research. This applies especially to the understood transport industry, or the processing of mineral resources, where machines and devices are characterised by large dimensions. The analytical approach to the design of machines and devices often becomes insufficient as it does not provide much important information, for example, related to the behaviour of a material with specific physical properties during its transport [9]. Numerical tools that support the process of designing and optimising devices for transporting bulk materials based on the Discrete Element Method (DEM) come to the rescue. Having a calibrated material model, it is possible to reproduce the actual behaviour of the material bed during its processing, for example grinding, consolidation or transport [10, 11, 12, 13].

One of the very popular devices used in industrial production lines in many industries is rotary feeder. These are devices whose primary function is to ensure stable dosing of the material, e.g. from a storage tank or other transport device. Rotary feeders are popular used as devices that function as a sluice that cuts off zones with different pressures. They allow limiting fill the material of transport devices collecting material from under the hopper, bag filters, cyclones, etc. They enable stable, continuous feeding of material and maintain a constant air pressure between the inlet and outlet, which is achieved, among others, by proper sealing of the rotor [14]. Rotary feeders are devices built of several basic components, as shown in Figure 1.

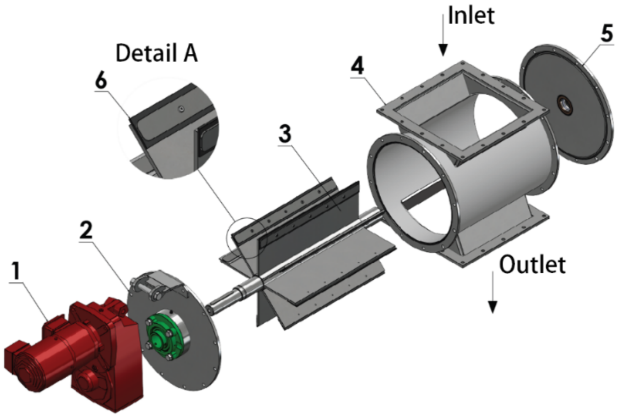

Fig. 1 Construction of a rotary feeder, where:
1 – drive unit, 2 – front plate with shaft bearings, 3 – rotor, 4 – housing, 5 – rear plate, 6 – rotor sealing

During the rotation of the rotor, it poured the material from the inlet to the rotor cages and then to the outlet. The material flow is regulated by changing the rotational speed of the rotor.

LITERATURE REWIEV

Incorrect design of the feeder can lead to many operational problems and costly shutdowns of entire production lines. The current methods of designing feeders are based on an algorithm that considers the characteristic dimensions, bulk density of the material, the theoretical factor of a single cell filling and the rotational speed of the rotor shaft [15]. For feeders that function as a sluice, it is also important to consider the method of sealing the rotor, which affects the operational parameters of the device [16].

The article [10] presents the formula (1) for the mass efficiency of a rotary feeder.

$$Q = 60 \cdot \rho \cdot n \cdot V_k \cdot \psi \cdot k \tag{1}$$

where:
Q – mass capacity of the feeder in kg/s,
ρ – the bulk density of the material in kg/m^3,
N – shaft rotational speed in rpm,
V_k – working chamber capacity in m^3,
ψ – working chamber filling rate,
k – number of rotor working chambers.

In the simulation studies, the authors used the DEM method to determine the relationship between the rotational speed of the rotor shaft and the mass efficiency of the device for three different filling levels in the working chambers. The test results show that the increase in the efficiency of the rotary feeder along with the increase of the shaft rotational speed occurs up to a certain limit value of the rotation above, at which the mass efficiency decreased slightly. The authors explained this effect because it did not fully discharge the material from the working chambers and some of it was transported back upwards. It was observed that the increase in the filling degree of the working chamber increased the mass efficiency. However, the authors observed the doubling of the efficiency did not match that the doubling of the filling degree.

According to the work [17], the actual volumetric efficiency of the rotary feeder depends on the outer diameter of the rotor. The formula expresses shaft rotational speed and the degree of filling the trough (2).

$$V = 60 \cdot n \cdot V_1 \cdot \psi \tag{2}$$

where:
V – volumetric capacity of the feeder in m^3/h,
n – shaft rotational speed in rpm,
V_1 – volumetric efficiency per 1 rpm (value depends on the dimensions of the feeder),
ψ – working chamber filling rate.

The mass capacity of the feeder can be calculated by multiplying of the equation (2) by the bulk density of the material. The filling factor of the working chamber for dry materials ranges from 0.3 to 0.5 and depends on the ease of pouring the material. The authors confirm in their work that the value of the coefficient should be verified for a specific granular material. According to the paper, the maximum value of the rotating speed for which the feeder can work is 45 rpm. However, it was not specified what the device malfunctions for higher rotational speeds of the rotor shaft appear.

With simple, non-complicated applications, the method based on the analytical selection of geometric features is sufficient, while with more demanding applications, classical computational methods turn out to be insufficient.

In the event of uncertainty related to, inter alia, ensuring the required capacity of the feeder, the designers oversize the devices.

To analyse the behaviour of bulk material in the rotary feeder and its impact on structural elements, advanced numerical methods have been used. For example, the work [14] presents the effect of the cell speed on the feeder efficiency determined using the Discrete Element Method (DEM). The work [18] presents the use of tools based on the finite element method to analyse the deformation of a rotary-box feeder rotor. The article [19] presents the basic operational problems encountered during operating of rotary feeders, which supply low-density materials. Exemplary modifications of conventional structures were proposed, thanks to which the problems related to blocking the material in the discharge hopper were eliminated. The article [20] presents the method of the functional analysis of the individual components of the rotary valve and proposed a plausible way to reduce the costs of its construction while maintaining the required operating parameters. The influence of various types of bulk materials and their particle size on the efficiency of a rotary feeder are presented in article [21]. Authors have presented the change of the material model to actual conditions with the use of DEM and CFD (Computational Fluid Dynamics) numerical tools. The possibilities of using computer simulations using the DEM method for analysing the trajectory of grain movement in the rotary feeder are presented too. The computer simulation results were also very consistent with the results of the mass efficiency measurements of the feeder.

Selection of the design parameters of the rotary feeder, such as the outer diameter of the rotor, the number of blades or the rotational speed, is often arbitrary, based on the developed design and operation experience. The major disadvantage of the analytical methods of determining the feeder efficiency is the acquire a constant filling factor for the chambers between the rotors. This factor depends on the type of design of the roller feeder, the physical properties of the transported material and the method of feeding the material to the device. The influence of the above design parameters on the characteristics of the feeder operation, in particular on distributing the dosed material over time, remains an unrecognised issue. The knowledge of the instantaneous output capacity of the feeder is crucial for technological reasons with precise dosing of the material. Therefore, the paper presents the possibility of using computer simulations using the DEM method to investigate the influence of selected design parameters of a rotary-shaped feeder on its performance characteristics.

RESULTS OF RESEARCH

Calibration of the model parameters

The Discrete Element Method (DEM) is used to model the behaviour of granular materials [22, 23]. Its theoretical basis is the assumption that the modelled material is treated as a set of rigid solids, called particles, interacting with each other through contact forces [24].

To simulate the behaviour of specific bulk material in a way that is consistent with reality requires an appropriate definition of the input parameters of the DEM material model [25]. The model parameters can be divided into two groups. The first one defines the physical and geometric features of the particles representing the grains of granular material, which include such features as the size, shape and density of the modelled particle. The second group defines the contact parameters between the particles and the working surfaces [26, 27]. This group includes parameters such as internal and external friction coefficients, rolling resistance coefficient, restitution coefficient, contact stiffness, or type of contact model. In the DEM method model parameters are defined on a microscale at the level of a single particle. In current work all physical and contact properties are assigned to each particle. The set of these individual particles forms an entire bed of bulk material with specific physical properties considered on a macro scale. Defining a DEM material model describing a specific granular material, it is essential to find the relationship between the properties considered at the micro and macro scales. What physical and contact properties it will assign to an individual DEM particle determines how the entire mass of bulk material will behave. Figure 2 shows a diagram of the calibration procedure for the DEM material model.

Calibration comprises adjusting the input parameters of the DEM material model, defined on a microscale, to get such a state in which the global model of the material l (macroscopic approach) will reflect the behaviour of the bulk material [28, 29].

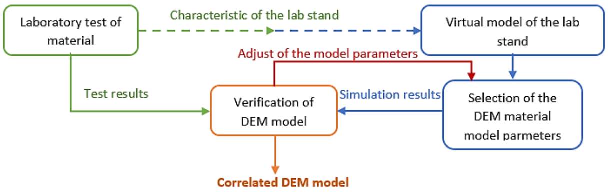

Fig. 2 Algorithm of calibration procedure for the DEM material model

This process is carried out by mapping a laboratory test that determines a physical property of bulk material, for example reflecting a test of the natural angle of repose, measuring the bulk density, etc [30, 31], physical properties of bulk material, and then reflecting these tests to determine the input parameters of the model [32, 33].

Simulation tests of operating parameters of the rotary feeder

The simulation tests concerning the establish of the operating characteristics of the rotary feeder operating in the rotational speed range from 20 to 80 rpm were carried out for three external rotor diameters: 250 mm, 300 mm and 350 mm and for three configurations of the number of blades: 6, 8 and 10, as shown in the Figure. 3. The width of the feeder for all design variants was the same and amounted to 365 mm. Also, for each feeder, an appropriate transverse dimension of the inlet and outlet passage is provided, adequate for the rotor diameter.

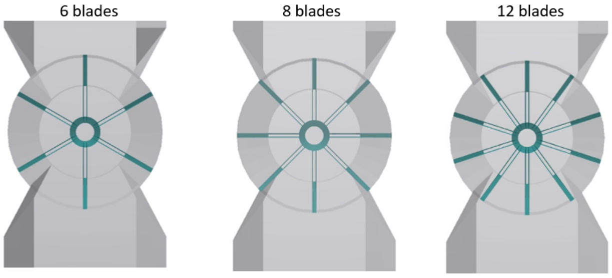

Fig. 3 Configurations of the rotary feeder rotor blades

It was assumed for the research that the cell feeder is filled with a stream of material with the efficiency Q_{inlet} = 8.33 kg/s (30 Mg/h). This reflects the system of feeding the feeder through another conveyor, such as a belt or screw conveyor, often found on technological lines. It showed the DEM model of the conveyor in Figure 4.

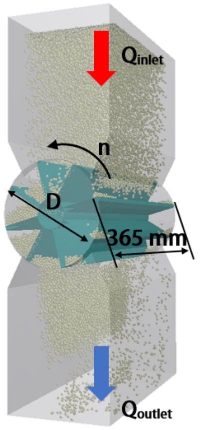

Fig. 4 DEM model in a rotary feeder

It adopted limestone powder as the material transported in the rotary feeder. It presented the physical properties and calibrated parameters of the DEM material model in Table 1.

Table 1
Physical properties and calibrated DEM parameters of limestone powder

Physical properties			
Angle of repose [°]	Coefficient of external friction	Bulk density [kg/m³]	Grain size [µm]
36.4	0.44	1170	1-20
Calibrated DEM parameters			
Coefficient of internal friction	Coefficient of external friction	DEM particle density [kg/m³]	DEM particle radius [mm]
0.24	0.44	1980	3

Exemplary time histories of the output efficiency of a rotary-valve feeder operating at a rotational speed of 20 rpm, 50 rpm and 80 rpm is presented in Figure 5.

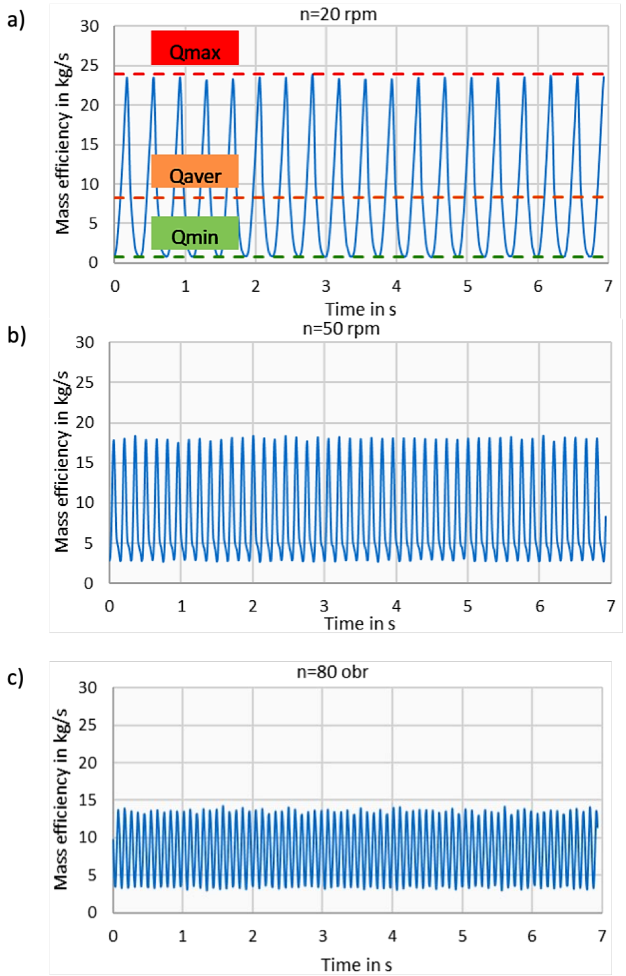

Fig. 5 The graph of the efficiency of the circular feeder in the configuration D = 300 mm and i = 8 blades, where:
a) rotational speed n = 20 rpm,
b) rotational speed n = 50 rpm,
c) rotational speed n = 80 rpm

The graphs showing the efficiency of the rotary feeder show the cyclical change of the output capacity of the device from the minimum value of Qmin to the maximum value of Qmax. The change of efficiency takes place cyclically in period T. It can be observed that the higher the rotational speed of the rotor shaft, the shorter the period T. In addition, as the rotational speed increases, the peak-to-peak capacity decreases, the minimum capacity increases, and the maximum value decreases. Collective charts showing the change in average, minimum and maximum capacity depending on the rotary feeder configuration and the rotational speed of the rotor shaft are present in Figure 6.

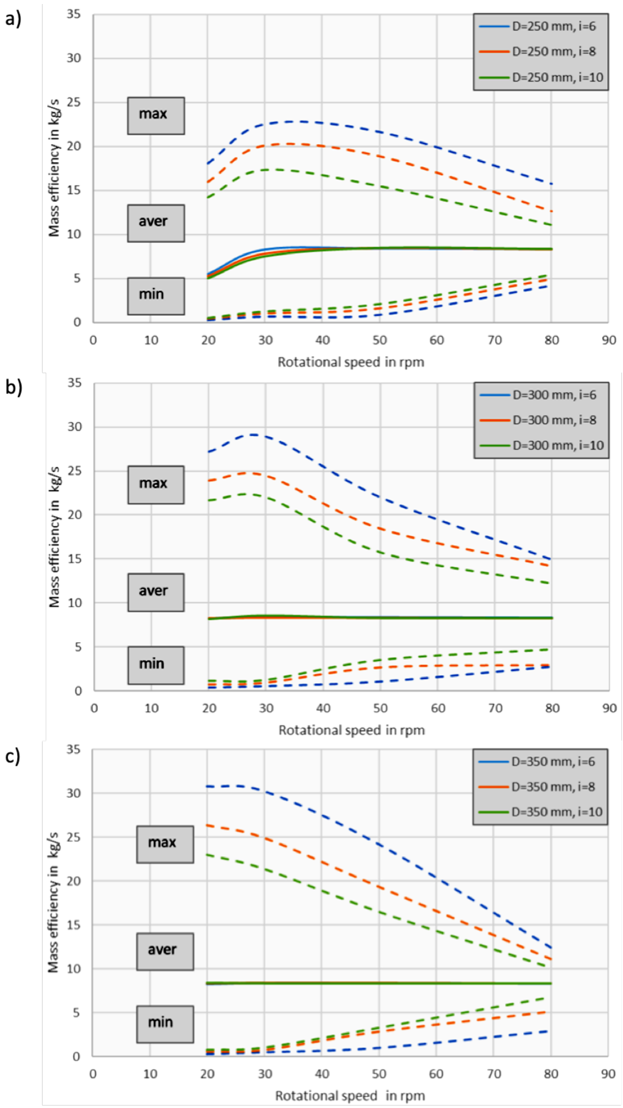

Fig. 6 Change of efficiency depending on the rotational speed of the rotor shaft and the feeder structure, where:
a) the outer diameter of the blades D = 250 mm,
b) the outer diameter of the blades D = 300 mm,
c) the outer diameter of the blades D = 350 mm

The presented diagrams show that the efficiency of the rotary feeder with the outer diameter of the rotor D = 250 mm between rotational speeds up to about 40 rpm is lower than the capacity of feeding the feeder. This shows an insufficient capacity of the device, which, over a while, will cause a significant accumulation of material between the feeding conveyor and the rotary feeder. Above this rotational speed, the feeder's output is equal to the input capacity. The situation is similar for the other two configurations of the feeder, i.e. D = 300 mm and D = 350 mm, operating in the rotational speed range from 20 to 80 rpm. It can be also seen that, for a smaller number of blades, the peak performance value increases. The general trend of the change in efficiency is such that the maximum efficiency decreases and the minimum efficiency increase with the increase of rotational speed, while some extremes of maximum efficiency can be observed near rotational speed equal to n = 35 rpm for D = 250 mm and n = 28 rpm/min for D = 300 mm.

Figure 7 shows the change in the capacity period (defined as a time interval between the following peaks of the mass efficiency) for individual configurations of a rotary feeder operating at different rotational speeds.

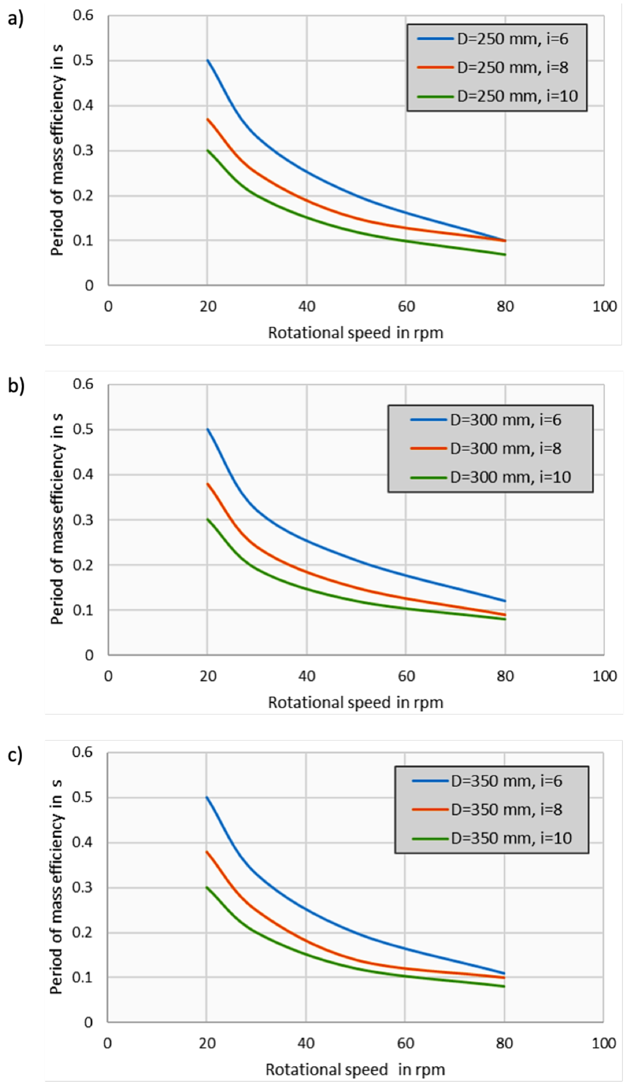

Fig. 7 Change of the capacity period depending on the rotational speed of the rotor shaft and the feeder structure:
a) the outer diameter of the blades D = 250 mm,
b) the outer diameter of the blades D = 300 mm,
c) the outer diameter of the blades D = 350 mm

It can be seen from the above graphs that the period of changes in the output efficiency of the rotary feeder decreases with the increase in the rotational speed of the rotor shaft. Also it can be noticed that a higher period of efficiency changes characterises the designs with a smaller number of rotor blades.

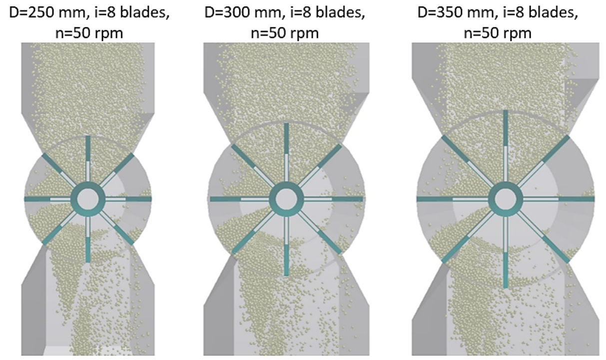

Fig. 8 The result of the simulation of the operation of rotary feeders for different outer diameters, 8 blades and the rotational speed of the rotor equal to 50 rpm

The simulation results show that filling in the chamber between adjacent rotor blades decreases with the increase in the outer diameter.

Figure 9 shows the effect of the rotary speed of the rotary feeder on the distribution of the dosed material on the belt of a belt conveyor operating at a speed of 1 m/s. A feeder with an outer diameter of the rotor D = 300 mm and it used the number of blades equal to i = 8 for the tests.

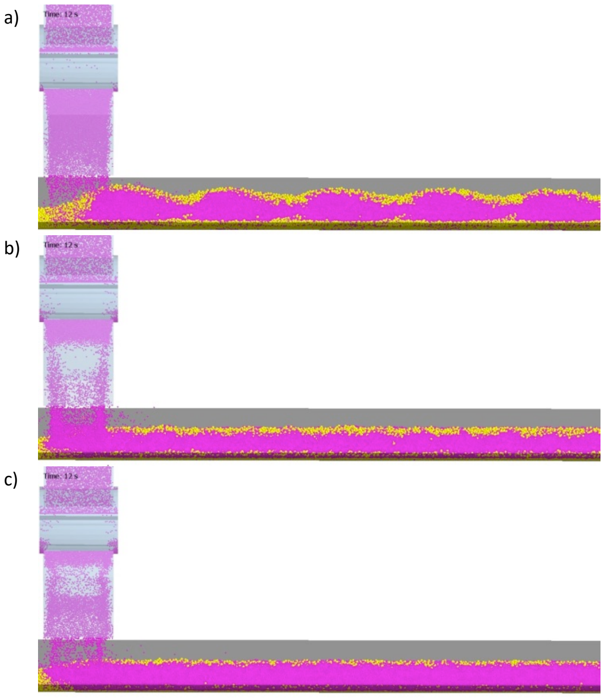

Fig. 9 Influence of the rotary speed of the rotary valve on the distribution of the dosed material on the conveyor belt:
a) rotor blade speed n = 20 rpm,
b) rotor blade speed n = 50 rpm,
c) rotor blade speed n = 80 rpm

Figure 9 shows a significant influence of the rotary speed of the rotary feeder on the distribution of the dosed material on the belt conveyor. With the rotational speed n = 20 rpm, the characteristic cyclically piled on the conveyor belt are visible. As the rotor rotational speed increases, the got distribution of the dosed material on the belt surface becomes even, which proves a more stable dosing of the material onto the conveyor.

CONCLUSIONS

The results of the computer simulations showed that the efficiency of the rotary feeder varies with time. Its value changes cyclically from the minimum to the maximum value, with the period of these changes decreasing with an increase in the number of blades. DEM simulations make it possible to verify the actual filling factor of the working chambers, the efficiency of the rotary valve, and to determine their temporary changes depending on the assumed design parameters. It increased the filling of the working chambers for smaller rotor diameters and lower speeds. The tests have shown that with the too small outer rotor diameter and low rotational speed, the efficiency of the rotary feeder is lower than the efficiency of the feeding system, which leads to buffering of the material in the inlet passage. It can eliminate this effect by increasing the rotational speed of the rotor or increasing its outer diameter. With a large outer diameter of the rotor, the rotary feeder worked with a constant capacity equal to the capacity of the feeding system in the entire range of the tested rotational speeds. The difference between the maximum and minimum capacity of the rotary feeder decreased with the increasing rotational speed of the rotor. With the rotary feeder of diameter D = 250 mm and D = 300 mm, certain extremes of the maximum efficiency were observed, regardless of the number of blades, not for the lowest of the tested rotational speeds, but for slightly higher values of rotations, above which the maximum efficiency dropped. Although the same rotary feeder efficiency was obtained for different rotational speeds of the rotor, the number of rotations in the operating system has a large impact on the distribution of the dosed material in the collecting devices. As shown by the low rotational speed of the rotor, it unevenly distributed the material on the belt surface (characteristic prisms cyclically on the belt). As the number of the feeder working unit increased, the distribution of the material on the belt was more even. DEM simulations made it possible to verify the influence of the design parameters of the rotary feeder on the distribution of the dispensed material. It is quite important from the point of view of further technological processes in which a mixture of two or more bulk materials is used.

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