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DETERMINING THE PATTERN OF LOOSE MATERIAL MOVEMENT IN SCREW AND TUBULAR-COMB FEEDERS

Volodymyr Nychehlod
Postgraduate Student
Department of Mechanical Engineering**
Oleksandr Burmistenkov
Doctor of Technical Sciences, Professor*
Volodymyr Statsenko
Corresponding author
Doctor of Technical Sciences, Associate Professor*
E-mail: statsenko.v@knutd.edu.ua
Tetiana Bila
PhD, Associate Professor*
Dmytro Statsenko
PhD, Associate Professor*
*Department of Computer Engineering and Electromechanical Systems**
**Kyiv National University of Technologies and Design
Mala Shyianovska (Nemyrovycha-Danchenka) str., 2,
Kyiv, Ukraine, 01011

The object of this study is the relationship between the structural and technological parameters of feeders for loose materials and the characteristics of particle flows at their outlet, namely: productivity and the magnitude of pulsations. The existing designs of this type of equipment were analyzed, and the most common methods for simulating their operation were determined. A structure of a tubular-comb feeder has been proposed, the performance of which is compared with the well-known screw feeder. Computer models of both structures were built based on the discrete element method. The simulation was carried out in the EDEM 2017 software environment. It was established that the resulting models take into account the discrete nature of the movement of loose materials and allow conducting research taking into account the physical and mechanical properties of individual particles.

An experimental bench was fabricated for experimental verification of the modes of operation of the tubular-comb feeder. The performance of this type of feeder was determined for two pipe rotation speeds (6 and 10 rad/s). The amount of material flow pulsations in the outlet nozzle was also determined. The correspondence of the results of calculations based on the computer model to the real process was confirmed. The current study was carried out the steady modes of operation.

It was established that with equal overall dimensions and speeds of rotation of the working bodies, the productivity of the screw feeder is 5...5.2 times greater than that of the tubular-comb feeder. But the latter provides 7.3...16.4 times smaller magnitude of pulsations of the flow of loose material. This makes it possible to reduce the heterogeneity of mixtures, especially in the case of using such feeders as part of continuous mixing systems.

The results make it possible to analyze the operation of bulk material feeders and reduce their design time

Keywords: loose material, tubular-comb feeder, discrete element method, DEM, pulsations of loose material

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1. Introduction

The production of a wide range of household and industrial goods involves the use of polymer materials [1, 2] with different physical and mechanical properties. They are formed by mixing polymer granules with various fillers, plasticizers, dyes, and other components, which are also supplied in the form of powders or granules. The mixture of these components is melted and fed under pressure into molds or fillers [3], which makes it possible to obtain a product with the necessary geometric parameters. It is fundamentally important for this technology to observe two main parameters of the mixture: compliance of the percentage composition with the given formulation and homogeneity [1]. They determine the physical and mechanical properties of the finished product and the presence of local defects in it.

Production of mixtures is carried out with the help of mixing systems, which include three main links: hoppers, dispensers or feeders, and mixer. The technological process involves feeding loose materials from hoppers to the mixer using feeders [1, 4]. In this case, it is the feeders that make it possible to control the amount of material entering the mixer per unit of time and the uniformity of this flow. Thus, the accuracy of this equipment determines the percentage composition of the mixture and largely affects its homogeneity. The magnitude of this effect depends on the type of mixing process used: batch or continuous. Continuous mixing equipment has a higher output but is more sensitive to pulsations in the flow of materials fed into the mixer. This is due to the fact that in continuous mixers there is a much smaller volume of material at each individual moment of time compared to batch mixers. Accordingly, the possibilities of smoothing out such pulsations during the mixing process are reduced. Ideally, the feeders should supply the mixture components in a continuous flow with the specified capacity and without pulsations. But, despite the fact that the development of appropriate devices has been carried out for more than a hundred years, it has not been possible to fully solve this problem. To a large extent, this is due to the complex nature of the movement of loose materials, their tendency to form lumps. Research into the operation of technological equipment is also a separate task. Installation of appropriate sensors is in many cases impossible as it affects the movement of the material.

Thus, the construction of mathematical models that allow calculating the trajectories of the movement of individual particles and their interaction with working bodies could simplify the process of designing new structures of feeders. This determines the relevance of investigating such equipment and forecasting its parameters.

2. Literature review and problem statement

Paper [5] reports the results of a study into the operation of a tubular belt conveyor (TBC) for the transportation of loose materials. It is shown that TBCs have unique mechanical characteristics that have not yet been sufficiently studied. The authors have built a model based on the finite element method (FEM) and discrete element method (DEM), which allows the calculation of contact forces in pipe sections. It is shown that predictions of contact forces agree well with experimental data. At the same time, the work considers TBC with a smooth inner surface.

Study [6] considers determining the influence of nutrients on the mixing of loose materials in pharmaceutical processes. The authors applied DEM for modeling the unloading process of a twin-screw feeder. Three models of different levels of complexity have been built, which allow predicting the process of material movement. The authors also showed the need to construct more complex models to represent the dynamics of particles inside the equipment.

The use of TBC for moving powdery and loose materials is considered in [7]. The results of the analysis of failure modes during belt rotation are presented, and a mathematical model and application for calculating the belt's holding moment and rotational moment are developed. Factors leading to malfunctions in the operation of the equipment have been determined. The proposed model considers only the TBC with a smooth inner surface and does not take into account the influence of additional working bodies on the movement of particles.

The authors of work [8] show the advantages of using DEM in the design and optimization of equipment for moving loose materials. The results showed the importance of the accuracy of the assignment of input parameters. The procedure for calibrating the input parameters for the pearlite transportation model in the screw conveyor is proposed. At the same time, the study does not show possible pulsations in the flow of loose material.

The efficiency of using screw feeders for the controlled removal of loose materials from bunkers is shown in [9]. With the help of DEM, models have been built that make it possible to calculate the circulation of the material, the residence time of particles inside the equipment, and to study the effect of segregation. Also, the authors conducted studies for particles of different shapes and showed their influence on the parameters of material movement. The proposed model can be used to predict the quality of mixtures, but the effect of structural and technological parameters on particle flow pulsations is not considered in the cited work.

In [10], the authors built a model of the movement of particles in a screw feeder based on DEM, which takes into account the effect of van der Waals forces for small particles and capillary forces for wet particles. A correlation was determined for predicting the consumption of solid matter as a function of the magnitude of the cohesive force and the speed of rotation of the screw. Possible methods of reducing the influence of the cohesion force on the flow of solid particles were proposed. The results are advisable to use in the development of screw feeders, but it is difficult to apply them to the analysis of material movement in other types of feeders.

The model of the movement of particles in a screw feeder is given in [11]. The instability of the flow of loose material over time and the dependence of throughput on changes in the physical and mechanical properties of the substance are shown. Model parameters, in particular, friction forces, internal shear forces, natural slope angle, are determined based on the results of experimental studies. The results can be used for feeders with screws of various types, but it is difficult to apply them to equipment with a different design.

The study of the productivity of the screw feeder is reported in [12]. The authors determined the main parameters that affect productivity, in particular the speed of rotation of the screw, the inclination of the screw conveyor, the volume level of filling with loose material. The mathematical model was built on the basis of DEM. It is used to determine the impact of particle velocity, mass flow rate, energy dissipation, and power consumption on productivity. The main limitation of the proposed model is the possibility of its use only with screw feeders.

A comprehensive review of DEM use in the research of systems for transporting powder materials is given in [13]. Particular attention is paid to electrification of powder during pneumatic transportation, erosion on pipe bends, transportation of non-spherical particles. It is shown that the use of DEM increases the accuracy of predicting the movement of particles and helps speed up the design of new equipment.

The results of our analysis reveal that screw feeders are most widely used for transporting loose materials. At the same time, preliminary studies indicate that during their operation, pulsations occur in particle flows, which lead to a decrease in the homogeneity of the mixture. Tubular conveyors are also known, in which the nature of particle movement is significantly different from screw feeders. Therefore, it is advisable to investigate the possibility of combining the advantages of both designs. The use of DEM to construct computer models of the movement of loose materials has become widespread in recent years and has made it possible to increase the accuracy of calculations [4–6, 8–12, 14, 15]. This predetermines the choice of DEM as the main modeling method when conducting research into new equipment.

3. The aim and objectives of the study

The purpose of this work is to determine the influence of the structural and technological parameters of a tubular-comb feeder on its productivity and the magnitude of pulsations of the flow of loose material and to compare them with similar parameters of the screw feeder. This will make it possible to reasonably choose the design and operating modes of feeders when using them as part of mixing systems for loose materials.

To achieve the goal, the following tasks were set:

– to construct computer models of screw and tubular-comb feeders using DEM;

– to design a test bench and conduct experimental studies of the productivity and pulsations of the flow of loose material at the outlet of the tubular-comb feeder;

– to investigate the magnitude of pulsations at the output of tubular-comb and screw feeders.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our research is the relationship between the design and technological parameters of feeders of loose materials and the characteristic of particle flows at their outlet, namely: productivity and magnitude of pulsations.

The main hypothesis of the study assumes that the combination of the design features of the screw feeder and the tubular belt conveyor will make it possible to reduce the pulsation of the flow of loose material at the outlet of the feeder,

The following assumptions were accepted in the work:

1) the use of DEM will make it possible to determine with sufficiently high accuracy the magnitude of pulsations of the flow of loose material;

2) the physical and mechanical parameters of the loose material do not change over time;

3) during the operation of the equipment, there are no forces that can lead to the destruction of the material, working organs, or changes in structural or technological parameters.

The work adopted the following simplifications:

1) particles of loose material are represented in the form of ideal spheres with the same radii;

2) electrostatic forces of interaction between particles are equal to zero;

3) the speed of rotation of the working bodies of the equipment is constant;

4) the influence of vibration that may occur during the operation of feeders is taken into account.

4. 2. Principles of operation of screw and tubular-comb feeders

Our paper considers feeders for loose materials of two types: screw (Fig. 1) and tubular-comb (Fig. 2).

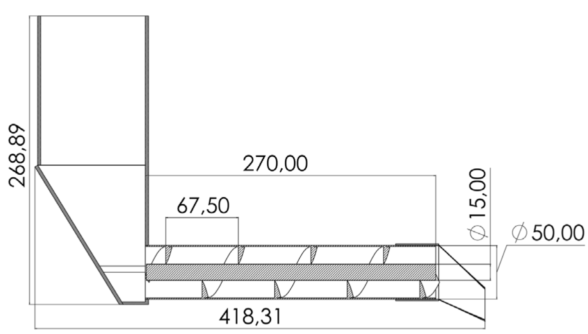


Fig. 1. Screw feeder

The structure of the screw feeder (Fig. 1) is widely known. The loose material is loaded into the hopper (1) and moved along the horizontal pipe (2) with the help of the auger (3), which rotates at a given speed. The horizontal movement of the material is ensured by the frictional forces between the auger and the particles. At the same time, the pipe (2) remains stationary.

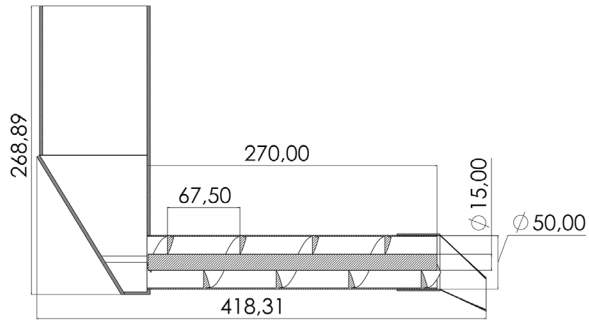


Fig. 2. Tubular-comb feeder

The tubular-comb feeder (Fig. 2) proposed in the work has a similar design. Loose material is also loaded into the hopper (1) and moved along the pipe (2) to the outlet. But in this feeder, instead of an auger, spiral ridges are located on the inner surface of the pipe. The horizontal movement of the material is ensured by the rotation of the pipe (2) around its own axis at a given speed. Before the start of work, particles fall out of the hopper (1) into the pipe (2) under the influence of gravity. When the pipe starts to rotate, the particles move with it due to the frictional forces between them and the surfaces of the pipe and ridges. As soon as the magnitude of the frictional force becomes insufficient to hold the particles on the side surface of the pipe, they begin to slide down. Movement in the horizontal direction is ensured due to the fact that during the movement of particles, together with the side surface of the pipe, particles from the hopper are poured into their place. As a result, the particles roll down and forward. The combs located on the surface of the pipe simultaneously perform two functions: they increase the area of contact with particles and limit the horizontal movement of particles due to inertial forces.

4. 3. Investigating the movement of particles of loose material in feeders by the discrete element method

We investigated the movement of particles inside the feeders on the basis of models built by the discrete element method, using the specialized software EDEM 2017 [16].

In this case, the loose material was considered as a set of spherical particles with a constant radius, which have elastic properties. DEM involves determining the forces acting between particles. We determined the normal components of interaction forces on the basis of Hertz's contact theory. The Mindlin-Deresiewicz algorithm [17] was used to calculate the tangential component. The parameters of the particles and materials from which the housings and working bodies of feeders are made are given in Table 1.

Table 1

Parameters of particles, working bodies and feeder housings

Parameter name	Loose material particles	Feeder housing Material	Tubular-comb feeder pipe material
Poisson's ratio	0.25	0.3	0.5
Density, kg/m^3	880	7300	1100
Shear modulus, Pa	$1*10^8$	$1*10^9$	$5*10^6$
Young's modulus, Pa	$2.5*10^8$	$2.6*10^9$	$1.5*10^7$
Radius, mm	2.5	–	–

Also, before conducting DEM calculations, the interaction parameters of all interacting materials were set. Their list is given in Table 2.

Table 2

Parameters of interaction of contacting objects

Parameter name	«particle – particle»	«particle – the material of the feeder body»	«particle – tubular-comb feeder pipe material»
Coefficient of elasticity	0.3	0.3	0.4
Coefficient of static friction	0.3	0.5	0.5
Rolling friction coefficient	0.05	0.05	0.1

Values listed in Tables 1, 2 are typical for polymer granular materials (particles) and steel (feeder housings). The properties of the pipe of the tubular-comb feeder correspond to the parameters of the coPET material used in the experimental studies.

Statistical treatment of the results was carried out using programs developed in the Python programming language [18], NumPy library [19], and Jupyter software [20]. The coefficients of the regression equations were calculated by the method of least squares, the adequacy of the computer model was checked by the Fisher test.

4. 4. Experimental study of the tubular-comb feeder

Checking the performance and characteristics of the tubular-comb feeder was carried out with the help of a test bench (Fig. 3). It consists of a hopper (1), a pipe with ridges on its inner surface (2), an electric drive (3), which ensures the rotation of the pipe, and a strain gauge (4).

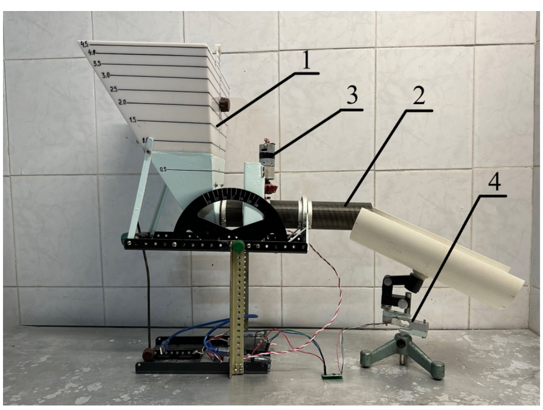


Fig. 3. Bench for experimental study of tubular-comb feeder operation

The structure of the bench is designed to be similar to the well-known industrial feeder for loose materials manufactured by Palamatic Process Inc. (USA) [21]. Bega (Mexico) [22], TekhnoMashStroy (Ukraine) [23], and others also produce equipment similar in design and operating principle. The geometric similarity of the bench and industrial equipment is ensured by the identical shape of the pipe, inside which the working bodies are located, and the shape of the hopper, which has a rectangular horizontal section. The volume of the bench hopper is reduced compared to the industrial model. But the supply of material in it is sufficient for the bench to enter the established mode of operation and to determine the parameters of the movement of the material in this mode. The speed of rotation of the working body of the bench is regulated with the help of a controlled electric drive, which makes it possible to set it at the speed level of the industrial model. Physical similarity is ensured due to the same nature of the forces that act on the particles and lead to the movement of the material. Inside the hopper, the material moves under the influence of gravity. Horizontal movement (along the pipe) is ensured due to the action of frictional forces between working bodies and particles.

The design of the bench makes it possible to change the angle of inclination of the pipe, but during the research it was installed horizontally.

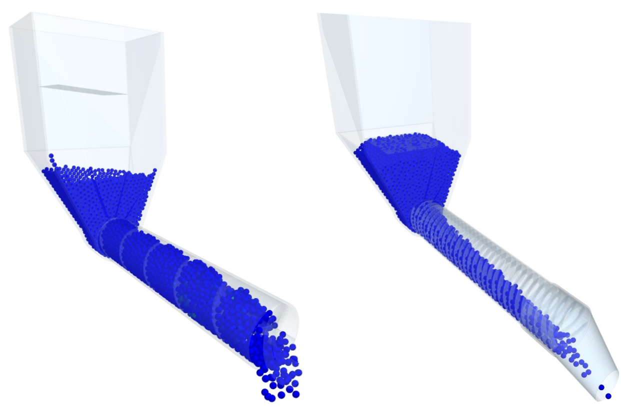
The tube with the combs is made using 3D printing from coPET material. Its geometric parameters correspond to the dimensions shown in Fig. 2.

When conducting research, information from the strain gauge was transmitted through an analog-to-digital converter (ADC) to a microcontroller (MC), which in turn transmitted it to a personal computer for further analysis. As a result, the magnitude of the sensor signal was proportional to the amount of material supplied by the feeder per unit of time, that is, its productivity.

5. Results of research into the operation of tubular-comb and screw feeders

5. 1. Computer models for conducting studies of feeders based on the discrete element method

Models of screw and tubular-comb feeders, built on the basis of DEM using the EDEM 2017 software, are shown in Fig. 4.



a *b*

Fig. 4. Models of feeders built on the basis of the discrete element method: *a* — screw, *b* — tubular-comb

The geometric parameters of the models coincide with the values shown in Fig. 1, 2. Experiments were conducted for two speeds of rotation of the pipe and screw: 6 and 10 rad/s. As a result of the simulation, the dependences of the mass of the material supplied by the feeder on time were derived (Fig. 5).

Solid lines in Fig. 5 show the plots of approximating linear dependences and the coefficients of the corresponding equations, which were calculated by the method of least squares.

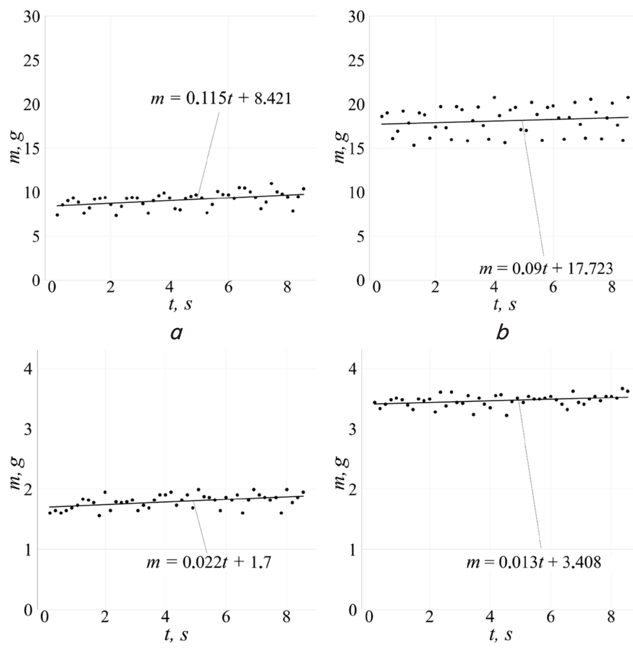


Fig. 5. Dependence of the mass of the material on time at the outlet of the feeders: *a* – screw (6 rad/s); *b* – screw (10 rad/s); *c* – tubular-comb (6 rad/s); *d* – tubular-comb (10 rad/s)

5. 2. Results of experimental studies of the movement of particles in a tubular-comb feeder

When conducting experimental studies of the tubular-comb feeder using a bench (Fig. 3), the tube rotation speed was set equal to 6 and 10 rad/s. The readings of the strain gauge were taken for the steady state of operation. The resulting dependences are shown in Fig. 6.

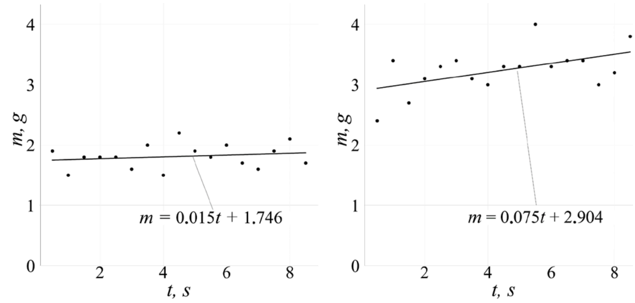


Fig. 6. Dependence of the mass of the material on time at the outlet of the tubular-comb feeder at the speed of rotation of the tube: *a* – 6 rad/s; *b* – 10 rad/s

As in the case of research using DEM, the solid lines in Fig. 5 show plots of approximating linear dependences.

5. 3. Results of investigating the magnitude of pulsations of the flow of loose material at the outlet of screw and tubular-comb feeders

Determination of the influence of feeder structures and their modes of operation on the movement parameters of loose material was carried out for all experimentally obtained dependences. The following statistical parameters were calculated: mean value, median, standard deviation, variance, confidence interval, coefficients of determination. Their values are given in Tables 3–5.

Table 3

Statistical parameters of the material movement process in the screw feeder, calculated using DEM

Parameter name	Screw rotation speed	
	6 rad/s	10 rad/s
Average value, g	9.097	18.151
Median, g	9.292	18.426
Mean square deviation	0.867	1.621
Variance	0.752	2.627
Confidence interval (for 95 % confidence)	8.842...9.351	17.639...18.591
Coefficient of determination	0.199	0.019

Table 4

Statistical parameters of the material movement process in the tubular-comb feeder calculated using DEM

Parameter name	Pipe rotation speed	
	6 rad/s	10 rad/s
Average value, g	1.793	3.467
Median, g	1.818	3.479
Mean square deviation	0.118	0.099
Variance	0.014	0.01
Confidence interval (for 95 % confidence)	1.758...1.827	3.438...3.496
Coefficient of determination	0.208	0.115

Table 5

Statistical parameters of the material movement process in the tubular-comb feeder obtained experimentally

Parameter name	Pipe rotation speed	
	6 rad/s	10 rad/s
Average value, g	1.812	3.241
Median, g	1.8	3.3
Mean square deviation	0.2	0.368
Variance	0.04	0.135
Confidence interval (for 95 % confidence)	1.71...1.914	3.052...3.43
Coefficient of determination	0.035	0.265

In order to verify the correspondence of experimental and calculated (based on DEM) results, the values of the corresponding variances were calculated for the tubular-comb feeder. For experimental values at a rotation speed of 6 rad/s, the variance is $\sigma^2_{E6} = 0.011$ and for values calculated using DEM – $\sigma^2_{DEM6} = 0.038$. At a rotation speed of 10 rad/s, the corresponding variance values are equal to $\sigma^2_{E10} = 0.008$ and $\sigma^2_{DEM10} = 0.099$. The verification of both cases by Fisher's test of equality of variances proved the correspondence of the simulation results to the actual process.

6. Discussion of results of investigating the magnitude of pulsations at the outlet of feeders

Our results (Fig. 5, 6) confirm the discrete nature of the movement of loose material at the outlets of feeders of both types. That is, despite the fact that the parameters of the loose material are idealized when modeling with the help of DEM, the nature of their movement coincides with experimental studies. Quantitative verification of particle flow parameters in steady-state operating modes, which was carried out on the basis of Fisher's criterion of equality of variances, also showed the correspondence of the computer model to the real process. This means that the model of the tubular-comb feeder obtained with the help of DEM makes it possible to model the movement of particles with sufficient accuracy, and therefore can be used in the design of new equipment. In particular, it can be used to analyze the movement of particles under various geometric and technological parameters of tubular-comb feeders.

We also calculated values of the coefficients of determination, which are close to zero, which indicates that the average values coincide with those calculated according to the regression equation. This allows us to conclude that the nature of the movement for all studies corresponds to the established mode of operation.

The average values of the mass of particles (Tables 3, 4) make it possible to compare the productivity of feeders. Screw feeders provide maximum efficiency in this regard. Their productivity is 5...5.2 times higher than that of the tubular-comb one for the same dimensions and angular speeds of rotation of the auger and pipe. This is confirmed by the nature of particle movement, which can be observed in Fig. 4. In the tubular-comb feeder, in contrast to the screw feeder, the filling of the pipe with material decreases when approaching the outlet nozzle.

At the same time, the magnitude of material pulsations in the screw feeder is much greater than in the tubular-comb feeder. This conclusion is confirmed by the values of root mean square deviations and variances (Tables 3, 4), in particular, root mean square deviation for the screw feeder is 7.3 times greater at a rotation speed of 6 rad/s and 16.4 times greater at 10 rad/s. In practice, this means that the tubular-comb feeder ensures a more uniform supply of material, and its use as part of continuous mixing systems will reduce the inhomogeneity of the mixture.

Also, in comparison with screw feeders, the surface area of the contact surface of particles with the working bodies is much smaller in tubular-comb feeders. This feature is due to the fact that the dimensions of the combs are much smaller than the blades of the auger. Thus, the proposed design avoids additional compression of particles, which is characteristic of screw feeders. Determining the magnitude of the forces acting on the particles and searching for zones of probable occurrence of breaks in their flows is a promising area of research for this type of equipment. Also, the presence of ridges on the surface of the pipe prevents particles from rolling. This opens up the possibility of increasing the productivity of such feeders due to the inclination of the pipe.

Unlike [5, 7], our research results of tubular-comb feeders take into account the presence of additional working elements (combs) on the inner surface of the pipe. This makes it possible to determine their influence on the horizontal movement of particles due to inertial forces. In contrast to the results reported in works [6, 8–13], the developed computer models make it possible to determine the trajectories of particle movement inside the tubular-comb feeders. They make it possible, based on the design and technological parameters of such feeders, to calculate their performance and determine the magnitude of pulsations in the flow of loose materials. In addition, the current study includes a comparison of the specified parameters for auger and tubular-comb feeders, which makes it possible to make a reasonable choice of equipment based on the requirements of technological processes.

The computer models of the work of tubular-comb and screw feeders presented in this work take into account the design features of this type of equipment. This makes it possible to determine both their technological parameters and to compare their influence on the parameters of the finished product, in particular, the homogeneity of mixtures.

The main limitations of the obtained computer models are typical for DEM. This is, first of all, a strict binding to the design of the equipment and its modes of operation and the representation of particles, which can have a complex shape, in the form of spheres.

The shortcoming of the research is that the proposed models do not take into account possible changes in the physical and mechanical properties of loose materials. Such changes can be observed even within a single batch of material (compression, humidity, etc.), and can lead to significant changes in particle movement trajectories.

Thus, two main areas to advance our research can be identified:

1) determination of the effect of changes in the design parameters of the feeder (pipe diameter, its slope, step, and height of ridges) on the movement of material;

2) determining the impact of changes in the physical and mechanical parameters of particles on the trajectory of their movement.

7. Conclusions

1. Computer models of screw and tubular-comb feeders were built using DEM. It was established that the resulting models take into account the discrete nature of the movement of loose material and allow calculating the trajectories of the movement of individual particles.

2. An experimental bench was built, and experimental studies of the tubular-comb feeder were conducted. The performance of the equipment for two speeds of rotation of the pipe (6 and 10 rad/s) and the nature of the movement of the loose material were determined. It was established that the results obtained on the basis of the mathematical model correspond to the actual process (the test was carried out on the basis of Fisher's criterion of equality of variances).

3. It was established that the magnitude of pulsations of the flow of loose material at the outlet of the tubular-comb feeder is 7.3...16.4 times smaller than that of the screw feeder. At the same time, the screw feeder has 5...5.2 times higher productivity.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Mathematical models built in the EDEM 2017 software environment will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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