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DETERMINING THE MOTION CHARACTER OF LOOSE MATERIALS IN THE SYSTEM OF CONTINUOUS ACTION «HOPPER – RECIPROCATING PLATE FEEDER»

Розглянуто методи моделювання руху сипкого матеріалу в дозувальному обладнанні безперервної дії. Встановлено, що моделювання пульсацій та розривів у потоці сипкого матеріалу можна здійснити за допомогою методу дискретних елементів. На його основі створена модель системи, що складається з бункера циліндрично-конічної форми та тарілчастого живильника безперервної дії. Частинки сипкого матеріалу представлені у вигляді сфер із постійним радіусом, між яким діють сили тертя та пружності.

В результаті моделювання визначено швидкості руху та положення кожної частинки у поперечному перерізі системи «бункер – тарілчастий живильник» та на поверхні тарелі живильника. Визначено зони із характерними швидкостями руху сипкого матеріалу та продуктивність системи. Найбільша швидкість частинок спостерігається у зоні вихідного патрубка бункера, вздовж його центральної вісі та у зовнішньому шарі матеріалу, який знаходиться на поверхні тарелі. Найменші швидкості спостерігаються біля стінок бункера та в центрі тарелі. Встановлено, що у процесі роботи живильника спостерігається збільшення радіусу конусу сипкого матеріалу на 15,2 %, який знаходиться на поверхні тарелі.

Експериментальне дослідження системи здійснено із використанням дослідного стенду, що складався з конічно-циліндричного бункера, тарілчастого живильника безперервної дії та системи збору даних. Визначено продуктивність живильника в усталеному режимі роботи. Встановлено, що вона має пульсуючий характер, який співпадає із результатами аналітичних розрахунків на основі розробленої моделі. Висновок про відповідність отриманих результатів зроблено на основі рівності дисперсій продуктивності, яку перевірено за допомогою критерію Фішера.

Отримана модель може бути застосована для аналізу усталеного режиму роботи тарілчастих живильників безперервної дії у випадку, якщо сипкий матеріал надходить в центр тарелі

Ключові слова: циліндрично-конічний бункер, тарілчастий живильник, сипкий матеріал, метод дискретних елементів, взаємодія частинок

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1. Introduction

Polymeric materials are used in many products for industrial and domestic purposes [1, 2]. The base for their production is the mixtures of granulated or powdered polymeric materials, dyes, fillers, plasticizers, and other components. Subsequent technological process implies melting the mixture and feeding it under pressure to shape-forming devices and fillers in the production of pipes, or molds when manufacturing shoes and other molded articles [3, 4]. This technology puts forward strict requirements to the quality of the mixture, which is defined by two basic parameters: uniformity and correspondence between the percentage of composition and a formulation [5–7]. When these parameters deviate from the assigned values, in the majority of cases it points to a change in the physical-mechanical properties of the resulting product and, therefore, deterioration in its quality.

Technological complexes for the manufacture of mixtures of loose materials can be conditionally divided into three nodes: hoppers, dispensers, and a mixer. Starting components are placed in hoppers, dispensers or feeders are used to control their movement, and a mixer ensures their even distribution throughout the entire volume of the composition [6]. In this case, precision in the operation of dispensers and feeders is critical for ensuring the assigned percentage composition and, largely, the homogeneity of the mixture. The impact of accuracy of dosing is especially pronounced at mixing complexes of continuous action. In these complexes, bulk material moves in a continuous flow, which greatly complicates the adjustment of deviations in its parameters from the assigned values [6, 7]. One of the major problems arising in the design of technological equipment for dosing loose materials is a lack of information about the speed and direction of particles' movement in all its regions. Installing appropriate sensors for experimental evaluation of these parameters is in many cases impossible from a technological point of view. That complicates analysis of influence of structural elements in equipment on the characteristics of flow of a loose material, determining the magnitude of its pulsations, probability of the occurrence of discontinuities and stagnation zones. The result is the hundreds of different designs of feeders and dispensers of continuous type. Studying them has been addressed in a significant number of works [8–13], in which authors assessed the effectiveness of equipment based mostly on initial parameters (performance and its pulsations under a steady mode of operation).

Applying mathematical models of the motion of loose materials inside the dosing equipment would make it possible to detect possible problems at initial stages and to reduce the time to design. This predetermines the relevance of undertaking such a research and constructing appropriate models.

2. Literature review and problem statement

Designs and principle of operation of devices for continuous dosing of loose materials are given in papers [8–10]. The mathematical models that were suggested by their authors relate the structural and technological parameters of equipment. For example, the dependence of performance of the hopper on the diameter of its outlet branch pipe. These dependences do not take into consideration the physical and mechanical parameters of loose material such as coefficients of friction, elasticity, the angle of repose. Impact of these parameters is accounted for by using generalizing coefficients obtained empirically. These coefficients are given mostly in the form of ranges of values for certain groups of materials.

Paper [14] proposed a model of the movement of loose materials based on the theory of continuous media. This approach is based on well-studied physical processes of fluid motion and their mathematical notation, but it does not make it possible to take into consideration the discrete nature of the movement of individual particles and their interactions with the structural elements of equipment. The initial parameter of the model is productivity, which corresponds to the average value of performance of an actual process. Flow pulsations, possible disruptions due to the formation of clusters and accumulations of particles are not taken into consideration. Such models should be used for the case when it is known that the probability of the occurrence of these phenomena is low. This limits the applicability of the models in terms of studying the operation of equipment with loose materials whose granulometric composition or physical-mechanical properties differ significantly from the «exemplary».

Higher accuracy in modeling is demonstrated by a discrete element method (DEM) [15], which makes it possible to consider the movement of particles as a totality of solids, with their interaction to be described using the laws of classical mechanics. The work outlines the principles of model construction based on DEM, determining the interaction among particles, as well as with the structural elements of equipment. Based on the proposed approach, one can build models for almost any design of equipment and loose material. At the same time, constructing such a model requires consideration of both structural and technological parameters in the work of specific equipment, which is disregarded in work [15].

Study [16] analyzed the radial characteristics of a loose material flow via a conical hopper using DEM. The researchers proposed a local index of mass flow in order to categorize the movement modes of a material in hoppers. The model suggested makes it possible to determine the effect of physical and mechanical properties of particles on motion speed of a material in a hopper. At the same time, the study does not consider the impact of other components at a technological complex on the speed of particles in the region of a hopper's outlet branch pipe.

Paper [17] reports results of a two-dimensional computer simulation of a loose flow in hoppers using a discrete element method, as well as findings from experimental verification of the results obtained, which confirm reliability of the proposed mathematical model. The suggested approach significantly reduces the amount of required computations; it is advisable to apply it for the case when a material moves in one plane, that is, to study separate nodes within a technological complex. At the same time, the proposed model cannot be applied for the case when a material moves in several planes, which is the case when a loose material is transferred from the hopper to the reciprocating plate feeder. In such cases, it is necessary to use 3D modeling.

Work [18] addresses analysis of the influence of physical-mechanical parameters of loose materials on simulation results using DEM. The authors investigated the influence of values for coefficient of elasticity, Young modulus, coefficients of rolling friction and particles' sliding on the speed of their movement in conical hoppers. The obtained results make it possible to reasonably choose the parameters for particles of a loose material when modeling their motion in a hopper and in a feeder. However, the model proposed takes into consideration only the effect of the force of gravity in the region of a hopper's outlet branch pipe. That predetermines the introduction of additional constraints for studying the system «hopper – reciprocating plate feeder».

DEM is widely applied for analysis of flows of loose materials in feeders of various types. Thus, study [19] considers operation of the drum-type feeders. Paper [20] addresses modelling of work of belt feeders. These works report results of research into formation of the flow of a loose material that arrives from the hopper and moves steadily. The results obtained can be used to study the reciprocating plate feeders in order to describe the relative motion of particles. In order to proceed to the description of their absolute velocity, it is necessary to take into consideration the rotational component of the movement of the plate.

Article [21] investigated the dispersion of a loose material in the rotating equipment. The authors show the movement of particles under the action of centrifugal forces and investigate the occurrence of random fluctuations in the distribution of particles inside the equipment. Similar fluctuations (irregularities) in the distribution of particles are observed in the operation of reciprocating plate feeders, which makes it possible to use the obtained results to compare the character of particles motion in rotating equipment. The model suggested examines the movement of a material in the space, confined to the dimensions of equipment, and does not take into consideration the translational component of its movement, which is the case for a reciprocating plate feeder.

A study technique involving integrated evaluations of the dynamic properties of belt dispensers is proposed in [22].

The results obtained made it possible to minimize the impact of jump-like effects at the input to the measuring part of a dosing system. Given that the measuring system is located at the dispenser's outlet, the results obtained can be used to reciprocating plate feeders. To this end, the proposed model must be supplemented with the parameters that characterize the movement of a plate and the interaction between a knife and a loose material.

Thus, it is advisable to determine the character of movement of a loose material in the system «hopper – reciprocating plate feeder» by using a discrete element method. Models that are available require the generalization of parameters, which characterize the features of the system, specifically: mutual arrangement of the hopper and feeder, and the technological parameters for their operation (a plate's speed of rotation and a knife's position).

3. The aim and objectives of the study

The aim of this study is to construct a model of the motion of flows of a loose material inside the system «hopper – reciprocating plate feeder», which would make it possible to determine the position and speed of individual particles.

To accomplish the aim, the following tasks have been set:

– to take into consideration, when constructing a model by DEM, the mutual arrangement of components in the system «hopper – reciprocating plate feeder» and the forces acting among the particles.

– to determine the impact of working bodies on the distribution of particles' motion velocity inside equipment;

– to apply DEM in order to determine the system's performance;

– to design a testing bench and to perform experimental research into performance of the system «hopper – reciprocating plate feeder».

4. Materials and methods to study the movement of particles in a loose material in the system «hopper – feeder»

4. 1. Principle of operation of the system «hopper – feeder»

The study examines a system that consists of a conical-cylindrical hopper and a reciprocating plate feeder (Fig. 1).

Prior to starting the operation a loose material is loaded into the hopper (1) whose upper part has the shape of a cylinder, and bottom part is a cone with an inclination of the lateral wall of 45°. The bulk material freely passes through the outlet hole (2) and arrives at the feeder's plate. Such a design is one of the most common and ensures continuous supply of a material into the feeder. Performance of the hopper is defined by the size of the outlet. At the same time, the ratio of size of the discharge opening and the size of the loose material's particles defines probability of the occurrence of clusters [9]. In order to reduce it, it is advisable to maximally increase the diameter of the discharge opening in the hopper, and to control the system's performance via technological parameters of the feeder.

A reciprocating plate feeder consists of a plate (3), whose rotation is enabled by electric motor (M1), a cylindrical cup (4), a knife (5), and a servo drive (M2), which makes it possible to control position of the knife.

After leaving the hopper, a loose material under the action of gravity forces hits the plate, where it resides in the form of a cone, whose height is limited by the positions of the cup, and the angle of inclination of the lateral wall is equal to the material's angle of repose φ.

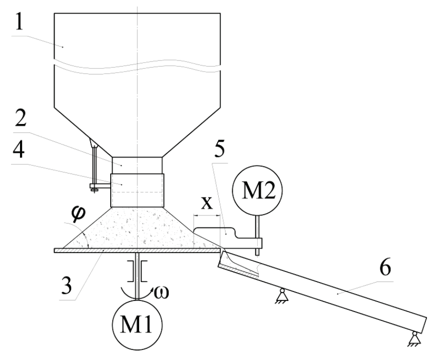

Fig. 1. System hopper – feeder

During operation, the feeder's plate rotates at constant speed; the knife removes a loose material from it and pushes it to a shaper (6). Performance is controlled by changing the amount of the material that is removed with a knife per unit time. Theoretically, this design has three options to control performance: by changing the plate's speed of rotation; by changing the distance between a plate and a cup; by changing position of the knife.

The first variant has a limitation related to that the centrifugal forces acting on particles must be smaller than the forces of friction, otherwise the material would crumble off the entire surface of the plate. That is, there is a limit on the maximum permissible speed of the plate's rotation, which reduces the range of control. The second variant is non-symmetrical, since after reducing the distance between a plate and a cup the amount of a material in the cone will not change instantly, but only after all the material that is found in the outer layer of the cone has been removed. When increasing the distance between a plate and a cup, additional material immediately begins to arrive from the hopper and, consequently, it would change the performance. The most universal is the last variant of control – by changing position of the knife. Its implementation is possible by using a low-capacity servo drive M2, and the performance in this case depends on a single parameter – position of the knife x, which can be changed at a small step.

The particles that are removed with the knife arrive at the surface of the shaper, through which they proceed to the next node of the technological complex, for example, to the mixer.

4. 2. Examining the movement of particles in a loose material using the discrete element method

In this paper, we examined movement of particles inside the hopper and feeder using DEM and the specialized software EDEM 2017. During simulation, loose material was considered to be a set of elastic spherical particles of radius R. According to the laws of classical mechanics, linear and angular displacement of each particle can be described using the following equations:

$$m_i \frac{d^2 x_i}{dt^2} = F_i, \quad I_i \frac{d^2 \theta_i}{dt^2} = M_i, \tag{1}$$

where t is the time, x_i, θ_i is the linear and angular displacement of a particle, respectively, m_i is the mass of a particle, I_i is the moment of inertia, F_i is the sum of forces acting on a particle, M_i is the sum of moments acting on a particle.

The sum of forces acting on a particle is composed of the totality of forces that act from the side of other particles F_{ij}, and the force of gravity.

$$F_i = \sum_{i=1,\, i\neq j}^{N} (F_{ij} + m_i g). \qquad (2)$$

A similar relation holds for the equation of moment:

$$M_i = \sum_{i=1,\, i\neq j}^{N} M_{ij} = \sum_{i=1,\, i\neq j}^{N} \left(x_i - x_j\right) F_{ij}. \qquad (3)$$

Surface forces F_{ij} are composed of repulsion forces F_n and friction forces F_t (Fig. 2, *a*). Fig. 2, *a* shows the interaction between two particles with centers at points O_1 and O_2, which have the linear υ_1, υ_2 and angular ω_1, ω_2 velocities.

We calculated positions of the particles at a certain step, which is why, during interaction, they partially «overlap» at certain points in time (Fig. 2, *b*). The absolute value of «overlap» δ is used to determine the magnitude of the normal component of force F_n, which acts between the particles.

The calculation of the normal component of the force was performed in accordance with the contact theory by Hertz [23]. We calculated the tangential component of force F_t based on the algorithm, proposed in the work by Mindlin-Deresiyevitch [24].

For both components of the force, we calculated damping components, which are defined by the coefficients of elasticity, the tangential force of friction was determined by Coulomb's law, and the force of rolling friction – based on the torque of the particles, which is derived from the algorithm described in [25].

Parameters for contacting objects and their interaction are given in Tables 1, 2.

The values for parameters of particles in a loose material, given in Tables 1, 2, are characteristic of the granulated polymeric material. The values for parameters of the hopper's body correspond to the properties of steel, which is most often used in the manufacture of equipment of this type.

Table 1

Parameters of particles and hopper's body

Parameter title	Particles of loose material	Hopper's body material
Poisson ratio	0.3	0.3
Density, kg/m^3	2,300	7,800
Shear modulus, Pa	$1.48 \cdot 10^8$	$7 \cdot 10^{10}$
Young modulus, Pa	$3.84 \cdot 10^8$	$1.82 \cdot 10^{11}$
Radius, mm	1	

Table 2

Parameters for the interaction of objects in contact

Parameter title	«Particle – particle»	«Particle – hopper's body material»
Elasticity coefficient	0.3	0.3
Static friction coefficient	0.3	0.4
Rolling friction coefficient	0.05	0.1

4. 3. Experimental study into performance of the reciprocating plate feeder

The experimental study was conducted using a testing bench whose principal diagram is shown in Fig. 3.

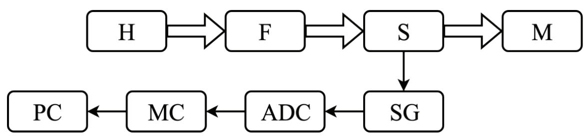

Fig. 3. Principal diagram of the bench for determining performance of the reciprocating plate feeder

The bench includes: a conical-cylindrical hopper (H), a reciprocating plate feeder of continuous type (F), a shaper (S), a mixer (M), a strain gauge (SG), a 24-bit analog-to-digital converter (ADC) based on the chip HX711, a microcontroller (MC) of the type ATMega328, and a personal computer (PC). Double arrow show the direction of a loose material between the bench's units, single arrows indicate the direction of transmission of information signals. The shaper is mounted so that its mass defines a signal from the strain gauge. Changing the number of particles at the surface of the shaper changes its mass and, consequently, changes the signal from the sensor. This signal through ADC is converted into a digital form and read by the microcontroller. The obtained data are transmitted by the microcontroller via the USB interface to a PC where they are stored for further processing. Before starting the bench operation, we calibrated it in order to eliminate the influence of natural weight of the shaper on signals from the strain gauge. To this end, the surface of the shaper hosted an immobile sample of the material with known mass. The signal from ADC was read; based on it, the ratio coefficient of the mass of a material to the signal from ADC was computed.

Next, the bulk material was loaded into the hopper at an open outlet branch and the disabled drive of the feeder in order to form the starting cone of the material at the surface of the plate. In this case, the feeder's knife was in a fixed position, which is necessary to remove the particles from the plate.

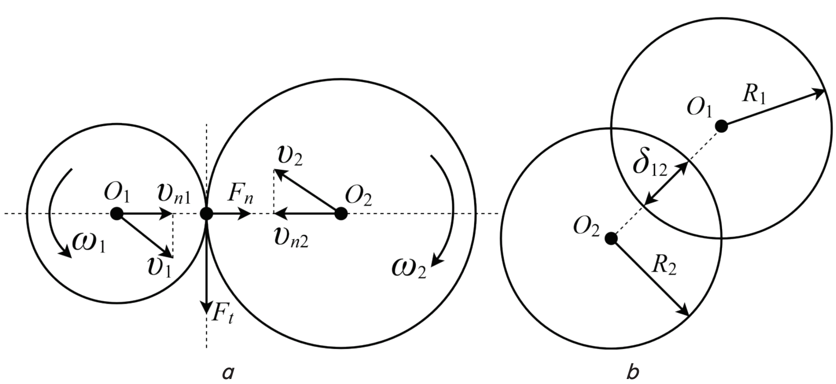

Fig. 2. Estimation schemes for determining parameters of particle interactions: *a* — forces of repulsion and friction; *b* — magnitude of the normal component of the force

During experiments, the electric motor of the feeder's drive received constant voltage, enabling its rotation at a constant speed; the program to read the signals from the strain gauge was run simultaneously. The software to control the microcontroller and transfer of data to a PC is written in the C language [26].

The timing of acquiring the sensor's signal was determined by the time required by ADC for converting the signal and its processing by MC; for our study, it was approximately 0.09 sec. The signals from the sensor were used to calculate the mass of a material and current time. This information via the USB-interface was sent to a PC. Following this, the measurement cycle was repeated.

5. Results of studying the movement of particles in a loose material in the system «hopper – feeder»

5. 1. Results of calculation of parameters for a loose material flow

The study that was conducted using the discrete element method has made it possible to determine the speed and position of particles in a loose material in the cross section of the system (Fig. 4, *a*) and at the surface of the plate (Fig. 4, *b*).

In Fig. 4, *a*, position of the particle is shown as a dot; in Fig. 4, *b* – in the form of a vector, whose beginning corresponds to the coordinates of a particle at a given time, the length and direction – to the vector of its velocity. Solid lines separate regions with certain speeds of the particles, the respective value for speed in m/s is given at each isoline.

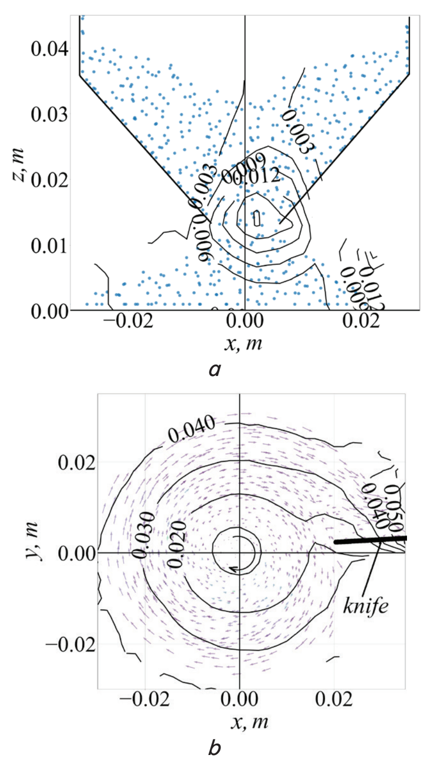

Fig. 4. Position, direction, and motion speed of particles: *a* – in the cross section of the system «hopper – feeder»; *b* – at the surface of the feeder's plate (top view)

Based on the derived values, we calculated performance of the feeder (Fig. 5, *a*). To this end, using the discrete element method, at each step of the calculation we determined the number of particles that were at the surface of the shaper and, accordingly, their mass. The obtained results are shown for the steady mode of operation whose onset corresponds to time t=0.

5. 2. Results of experimental research into the motion of particles in the system «hopper – feeder»

Based on the experimental research that we conducted, the dependence has been derived of the strain gauge's signal (the mass of a material at the surface of the shaper) on (Fig. 5, *b*) for the steady operation mode of the reciprocating plate feeder.

We determined signals from the sensor under a steady mode of feeder operation at the fixed values of the plate's rotation speed and position of the knife. Time t=0 corresponds to the onset of the steady mode. The duration of measurement chosen equals the duration of modeling by DEM, which is equal to 7 s.

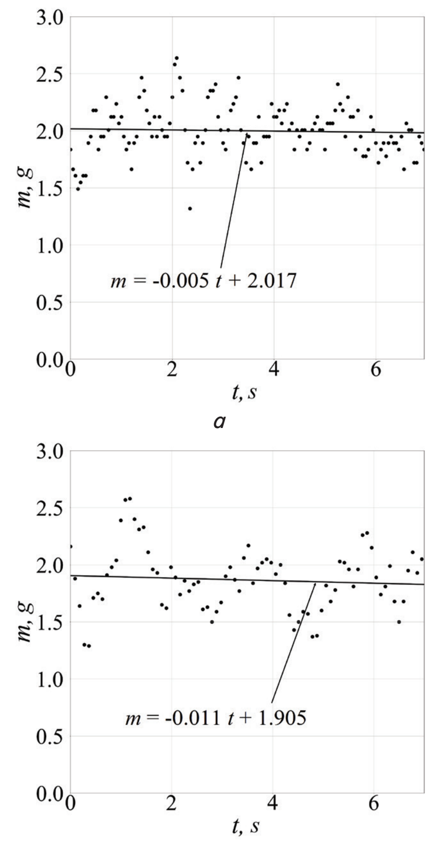

Fig. 5. Dependence of a material's mass on time at the surface of the shaper, determined: *a* – by a discrete element method; *b* – experimentally

We have calculated for the experimentally obtained data and the results that were derived using DEM (Fig. 5, *a, b*) their basic statistical characteristics (Table 4). Solid lines in Fig. 5, *a, b* show charts of the approximated linear functions. In addition, the charts demonstrate their equations in a natural form.

6. Discussion of results of studying the movement of particles in a loose material in the system «hopper – feeder»

The results obtained (Fig. 5, *a, b*) show that the flow of a loose material at the outlet from a reciprocating plate feeder demonstrates a pulsating character that corresponds to the discrete nature of its movement. During actual equipment operation the movement of a material is affected by factors that are not accounted for when calculating by DEM, for example, the particles are considered to be ideal spheres, there are neither vibrations nor deviations in the plates' speed of rotation. That predetermines the need to check agreement between those values that were calculated by DEM and those derived experimentally. To this end, in the course of the study we tested the steady operational modes, calculated basic statistical characteristics of processes, and checked the equality of variances.

To check the steady modes of operation, we calculated determination coefficients R^2 between the data obtained and those values calculated from the regression equations shown in Fig. 5, *a, b*. Results of calculations are given in Table 3.

Table 3

Values for determination coefficients

Magnitudes for which determination coefficient was calculated	Value R^2
Results from calculation by DEM – values obtained from regression equation $m=-0.011\cdot t+1.905$	0.0902
Results of experimental study – values obtained from regression equation $m=-0.055\cdot t+2.017$	0.0021

In the ideal case, under the steady mode of operation, performance of the feeder (mass of the material that passes at surface of the shaper per unit time) is a steady magnitude and must be equal to the average values of experimental data and to the values derived by DEM. The magnitude of a determination coefficient, which approaches zero, indicates that the results of calculations, obtained from the regression equations, coincide with the average values. That is, both for the case of using DEM and for the case of experimental research one can argue on that the feeder operates under a steady mode.

Table 4 gives results from calculating the parameters for flows of a loose material, determined using DEM and obtained experimentally. All values were calculated for a time range from 0 to 7 s. The averages, root-mean-squared deviations, variance, and confidence intervals were determined separately for the results from the experiment and for the results of calculation using DEM. The root-mean-squared deviations of regression and the variance of the regression were computed between the experimental values and the values obtained from the respective regression equation.

Table 4

Comparison of experimental results with calculated values

Parameter title	DEM	Experiment
Average value, g	2.0	1.87
Root-mean-square deviation	0.22	0.273
Variance	0.049	0.074
Confidence interval (for a 95 % reliability)	1.963...2.037	1.805...1.928
Root-mean-square deviation of regression	0.22	0.27
Regression variance	0.048	0.073

The obtained values, experimental and calculated by DEM, are random in character and their comparison in this work was performed based on a Fisher criterion (F-criterion) for the equality in variances. For this purpose, we calculated the variance of experimental values $\sigma^2=0.082$ and variance in the values calculated by DEM $\sigma^2_{DEM}=0.056$.

That allows us to draw a conclusion about the conformity of the model that was used for studying when applying the discrete element method to the actual process of movement of a loose material in the system «hopper – feeder». In addition, it can be argued that the study results, which are shown in Fig. 4, 5, correspond to the actual process as well.

An analysis of velocities and position of particles in the cross section of the hopper indicates the normal character of material motion inside the hopper, which is confirmed by the emergence of a characteristic funnel around the central axis of the hopper (Fig. 4, *a*). The obtained data make it possible to quantify velocities of the particles and to identify regions where their speed is greatest. In a given case, it is a zone of transition between the hopper's outlet branch pipe and the upper part of the cone of a loose material that resides at the surface of the plate, and a zone of the outer layer of the material at the plate's surface, which is at the largest distance from the axis of rotation (Fig. 4, *a*, isoline at a speed of 0.012 m/s).

Studying the movement of the lower layer of particles at the plate's surface makes it possible to evaluate a change in the shape of a cone, which arises due to the interaction between the particles and a knife, as well as their speed and the width of the flow of a material that comes from the feeder onto the shaper (Fig. 4, *b*). The minimum radius of a material is determined by the distance from the edge of the knife to the plate's axis of rotation; in this case, it is 0.02 m.

In this region, the angle of inclination of the lateral wall of the cone of a material is larger than the natural angle of repose. As a result, particles under the action of gravity force arrive from the hopper onto the plate's surface, which leads to a gradual increase in the radius of the cone. The greatest value for a radius is observed in the region in front of the knife where the material changes direction and starts moving along the surface of the knife to the shaper. In this case, this value is 0.032 m. Considering that the examined material has an angle of repose of ~30°, the radius of its cone at a stationary plate could amount to 0.028 m, that is, during operation of the feeder the radius of the cone of the material's arrangement would increase by 15.2 %. The condition for the proper operation of the feeder is to satisfy the ratio:

$$F_C < F_F, \quad (4)$$

where F_C is the centrifugal force acting on a particle that resides at the plate's surface, F_F is the force of friction between a particle and the surface of the plate.

This means that the calculations aimed at the verification of ratio (4) must be performed based on the angle of repose of a material and a coefficient of reserve, which in this case is 15.2 %.

These values should be considered when designing a reciprocating plate feeder, because in order to enable its correct operation, one must ensure that the magnitude of the centrifugal force acting on particles is less than the strength of their friction against the plate's surface. Considering the relatively long duration of calculations by the discrete element method, in practice, when designing reciprocating plate feeders, it is advisable to carry out check calculations using DEM for materials that demonstrate the smallest value for the angle of repose.

The results of studying the system «hopper – reciprocating plate feeder» make it possible to identify the character of movement of a material considering the mutual influence of the system's components. The calculated values for velocities of particles in a hopper significantly differ in absolute magnitude from speeds for the case of a free-flowing material [17–19]. At the same time, the movement of a material in the region of a reciprocating plate feeder was analyzed taking into consideration the continuous arrival of a material from the hopper. That made is possible to determine its position at the plate's surface under a steady mode of operation.

The resulting model of the system could be applied under condition for using a reciprocating plate feeder onto which a loose material is fed to the center of the plate and removed with the knife from the outer layer. The model also implies that the physical-mechanical properties of particles are constant and the particles are exposed to the forces of friction and elasticity. We disregarded those cases when particles are lumped, for example, due to excessive humidity in the environment.

The approach for studying equipment of continuous action, proposed in this work, forms a basis for the further research into mixing complexes. First of all, this concerns determining the influence of pulsations in a loose material flow on the percentage composition and homogeneity of a mixture, and, accordingly, on the quality of the resulting product.

7. Conclusions

1. We have constructed a model of the movement of particles in a loose material based on DEM taking into consideration the mutual arrangement of components in the system «hopper – reciprocating plate feeder» and the forces acting between the particles.

2. We have established the effect of working bodies in the system «hopper – reciprocating plate feeder» on the distribution of particles' motion velocities inside the equipment.

3. The results obtained have confirmed the normal character of particles' movement inside the hopper. It was established that during operation of the reciprocating plate feeder one observes an increase in the radius of the cone of a loose material that resides at the plate's surface, by 15.2 %.

4. We have designed a test bench and performed an experimental study into performance of the system «hopper – reciprocating plate feeder». An analysis of the results obtained has confirmed the adequacy of the proposed model.

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DEVELOPMENT OF TRENCHLESS TECHNOLOGY OF RECONSTRUCTION OF «PULLING PIG P» PIPELINE COMMUNICATIONS

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Розроблено технологію безтраншейної реконструкції трубопровідних комунікацій протягуванням поршнем нового поліетиленового трубопроводу в зношений сталевий – «Тяговий поршень Т». Поршень рухається під тиском повітря, яке подається в запоршневий простір компресором.

Виконано математичне та CFD моделювання процесу протягування трубопроводу поршнем. Виведено формули для розрахунку сил опору, які діють на рухому систему, та тиску на виході компресора, при якому поршень протягне новий поліетиленовий трубопровід усією довжиною реконструйованого зношеного сталевого трубопроводу. Силами опору, які діють на рухому систему на горизонтальних ділянках траси, є: сила механічного тертя манжет поршня до стінок сталевого трубопроводу; сила тертя поліетиленової труби до сталевої; сила тертя поліетиленової труби в кільцевих манжетах ущільнювальної системи.

Результати CFD моделювання були візуалізовані в постпроцесорі програмного комплексу Ansys Fluent побудовою ліній течії, векторів швидкості, полів тиску на контурах і в повздовжньому перерізі міжтрубного та запоршневого простору. Визначались точні значення швидкості, тиску в різних точках міжтрубного та запоршневого простору. Досліджено структуру потоку повітря у запоршневому та міжтрубному просторі. Виявлено місця сповільнення та пришвидшення потоку повітря, падіння та зростання тиску. Визначено втрати тиску в міжтрубному просторі.

Виконавши експериментальні випробування, встановлено, що розроблена технологія «Тяговий поршень Т» може застосовуватись для реконструкції трубопровідних комунікацій. За результатами експериментальних вимірювань побудовано графіки зміни тиску повітря на початку трубопроводу в часі під час протягування поршнем поліетиленової труби зношеною сталевою. Тиск на початку трубопроводу до початку протягування збільшується, що обумовлено силою тертя спокою. Після початку протягування тиск зменшується на незначну величину, а під час протягування відбувається незначне його збільшення. Побудовано графіки залежності швидкості протягування від об'ємної витрати повітря та від довжини протягнутої ділянки поліетиленової труби. На початковому етапі швидкість протягування різко зростає і після такого зростання стабілізується

Ключові слова: втрати тиску, об'ємна витрата, сила тертя, тягове зусилля, швидкість протягування

1. Introduction

The large volumes of construction of steel pipelines (gas, heat and water networks) in the middle and the end of the last century caused considerable difficulties in maintaining them in proper condition today, when most of them are 60–90 % worn-out out. There are many sections of pipelines that have spent their life in two, three times and their volume