Effect of bulk material mechanics on optimal packaging geometry in adaptronic dosing systems

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Abstract

Introduction. The purpose of research is to substantiate the design and parameters of the feeding device of the functional module for dosing bulk products in a volumetric way with continuous operation of the rotor with measuring cups.

Materials and methods. The object of packaging is low-flux bulk products with particle sizes of 0.6–6.0 mm. The design of the feeding device is a combination of conical and cylindrical parts of the product pipeline. The analysis of the movement of bulk products in the channels of the feeding device was carried out using the methods of classical mechanics and discrete elements of Altair EDEM. Experimental studies were carried out on a packaging machine at a rotor rotation frequency of 5–20 rpm.

Results and discussion. The novelty of the conducted research is the consideration of the continuous movement of the rotor with measuring cups both at the stage of product dose formation and at the stage of bulk product feeding during the design of the effective design of the feeding device. The duration of packaging significantly affects the performance of the dosing and feeding adaptronic module of the packaging machine. With continuous rotation of the rotor with measuring cups, it is almost impossible to ensure the free movement of bulk product particles through the channels of the feeding device. To reduce the duration of interaction of particles with the inner cone surface of the feeding device, an effective method is to increase the coefficient of the cross-sectional area of the conjugation of the cone and cylindrical parts of the funnel. An eccentric arrangement of the cylindrical part of the product line relative to the conical part is proposed. An expression was obtained for determining the rational value of eccentricity at different kinematic parameters of the movement of measuring cups. In terms of the geometric construction of the cone-cylindrical feeding device, the eccentricity can be varied between 0 and 0.5 of the diameter of the cylindrical part of the funnel. To ensure the given productivity, the diameter of the base of the conical part of the feeding device is determined taking into account the kinetics of the particle's movement, geometric parameters of the rotor, kinematic and geometric parameters of the measuring cup. Using the same input data for both the theoretical and simulation models, the packaging time for a bulk product dose is 25–27% longer than that for a single characteristic particle. By increasing the cross-sectional area of the conjugation of the conical and cylindrical parts of the funnel, it is possible to reduce the duration of bulk product feeding for packaging by up to 11%.

Conclusions. By increasing the cross-sectional area of the conjugation of the conical and cylindrical parts of the funnel, it is possible to reduce the duration of of bulk product feeding for packaging to 11% and the productivity of the adaptronic module to 11%.

Introduction

Dosing and feeding is the most important and responsible operation of the process of packaging products. Bulk products, like other types of products, are characterized by different values of physical and mechanical parameters. The physical and mechanical properties of bulk products significantly affect the choice of an effective method of dosing and feeding. For easy-flux bulk products, while ensuring high productivity values, the volumetric method of dose formation is widely used.

In modern automatic machines, this method of dosing is implemented by adaptronic packaging modules, the working body of which is a cup dispenser with a continuous mode of rotation of the rotor (Gavva et al., 2023). Rotor rotation frequency and the number of cups in the rotor directly affect the performance of both the functional module and the packaging machine in general. In turn, the frequency of rotation of the rotor depends on the duration of bulk products dosing and feeding. In the rotary arrangement of the dosing and feeding module, the cycle time is the limiting packaging operation. In general, the duration of the kinematic packaging cycle includes the duration of opening the cup flap, moving products from the cup to the package, supplying and removing the container or package. Of the above cycles, the longest and most likely by definition is the cycle of moving bulk products from the cup to the package. The design of the funnel of the feeding device affects additional supports for the movement of products when it is exposed to the inner surface of the funnel and possible impact phenomena. One of the ways to minimize the duration of movement of bulk products in the product pipeline of the feeding device is to determine its rational geometric parameters.

Determining the rational parameters and geometry of the feeding device is a multi-parameter problem. The duration of product movement will be affected by its physical and mechanical properties, parameters of interaction with working bodies, initial conditions of product state and aerodynamic resistance (Stypnytskyy, 2013).

Today, various methods are used to study the movement of bulk products in the product pipelines of packaging and technological machines, which were developed to model the movement of substances in liquid, quasi-liquid and gaseous states (Burmystenkov et al., 2018).

Modern dosing and feeding modules consist of several devices (bunker, dosing and feeding elements), the nature of the movement of particles in which is significantly different. Therefore, when developing mathematical models, the module and its individual links are divided into zones, the movement of products in which can be described by applying known and adapted models. Such models include models used during the mechanics of continuous systems (Bertrand et al., 2005). In general, they are called flow structure models (Behjani et al., 2019). A characteristic feature of the functional dosing module of the cup type is the separation of flows of bulk products and the chaotic movement of individual particles during the formation and separation of the product dose from its massif. Mathematical models of the flow structure for such a module make it possible only to approximate the nature of the real process, since they do not take into account the peculiarities of the real physical and mechanical process of the interaction of particles with each other and with the structural elements of the module (Burmistenkov et al., 2019). In some cases, to simplify and speed up the development of a new functional module, mathematical models of the movement of the most characteristic particles of bulk products, their interaction with the working elements of the module are created (Kafashan et al., 2019).

Regression models are effectively used for the actual design of the dosing and feeding module and a specific type of bulk product (Di Renzo and Di Maio, 2004; Dubey et al., 2011). Such models ensure high accuracy of forecasting indicators of the quality of the operation (duration, dosing accuracy) within the selected ranges of parameter variation. Along with this, it is almost impossible to use them for other structures, since they do not take into account the nature of physical and mechanical phenomena that occur during the operation of dosing and feeding modules. This greatly complicates the use of such models in the design of dosing and feeding modules, since each design option requires the production of a prototype (Yuu and Umekage, 2011). Numerical methods, in particular, the method of discrete elements (MDE), are more universal and make it possible to analyze the phenomena that occur during the movement of bulk products in the product channels of dosing and feeding modules (Dubey et al., 2011; Munjiza, 2004). This method is based on the laws of classical mechanics used to calculate the motion of a large number of particles (Benvenuti et al., 2015).

The advantages of this method are the availability of information about the speed and position of individual particles and the ability to model breaks and pulsations in material flows. MDE does not require the creation of a physical model of equipment (Sarkar and Wassgren, 2009, 2010).

Numerical methods are also used to solve mathematical models describing the movement of individual particles of a bulk product in the field of action of mechanical forces (centered, frictional, gravitational, etc.) that arise during its movement in the working device of the dosing and feeding module and are presented in the form of differential and integral equations (Bila and Statsenko, 2012; Vera et al., 2015).

Derenivska et al. (2014) and Maslo (2013) provide data on the movement of bulk products in weight dispensers, and ways of intensifying the movement of finely dispersed bulk products under the action of vibration loads are proposed by Sholoviy et al. (2014) and Maherus (2014). However, these works separately consider the movement of bulk products in the hopper without taking into account the modes of movement of products in previously performed technological operations.

The purpose of the study is to substantiate the design and parameters of the feeding device of the functional module for dosing bulk products in a volumetric way with continuous operation of the rotor. According to the goal, the following tasks are formulated:

- analyze the kinematic parameters of the movement of the most characteristic particles of bulk products in the channels of the product pipeline of the feeding device;
- determine the effect of the displacement of the central cylindrical part of the funnel of the feeding device in relation to the cone part on the effective cross-sectional area of the movement of the product flow and the duration of movement;
- applying the method of discrete elements, to investigate the movement of the flow of bulk products in the product pipeline of the feeding device and the influence of the constructive execution of the funnel on the kinematic parameters of the packaging operation;
- check the adequacy of simulation models of the movement of bulk products in feeding devices with real processes.

Materials and methods

Research products

The object of dosing and feeding is low-flow bulk products with a size of 0.6–6 mm. Such products include cereals (rice, buckwheat, millet, oats, etc.), dry sugar and salt, small-leaf tea, etc.

Calculation model

Figure 1 shows a characteristic scheme of the functional module for dosing and feeding of bulk products of continuous action, the measuring containers of which are made in the form of telescopic cups. In such modules, unloading of measuring cups is carried out during their continuous movement. The design of the product feeding device is mostly a combination of conical and cylindrical parts of the product pipeline. The cylindrical part has the diameter of the sleeve of the film from which the package is made, or the dimensions of which are equivalent to the cross-sectional size of another type of package (pack, can, box). The conical part corresponds to a truncated cone, the larger diameter of which corresponds to the arc of movement of the cups in the packaging zone. And the smaller diameter – of the diameter of the cylindrical part. The angle of the generating side surface of the cone is taken depending on the mode of movement of bulk products (normal, hydraulic, solid). To implement a deterministic hydraulic mode of movement of bulk products, it is recommended (Statsenko et al., 2021) to take the angle of inclination of the conical surface within 60–70°. The length of the feeding device is determined by its layout depending on the diameters of the bases of the cone, the diameter of the cylindrical part, the angle of inclination of the cone surface and the location and structure of the film supply module, the formation of the package from it or the location of the supply transport system for other types of packaging.

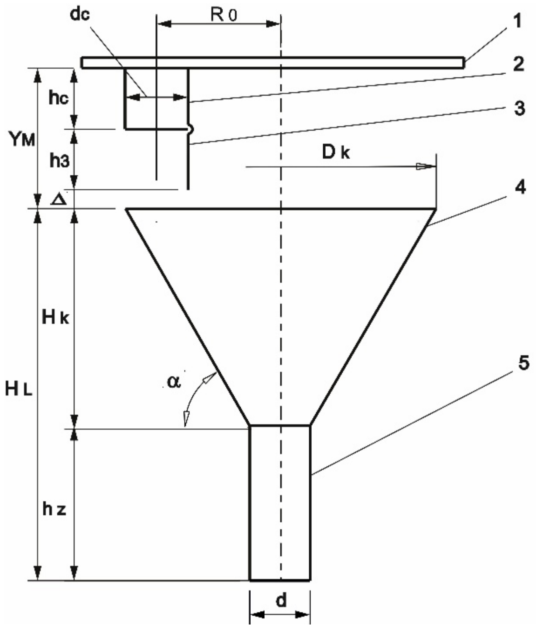


Figure 1. Scheme of dosing and feeding module for bulk products of continuous action: 1 – hopper with bulk products; 2 – cup measuring capacity; 3 – flap; 4 – conical part of funnel; 5 – cylindrical part of funnel

The technological duration of packaging is determined by the duration of the movement of products from the dosing container (cup) to the conical part of the feeding device, its movement in the conical and cylindrical part of the funnel.

In the optimal variant, regarding the minimization of the duration of product movement, it should move along the cylindrical part of the device, without contact with the inner surface of the product pipeline. However, for continuous dosing modules, it is quite difficult to achieve this type of movement.

For the most part, with the appropriate ratios of the geometric parameters of the feeding device, the frequency of rotation of the rotor with measuring cups, the physical and mechanical properties of bulk products, part of the products will move with sliding along the inner surface of the funnel cone. Along with this, force contact of the products is also possible on the inner surface of the cylindrical part of the feeding device. Such movement can lead to turbulence of movement, particle co-strikes. This increases the duration of packaging and, accordingly, reduces the performance of the module. To eliminate these negative phenomena, it is appropriate to apply several innovative proposals, one of which is the creation of a rational design of the feeding device, which involves increasing the effective cross-sectional area of the product channel and minimizing the metal capacity of the device.

In order to establish the limits of the change in the geometric parameters of the feeding device, it is appropriate to investigate the movement of characteristic particles of bulk products using the methods of classical mechanics – of the dynamics of the movement of a material particle. At the same time, the following assumptions are accepted: a particle of bulk products has mass, but its geometric dimensions can be neglected, the particle is an elastic-plastic body with a speed recovery coefficient after impact on the conical surface of the device, which is determined within $k \approx 0.1$–0.3, the influence of the action of the surrounding particles on the movement of the studied particle is conditionally also neglected.

To analyze the phenomena that arise during the movement of bulk products in the product channels of dosing and feeding modules, we will use numerical methods of MDE. MDE is based on the assumption that bulk products consist of discrete particles that can have different properties and surface shapes. In order to reduce the number of calculations, particles of complex shape are modeled as a set of spheres of different diameters. MDE makes it possible to simulate the movement of product particles, which is caused by the influence of gravitational and coulomb forces, as well as forces arising as a result of the action of the working bodies of functional modules on products.

The input parameters for the modeling process are the initial conditions: position (x_i, y_i, z_i), linear (υ_{xi}, υ_{yi}, υ_{zi}) and angular (ω_{xi},ω_{yi},ω_{zi}) velocities of all particles. The position and parameters of the movement of the working bodies of the dosing and feeding module interacting with the products are also set.

The modeling process is iterative. Before it begins, the modeling step Δt is determined, for this we apply the Rayleigh criterion (O'Sullivan and Bray, 2004; Otsubo et al., 2017)

$$\Delta t = \frac{\pi R}{0.163\nu + 0.87766}\sqrt{\frac{\rho}{G}}, \tag{1}$$

where R, ρ, G, ν are the radius, bulk mass, shear modulus, and Poisson coefficient of the particle (Zhu H. P. et al, 2006) respectively.

At the beginning of each iteration, based on the laws of classical mechanics, the total value of the forces acting on each of the particles and their moments of iteration according to differential equations is determined

$$m_i \frac{d^2 x_i}{dt^2} = \sum_{i=1, i \neq j}^{N} F_{ij} + m_t g; \tag{2}$$

$$J_i \frac{d^2 Q_i}{dt^2} = \sum_{i=1, i \neq j}^{N} M_{ij,} \tag{3}$$

where t is time;
m_i – particle mass;
J_i – moment of inertia of the particle;
Q_i – the angle of rotation of the particle;
M_{ij} – moment of forces acting between particles;
F_{ij} – forces acting on the particle from other particles and working bodies of the feeding device.

The sum of the forces F_i acting on the particle can be represented by the set of forces acting on the side of other particles F_{ij} and the force of gravity:

$$F_i = \sum_{i=1, i \neq j}^{N} F_{ij} + m_i g. \tag{4}$$

A similar expression can be written for a moment M_i

$$M_i = \sum_{i=1, i \neq j}^{N} M_{ij} = \sum_{i=1, i \neq j}^{N} \left(x_i - x_j\right) F_{ij.} \tag{5}$$

At each step, the position of the particles is calculated with the working bodies of the device and with each other. In the presence of such interactions, the values of tangential and normal forces are calculated and new vectors of particle movement speeds are calculated. Based on them, the positions of the particles in the next step of modeling (after Δt time) are calculated. Then the calculation cycle is repeated.

F_{ij} forces consist of repulsive forces and frictional forces that can be decomposed into normal and tangential.

The positions and velocities of movement of all particles after a period of time Δt, at defined forces and known initial velocities, are calculated according to Newton's second law.

$$x_i = x_{oi} + v_{xi} \Delta t + \frac{F_{xi}}{m_i} \cdot \frac{\Delta t^2}{2}; \tag{6}$$

$$y_i = y_{oi} + v_{yi} \Delta t + \frac{F_{xyi}}{m_i} \cdot \frac{\Delta t^2}{2}; \tag{7}$$

$$z_i = z_{oi} + v_{zi} \Delta t + \frac{F_{zi}}{m_i} \cdot \frac{\Delta t^2}{2}, \tag{8}$$

where F_{xi} F_{yi} F_{zi} – are the constituent sums of the forces acting on the i-th part along the x, y, z axes, respectively.

Once a new position of the particles has been determined, possible particle intersections between themselves and with surrounding objects are calculated. The values of these δ intersections are used as input parameters to determine the normal component forces acting on the particles. At each subsequent iteration, all calculation steps are repeated.

Herzen's contact theory was used to determine the normal component of the interaction force (Di Renzo and Di Maio, 2004; Zhu et al., 2007), and the tangential ratio is Midlin-Deresievich (Bertrand et al., 2005). For both of these force components, damping components determined by elasticity coefficients were calculated (Williams and O'Connor, 1999; Yan et al., 2015).

The tangential force of friction was calculated according to Coulomb's law, the force of rolling friction was calculated based on the rotational moment of the particles.

The normal component of the force was calculated according to the formula:

$$F_n = \frac{4}{3} E^* \cdot \sqrt{R^*} \delta_n^{\frac{2}{3}}, \quad (9)$$

where δ_n – is the overlap of particles;

E^* is the equivalent value of Young's modulus:

$$\frac{1}{E^*} = \frac{\left(1-v_i^2\right)}{E_i} + \frac{\left(1-v_j^2\right)}{E_j}; \quad (10)$$

R^* is the equivalent value of the radius of the spheres of particles

$$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j}, \quad (11)$$

E_i, v_i R_i, E_j, v_j R_j – values of Young's modules, Poisson coefficients and radii of spheres (i-th and j-th particles) between which the interaction is calculated.

The normal component of the elastic force was determined by the formula:

$$F_n^d = -2\sqrt{\frac{5}{6}} \beta \sqrt{S_n \cdot m^*} \cdot \overline{\upsilon_n^{rel}}, \quad (12)$$

where $m^* = \frac{m_i \cdot m_j}{m_i + m_j}$ the equivalent mass of the two contacting partics with the masses m_i and m_j;

$\overline{\upsilon_n^{rel}}$ normal component of relative speed in the normal direction;

β – damping coefficient, which depends on the recovery coefficient $\mathbf{e_0}$ (the recovery coefficient is related to energy losses in the event of a collision);

S_n – normal stiffness depending on Young's equivalent modulus E*, equivalent radius R* and normal overlap δ_n.

S_n and β are calculated using formulas

$$s_n = 2E^* \cdot \sqrt{R^* \cdot \delta_n}; \quad (13)$$

$$\beta = \frac{\ln e_0}{\sqrt{ln^2 e_0 + \pi^2}}. \quad (14)$$

The tangential component F_t of the interaction force was calculated based on the values of the tangential overlap δ_t t and the tangential stiffness S_t

$$F_t = -S_t \cdot \delta_t, \quad (15)$$

where

$$S_t = 8G^* \sqrt{R^* \cdot \delta_n}; \quad (16)$$

G^* – equivalent shear modulus.

In addition, tangential damping was defined as

$$F_t^d = -2\sqrt{\frac{5}{6}} \beta \sqrt{s_t \cdot m^*} \cdot \overline{\upsilon_t^{rel}}, \quad (17)$$

where $\overline{\upsilon_e^{rel}}$ – relative tangential velocity.

The tangential force is limited by the Coulomb friction value $\mu_s \cdot F_n$, where μ_s is the static friction coefficient.

When taking into account the force of rolling friction, calculations were performed taking into account the amount of torque of the contacting surfaces

$$T_i = -\mu_r \cdot F_n \cdot R_i \cdot \omega_i, \qquad (18)$$

where μ_r is the rolling friction coefficient;

R_i is the distance from the point of contact to the center of mass of the particle;

ω_i – is the unit vector of the angular velocity of the particle at the point of contact.

To study the movement of the flow of bulk products from the telescopic cup through the product pipeline of the feeding device, a three-dimensional model of a conical-cylindrical funnel was created at Solid Works CAD and was converted into a stl-format, which was used to transfer the model to the Altair EDEM MDE calculation environment. In the stl-format, information about a three-dimensional object is stored as a list of triangular faces describing its surface and their normals.

The MDE modeling process involves determining the geometric parameters of the working bodies of the module included in the model and the parameters of their interaction. In the present case, the funnel of the device is a stationary object, so that information about the geometric dimensions is sufficient for its simulation, which is transmitted in the stl-file and the physical and mechanical properties of the material from which it is made (Table 1).

Table 1

Materials parameters

Parameter name	Particles of bulk products	Funnel body material
Poisson Coefficient	0.25	0.30
Bulk, kg/m^3	660	7800
Shear Modulus, Pa	$1.0 \cdot 10^6$	$8.0 \cdot 10^7$
Young's Modulus, Pa	$0.2 \cdot 10^6$	$1.82 \cdot 10^{11}$
Radius, mm	3.0	
Weight, kg	$7.58607 \cdot 10^{-6}$	
Volume, m^3	$1.1494 \cdot 10^{-8}$	
Moment of Inertia, kg/m^2	$5.94748 \cdot 10^{-12}$	

To carry out MDE modeling, it is necessary to set parameters for two models of interactions: particle-particle and particle-material of the funnel. For both interactions, the Herz-Mindlin elastic contact theory is used (not including slip). The parameters of the interaction models are given in Table 2.

The modeling process was performed for several variations of the change in the eccentricity of the position of the cylindrical part of the funnel in relation to the conical part (e=0; 20 mm; 50 mm; -20 mm; -50 mm) and the angular speed of rotation of the rotor with measuring cups (ω_p = 0.525 rad/s; 0.790 rad/s; 1.05 rad/s; 1.57 rad/s; 2.10 rad/s), which corresponds to the following values of the performance of the automatic machine (z = 30 doses/min; 45 doses/min; 60 doses/min; 90 doses/min; 120 doses/min).

Table 2

Object interaction parameters

Parameter name	Type of interaction	
	Particle-particle	Particle-funnel material
Coefficient of Restitution	0.08	0.2
Coefficient of Static Friction	0.7	0.4
Coefficient of Rolling Friction	0.05	0.02

Calculations were made from determining the duration of movement of the entire dose of products (m_d=0.800 kg) at three levels of the feeding device: from the measuring cup to the conical part of the feeding device; in the conical part of the funnel and in its cylindrical part.

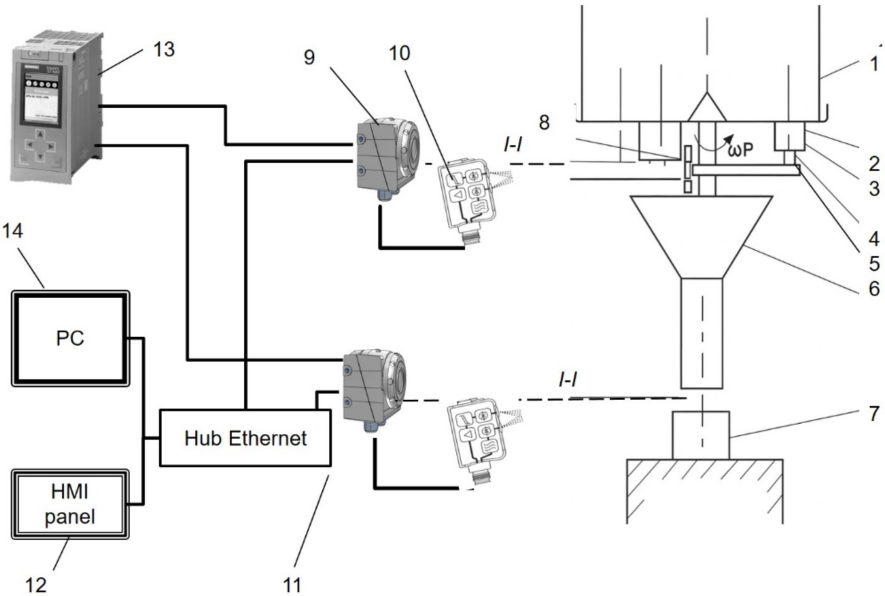
The shape and size of the particles remained unchanged at the entire stage of movement. The angle of inclination of the side walls of the conical part of the funnel was 70°, which ensures a hydraulic mode of movement of the flow of bulk products. The diameter of the cylindrical part of the funnel is taken to be d=100 mm, its length is H_c=450 mm. The diameter of the base of the conical part of the funnel D_k, calculated according to the formulas and accepted D_k=550 mm.

Checking the adequacy of the results of analytical simulation modeling of the movement of bulk products in the product pipeline of the feeding device was carried out on a actually operating automatic machine for packaging bulk food products, in particular cereals, into a polypropylene film (Figure 2).

The functioning of the system is based on the complex use of sensor technologies, intelligent image processing and logic-program control based on a programmable logic controller.

At the initial stage of the technological process, products (rice groats) are supplied from the hopper 1 to measuring cups 3, which are fixed on the disk of the rotating rotor 2. The movement of the rotor is driven by an electric drive with frequency adjustment of the angular speed. The measuring cup, in the zone of product dose formation, is closed by a valve flap, which contacts the copier 5 through the roller 4. In the feeding zone, the roller does not come into contact with the copier, which leads to its opening and movement of bulk products into the funnel 6 of the feeding device.

The measuring cup is fixed at the opening point of the flap using an inductive positional sensor of the Pepperl+Funchs model NBB5-18GM50-E2-V1, which is installed directly in the zero position zone of the rotor. Its action is based on the principle of changing the magnetic permeability in the presence of a metal label on the rotor. When the measuring cup approaches the control position, the sensor is activated and provides a corresponding signal to the controller for further start-up of the system logic. In the next phase, the vision sensor of technical vision 9 of the BVS UR-3-10-5-E model is activated. This sensor includes a built-in CMOS camera, an LED-based backlight module and a signal processing unit. After the trigger is activated, the device captures an image of the measuring cup and performs preliminary processing, including binarization, contour extraction, and analysis of the occupied area. This allows the system to determine whether the cup contains product or is empty, preventing the formation of empty packages and ensuring the reliability of the dosing system.



a

b

Figure 2 – Experimental installation for determining the duration of bulk products from measuring cup in a package:
a – *scheme:*
1 – hopper with products, 2 – rotor with measuring cups, 3 – measuring cup, 4 – roller, 5 – copier, 6 – funnel of the feeding device, 7 – packaging, 8 – position sensor inductive position, 9 – technical vision sensor, 10 – optical reflector label, 11 – Ethernet hub, 12 – HMI configuration panel, 13 – PLC S7 -1500 , 14 – PC programmer;
b – *general view*

The exact timing of product entry into funnel 6 is controlled using an optical reflector sensor 10 installed in the unloading area. This sensor operates on the photoelectric principle: a light beam emitted by the sensor is reflected from a mark or the product back to the receiver. A change in reflectivity—such as when a mark or bulk product interrupts the beam—alters the sensor output, which is recorded by the controller as an unloading event.

All sensor elements 8, 9,10 are integrated into a single automated system using a Siemens S7-1500 PLC (CPU1512SPF1PN) – position 13. Inductive and optical sensors are connected via standard discrete inputs, while the vision camera uses an Ethernet connection to transmit large amounts of data. Signal processing takes place in real time, which makes it possible to ensure accurate synchronization between mechanical events and actions of software logic. The interface of the NMI panel (Siemens SIMATIC Comfort Panel TP 700) – position 12 makes it possible to control and visualize the process, and the PC programmer 14 is used to change configurations, program or archive the results of experiments.

The method of conducting the experiment is based on the precision recording of events in the technological operation. In particular, four key time stamps are fixed:

T_1 – the moment of activation of the inductive sensor corresponding to the filling of the measuring cup;

T_2 – the moment when the vision sensor registers the presence of the product in the cup;

T_3 – the moment of passage of the product through the optical mark zone (start of unloading the measuring cup);

T_4 is a signal that indicates the completion of packaging (fixed by the fact of stopping the movement of products from the cylindrical part of the funnel).

Based on these time stamps, the following intervals are calculated:

$\Delta T_1=T_3-T_2$ – determines the time of movement of products to the funnel;

$\Delta T_2=T_4-T_3$– characterizes the duration of bulk product feeding.

The given time intervals make it possible to determine the influence of the physical and mechanical characteristics of bulk products, geometric and kinematic parameters of the dosing module on the duration of packaging. Experiments were conducted at different values of the linear speed of movement of the measuring cup:$\upsilon_{xo1}=0.21$ m/s; $\upsilon_{xo2}=0.316$ m/s; : $\upsilon_{xo3}=0.42$ m/s; : $\upsilon_{xo4}=0.628$ m/s, which corresponds to the productivity of $z_1=30$ doses/min; $z_2=45$ doses/min; $z_3=60$ doses/min and $z_4=90$ doses/min. The number of repetitions of the experiments corresponds to a reliable probability p=0.95. The experiment was performed at e=0.0 mm. Table 3 shows the technical characteristics of the control and measurement system.

Results and discussion

Determination of rational values of eccentricity

To establish the functional dependence between the parameters of the flow of bulk products and the parameters of the feeding device of the adaptronic module, we will consider the movement of characteristic material particles in the product pipeline of the device.

It is well known that if we shift the cylindrical part of the funnel relative to the conical part, then in the conjugation zone we will get an increased effective cross-sectional area of the movement of bulk products (Statsenko et al., 2021) (Figure 3).

Table 3
Technical characteristics of control and measurement system of the experimental installation

Device name	Appointment	Error estimation
Inductive positional sensor Pepperl+Funchs NBB5-18GM50-E2-V1	Fixation of the passage of the measuring cup through the control position (start of the event)	±0.5 mm (depending on mounting and marking)
Balluff BVS UR-3-10-5-E vision technical vision sensor	Control of the presence of products in the measuring cup by image synthesis	± 1 pixel, shape detection error ≤3%
Optical reflector label with photo sensor	Fixing the passage of the product to record the moment of the start of packaging	± 2 mm if the correct mark is present
PLC Siemens S7-1500 CPU 1512SPF-1 PN	Digital processing of signals from all sensors, formation of the logic of the system	Not determined, direction depends on external sensors

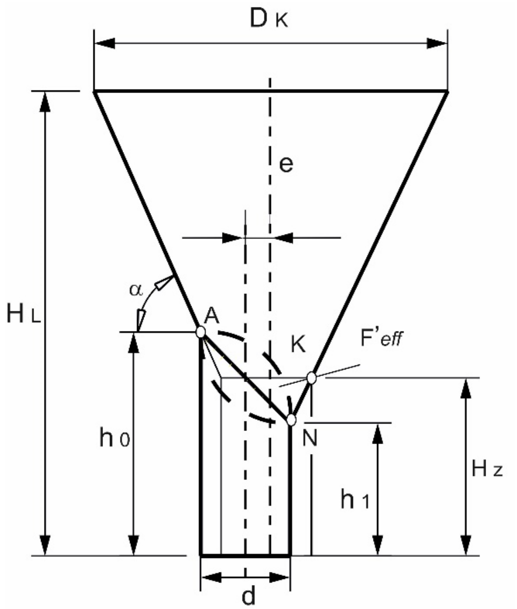


Figure 3. Scheme of the funnel of the feeding device with a shifted cylindrical part

It is known from geometric dependencies (Grewal et al., 2008) that for the cross-section of the conjugation of the conical and cylindrical parts of the funnel in the form of an ellipse, the effective area of movement of products is determined:

$$F'_{eff} = \frac{\pi d}{4}\sqrt{d + 4\left(e \cdot tg\alpha\right)^2}, \quad (19)$$

then the area increase factor will be equal to

$$k_F = \frac{F'_{eff}}{F_{eff}} = \frac{4\pi d\sqrt{d+4\left(e\cdot tg\alpha\right)^2}}{4\cdot\pi d^2} = \frac{1}{d}\sqrt{d+4\left(e\cdot tg\alpha\right)^2}, \tag{20}$$

where F_{eff} , F'_{eff} are the effective areas of movement of products along the circular and, accordingly, ellipsoidal conjugation;

d is an inner diameter of the cylindrical part of the funnel;

e is the eccentricity of displacement of the cylindrical part of the funnel relative to the conical part.

An increase in the value of k_F, with constant d and α , is possible with an increase in ***e***. From the point of view of the geometric construction of the cone-cylindrical packaging device, the ***e*** -value can be varied within $0 \le e \le 0.5d$. To determine the rational value of ***e***, it is necessary to consider the movement of characteristic material particles of bulk products under different geometric and kinematic parameters of the dosing and feeding module.

An important design parameter of the feeding device, which ensures a continuous mode of packaging bulk products, at a given productivity, is the diameter of the base of the cone part of the funnel D_k (Gavva et al., 2023).

When determining the rational value of D_k, it is necessary to take into account the duration of movement of bulk products from the measuring cup to consumer packaging, the number of cups in the dispenser and the frequency of rotation of the rotor of the dosing module (Figure 4).

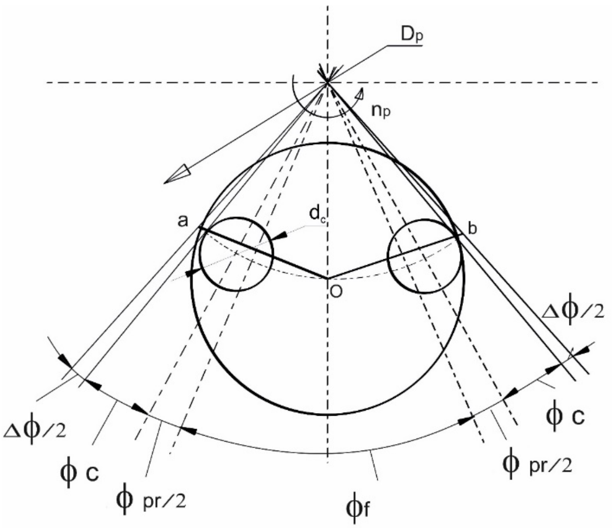


Figure 4. Scheme for determining rational value of diameter Dk of funnel cone part

The determination of the diameter of the base of the conical part of the funnel was carried out using the main provisions of the geometry, regarding the length of the chord O_a or O_B at a given diameter of the location of the measuring cups D_p and the central angle $\varphi_{\Sigma i}$, which characterizes packaging (Grewal, 2008).

$$D_к = 2D_p \cdot sin(0.5\varphi_\Sigma),\qquad (21)$$

where φ_Σ is the total central angle defined as:

$$\varphi_\Sigma = 0.5\varphi_f + 0.5\varphi_m + \varphi_c + 0.5\,,\qquad (22)$$

φ_f – angle to which the rotor with measuring cups will return, for which all products from the cup will move to the package, $\varphi_f=\omega_r \cdot t_f$;

ω_r – angular speed of rotation of the rotor, $\omega_r = \frac{\pi n_r}{30}$;

n_p – rotor rotation frequency, $n_r = \frac{z}{m_c}$;

z – performance of the dosing and feeding module;

m_c – the number of measuring cups in the rotor of the dosing module;

t_p – duration of packaging – movement of bulk products from the measuring cup into the package. For project calculations, and by adopting the mode of movement of bulk products by hydraulic, the duration of t_s can be determined (Statsenko et al., 2021):

$$t_f = k_1 \cdot \lambda \sqrt{\frac{2H_\Sigma}{g}}\;;\qquad (23)$$

k_1 – coefficient, which takes into account the movement of particles of bulk products on the inner surface of the funnel and possible co-impact phenomena between particles;

λ – the coefficient of aerodynamic resistance of the movement of particles in the funnel;

H_Σ – the length of the path of movement of bulk products in the feeding device, $H_\Sigma = H_м + h_c + H_к + H_ц$;

φ_m – rotor rotation angle corresponding to the duration of movement of the film sleeve over the length of the package or feed of the empty container

$\varphi_m = \omega_r \cdot t_m = \omega_r \cdot L_p / v_m$;

L_p – packaging length;

v_m – speed of movement of welded and drawing devices (for flexible packaging);

φ_c – is the central angle of the rotor corresponding to the radius of the measuring cup

$\varphi_c = 2 \cdot arcsin(d_c / 2D_p)$;

$\Delta\varphi$ is an angle adequate to the technological gap.

The obtained value of φ_Σ should be less than the angle of location of the measuring cups on the rotor, i.e. $2\varphi_\Sigma<\varphi_0$, where $\varphi_0=2\pi/m_c$.

The movement of a material particle in the product pipeline of the feeding device, in different periods of time, is characterized by a change in the effect of external loads on it. And therefore, according to the laws of classical mechanics, it is appropriate to consider the process of moving a particle as a set of characteristic stages (Statsenko et al., 2021).

The most unfavorable conditions of movement (interaction with the inner surface of the conical part of the funnel, impact on the cylindrical part of the funnel) will be in the particles furthest from the geometric center of the funnel, i.e. at point M (Figure 5).

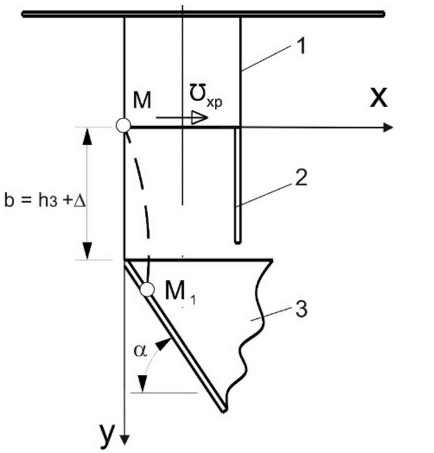


Figure 5. Scheme for calculating movement of a particle of bulk products at first stage of movement:
1 – cup; 2 – flap; 3 – cone part of funnel

To study the movement of a particle of bulk products in the product pipeline of the feeding device, the following assumptions are accepted:

– the particle has mass, but geometric parameters due to small dimensions compared to the dimensions of the funnel of the device, we neglect;
– the particle is characterized by elastic-plastic properties with a rate recovery coefficient after impact on the surface of the funnel k≈0,1–0,3;
– the influence of the action of surrounding particles on the movement of the studied particle is also neglected;
– the walls of the funnel are absolutely solid bodies, the mass of which is infinitely large; the coefficient of sliding of the particle on the inner surface of the funnel is a constant value;
– aerodynamic resistance to the movement of the particle is also neglected, due to small values of relative speed.

From the point of view of the action of uniform external forces on the particle, its movement in the funnel of the packaging device is given by a set of four characteristic stages:

– the first – movement of the material particle from the initial position, point M, to contact with the inner cone surface of the funnel;
– the second – oblique elastic-plastic impact of the particle on the inner surface of the conical part of the funnel;
– the third – movement with sliding of the material particle on the inner surface of the conical part of the funnel;
– the fourth – movement of the particle in the conjugation zone of the conical and cylindrical parts of the funnel and in the cylindrical part.

The duration of the packaging operation is the sum of the durations of all stages of movement of the material particle

$$T_{\Sigma} = t_1 + t_2 + t_3 + t_4 + t_5 + t_6, \quad (24)$$

where t_{1-4} is the duration of movement of the particle in the product pipeline;

t_5 – duration of movement of the particle in the package;

t_6 – duration of forming, feeding new containers (packaging).

At the first stage, the movement of the particle begins at the moment of opening the flap of the measuring cup. The opening duration of the flap is insignificant compared to the movement duration of the particle in the first stage, and therefore it can be assumed that the opening of the flap occurs instantly. At the initial moment of the first stage, the particle, together with the measuring cup, moves at a linear speed $\boldsymbol{v_{x0}}$, which is determined by $v_{xo}=\omega_p 0.5 D_p$. If we assume that the projection of the cone surface in the X0Y coordinate system is described by the equation $y = b + tg\alpha \cdot x$, where $b=H_M$ or $b=h_3+\Delta$, then the duration of the movement of the particle before contact with the inner cone surface at the point M_1 can be determined

$$t_1 = \frac{1}{g}\left[v_{x0} \cdot tg\alpha + \sqrt{\left(v_{xo} \cdot tg\alpha\right)^2 + 2gH_м} \right]. \tag{25}$$

The kinematic parameters of the particle's motion at the M_1 point will be

$$x_{1K} = v_{x0} \cdot t_1 \,;\; y_{1K} = 0.5g \cdot t_1^2$$

$$\dot{x}_{1K}=v_{x0};\; \dot{y}_{1K}=g \cdot t_1.$$

The coordinates $x_{1к}$, $y_{1к}$ correspond to the coordinates of the point M_1 at which the elastic-plastic impact of the particle occurs on the inner surface of the conical part of the funnel.

In the case when the X coordinate of the particle will be within $00{,}5(D_к-d) \le X \le 0.5(D_к+d)$ at $y \le H_к+H_м$, then the particle will not contact the lateral conical surface of the funnel, will further move along its cylindrical part. This type of particle movement is possible at $\omega_{p1} \le \omega_p \le \omega_{p2}$, where

$$\omega_{p1} = \frac{D_K - d}{D_p \cdot t_{10}} \,;\; \omega_{p2} = \frac{D_K + d}{D_p \cdot t_{10}}$$

$$t_{10} = \sqrt{\frac{2\left(H_к + H_м\right)}{g}}. \tag{27}$$

If $x>0.5(Dk+d)$, then the particle will contact the far conical surface of the funnel. The point of contact and kinematic parameters of the movement of the particle at the moment of impact are defined as (Figure 6)

$$x_{M03} = \omega_p \cdot 0.5D_p \cdot t_1' \qquad y_{M03} = 0{,}5\left(t_1'\right)^2 \,;\; \dot{y}_{M03}=gt_1' \tag{28}$$

$$t_1' = \frac{1}{g}\left[-0{,}5\omega_p \cdot D_p \cdot tg\alpha + \sqrt{\left(0{,}5\omega_p D_p tg\alpha\right)^2 + 2g\left(D_к \cdot tg\alpha + H_м\right)} \right].$$

To determine t_1', an expression describing the far generating cone surface in the HOY coordinate system was used

$$y' = D_к \cdot tg\alpha + H_м - tg\alpha \cdot x \tag{29}$$

Under the condition $\omega_p > \omega_{p2}$, the most unfavorable conditions regarding the duration of movement will be for the particle at the point M_0.

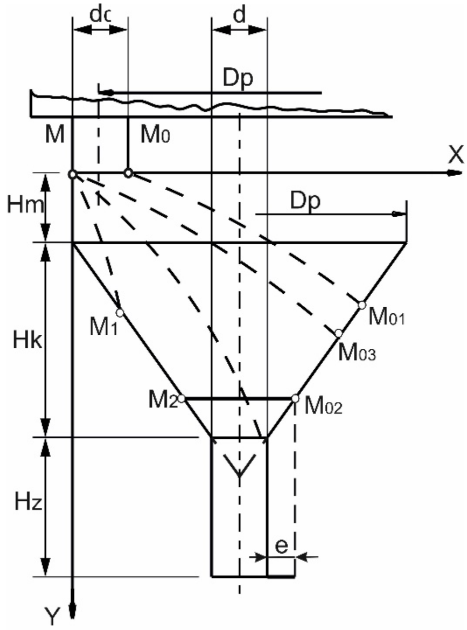


Figure 6. Scheme for calculating the movement of particle of bulk products at first stage at $\omega_p > \omega_{p2}$

The duration of movement and kinematic parameters of the movement of the particle from point M_0 to contact with the cone surface of the funnel at point M_{01} can be determined from the expressions:

$$x_{MO} = 0,5\omega_p \cdot D_p \cdot t_{1.0} + d_c;\ y_{MO} = 0,5g\left(t_{1.0}\right)^2;$$

$$\dot{x}_{MO}=0,5\omega_p \cdot D_p;\quad \dot{y}_{MO}=gt_{1.0} \tag{29}$$

$$t_{1.0} = \frac{1}{g}\left[-0,5\omega_p \cdot D_p tg\alpha + \sqrt{\left(0,5\omega_p \cdot D_p tg\alpha\right)^2 + 2g\left(D_к \cdot tg\alpha + H_м - d_c tg\alpha\right)}\right].$$

At point M_{01}, there will be an elastic-plastic impact of the particle on the inner conical surface of the funnel.

According to the obtained dependencies and accepted initial data: Dk=0.550 m; D_p=0.800 m; d_c=0.1 m; H_m=0.110 m; $H_к$ =0.618 m are given in graphic form the regions of movement of the particle without contact with the side surfaces of the conical part of the funnel (Figure 7).

According to Figure 6, all particles of the lower layer of the measuring cup will move in the cylindrical part of the funnel at only one value of angular velocity (ω_p =0.911 rad/s). To expand the range of angular speed of the dispenser rotor, it is appropriate to increase the effective cross-sectional area of the funnel at the junction of the conical and cylindrical parts due to the displacement of the cylindrical part by the appropriate eccentricity. The geometry of the funnel imposes restrictions on e_{max} =0.5d, and therefore it is important to find the rational value of e while ensuring the minimum T_Σ .

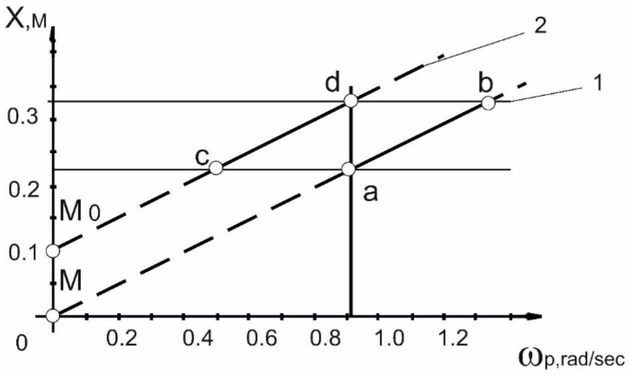


Figure 7. Nature of the movement of material particles of bulk products from points M and M_0 when condition $\omega_{p1} \le \omega_p \le \omega_{p2}$ is met

At $\omega_{p2} < \omega_p < \omega_{p1}$, at points M_1 and M_{01}, there will be a particle impact on the inner surface of the conical part of the funnel. Taking into account the trajectory of movement of a material particle and its physical and mechanical properties, it can be stated that at the second stage there will be an oblique elastic-plastic impact (Figure 8).

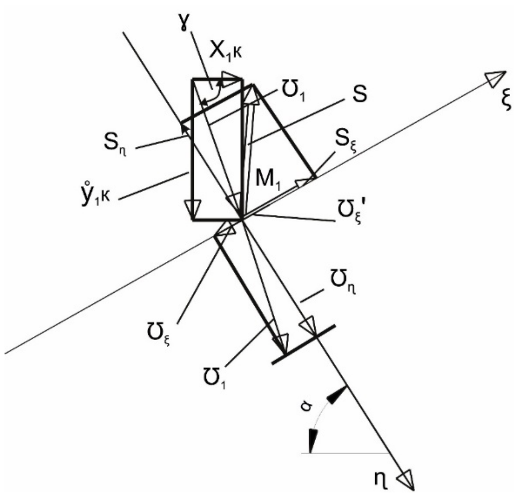


Figure 8. Scheme for determining kinematic parameters of movement of material particle of bulk products after affecting inner surface of conical part of funnel in second stage will be an oblique elastic-plastic impact

To determine the kinematic parameters of the movement of a particle of bulk products after hitting the conical part of the funnel, we use Newtonian impact theory (Lemos, 2018)

$$v_\zeta = v_1 \cdot cos(\gamma - \alpha); \quad v_\xi^{'} = v_\xi \cdot k = v_1 \cdot sin(\gamma - \alpha) \cdot k, \tag{30}$$

where

$$v_1 = \sqrt{\left(\dot{y}_{1k}\right)^2 + \left(\dot{x}_{1k}\right)^2}\ ,\ \ \gamma = arctg\left(\frac{\dot{y}_{1k}}{\dot{x}_{1k}}\right);$$

k-coefficient of recovery of the particle's speed after impact.

If $k > 0.5$, after impact the particle may bounce off the surface of the conical part of the funnel and experience a repeated collision. However, since for many food products the coefficient k typically lies within 0.1–0.3 (Bila and Statsenko, 2012), the rebound can be neglected, and the subsequent motion of the particle can be considered as occurring solely along the surface of the conical part of the funnel. During the impact, there are power loads on both the product and the wall of the funnel. The impact load can be estimated using either the impact force or the shock pulse (*S*). Determination of these parameters is important during verification calculations of the thickness of the funnel material and the strength properties of the products.

The third stage is characterized by the movement of the particle on the inner surface of the cone part of the funnel with sliding, which is taken into account by the sliding resistance coefficient. At this stage, the particle moves from point M_1 to A. Point A characterizes the beginning of the cylindrical part of the funnel when it is partially shifted from the axis of symmetry of the conical part (Figure 9).

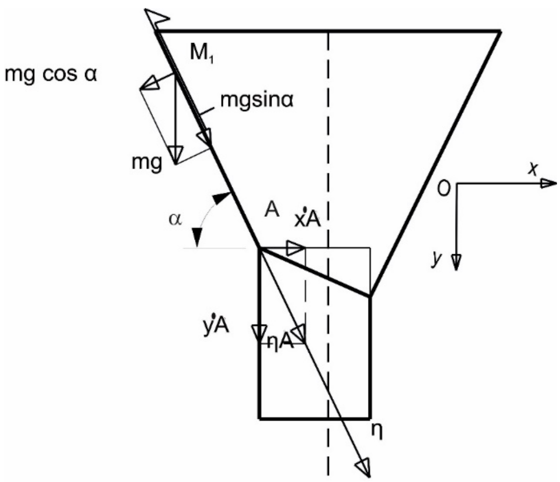


Figure 9. Scheme for determining kinematic parameters of movement of particle of bulk products on inner surface of conical part of funnel

If the distance from the point M_1 to A is taken as $\boldsymbol{l_{AM1}}$, then the duration of movement of the particle in the third stage is determined from the expression

$$t_3 = \left[-v_1 \cdot cos\left(-\alpha\right) + \sqrt{\left[v_1 cos\left(-\alpha\right)\right]^2 + 2l_{AM1}\left(gsin\alpha - gfcos\alpha\right)}\right] \times \left[gsin\alpha - gf \cdot cos\alpha\right]^{-1},\ (31)$$

where f is the coefficient of friction of the sliding of the material particle on the inner surface of the conical part of the funnel;

$$l_{AM1} = \left\{ \frac{d^2 \cdot g^2}{\left[-\dot{y}_A + \sqrt{(\dot{y}_A)^2 + 2gh_0} \right]^2 \cdot cos^2\alpha} - \left[v_1 \cdot cos(-\alpha) \right]^2 \right\} \times \left[2gsin\alpha - gf \cdot cos\alpha \right]^{-1}$$

$$\dot{y}_A = \left\{ \left[g \cdot sin\alpha - g \cdot f \cdot cos\alpha \right] \cdot t_3 + v_1 \cdot cos(-\alpha) \right\} \cdot sin\alpha;$$

$$h_0 = H_ц + etg\alpha.$$

In the future, let's assume that at the fourth stage the particle will move in the cylindrical part of the funnel (Figure 10) (Benvenuti et al., 2015)

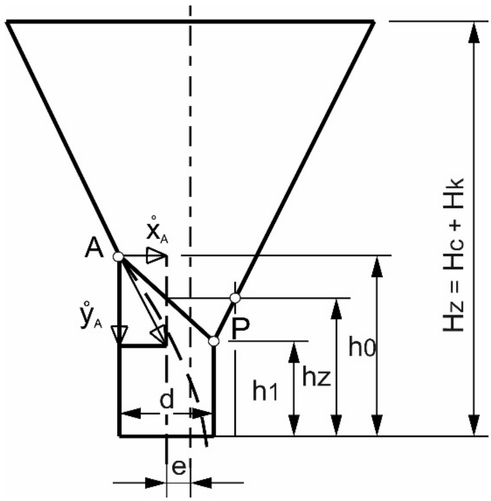


Figure 10. Scheme for determining kinematic parameters of movement of bulk product particle in cylindrical part of feeding device

The duration of movement of the material particle at the fourth stage, provided that $y_4=h_0$, $x_4 \le d$ is determined by the formula

$$t_4 = \left[-\dot{y}_A + \sqrt{(\dot{y}_A)^2 + 2gh_0} \right] \cdot \frac{1}{g}. \quad (32)$$

It is possible to fulfill the condition $x_4 \le d$ when choosing the rational value of the eccentricity, which is determined from the expression

$$e = \left[\frac{H_к}{sin\alpha} - \left[\left(\frac{\omega_0 \cdot 0,5D\left(\omega_0 D_p tg\alpha + \sqrt{(\omega_p 0,5D_p \cdot tg\alpha)^2 + 2gH_м} \right)}{g \cdot cos\alpha} \right) + l_{AM1} \right] \right] \cdot cos\alpha. \quad (33)$$

Analysis of expression (33) shows that for all other constant geometric parameters of the feeding device, the value of the eccentricity depends on the rotation frequency of the rotor of the dosing module in parabolic dependence. The greater the value of the rotor frequency, the smaller the ***e*** value (Figure 11).

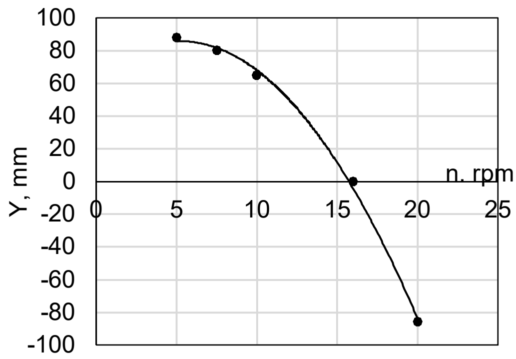


Figure 11. Changing value of eccentricity of feeding device at different values of rotation speed of dispenser rotor
(estimated data: m_0 = 6; Dp = 0.8 m; n = 5–20 rpm)

At appropriate values of the rotor speed, the eccentricity may be negative, that is, the cylindrical portion of the funnel may be located to the right of the axis of symmetry of the conical portion of the funnel.

The movement of bulk products in the well of the hopper dispenser under the action of vibration forces is considered in the works of Sholoviy and Maherus (2014). The obtained results make it possible to determine the rational parameters of the base of the funnel cone and the value of the eccentricity. The free movement of bulk product particles is considered in the works of Maslo (2013) and Derenivska et al. (2014) in weight dispensers, but without taking into account the interaction with the working bodies of the module.

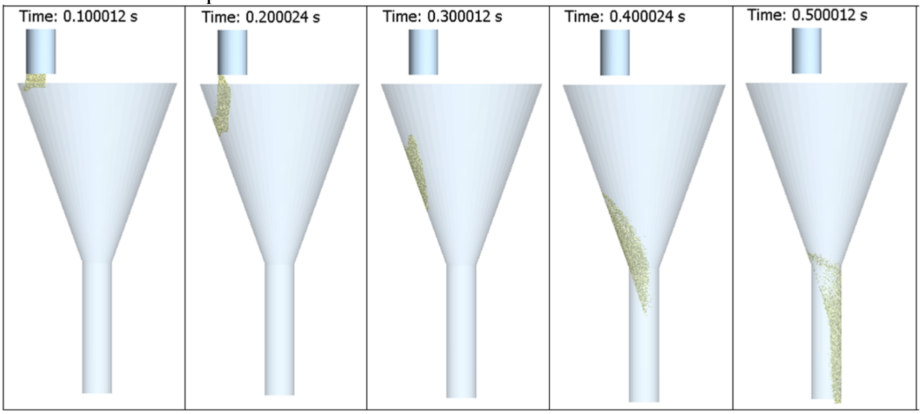
Simulation modeling

Figure 12 shows the results of simulation modeling of the movement of the dose of bulk products in the product line of the packaging device at ***e***=0.0 mm and axial movement speeds of the measuring cup: 0.316, 0.628 and 0.84 m/s, corresponding to the performance of the dosing-feeding module: 45, 90 and 120 packs/min.

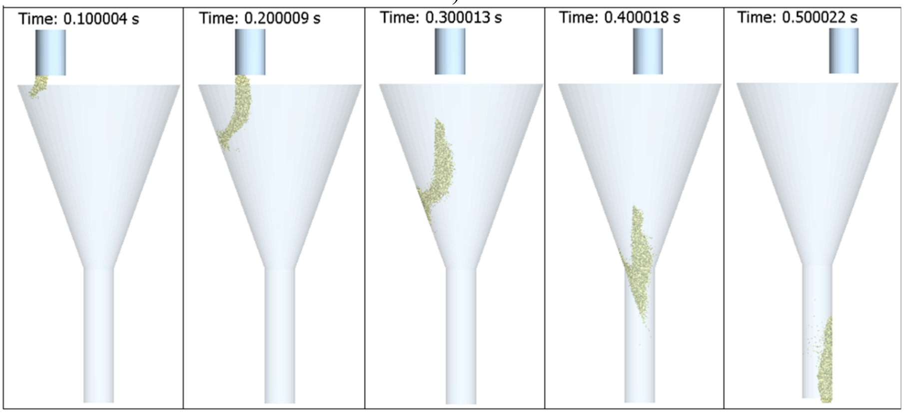
The results of the calculation are a change in the average value of the speed of movement of the flow of bulk products along the length of the feeding device and the duration of the packaging operation.

The analysis of the results of simulation modeling of the movement of bulk products makes it possible to state that at v_{x0}<0.628 m/s, a significant part of the products is slipped on the left side conical surface of the funnel, at v_{x0}>0.628 m/s – the products are mainly moved in the feeding device without contact with the conical surface of the funnel, and at v_{x0}>0.628 m/s –, the products are slipped on the right side conical surface of the funnel.

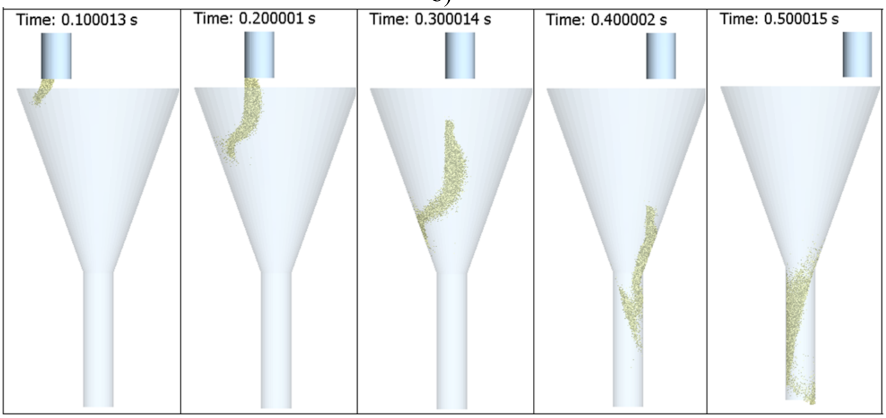
Figure 13 shows characteristic views of the path of movement of bulk products in the feeding device at ***e*** > 0.0 mm, that is, the eccentricity of the cylindrical part of the funnel relative to the conical part.



a)

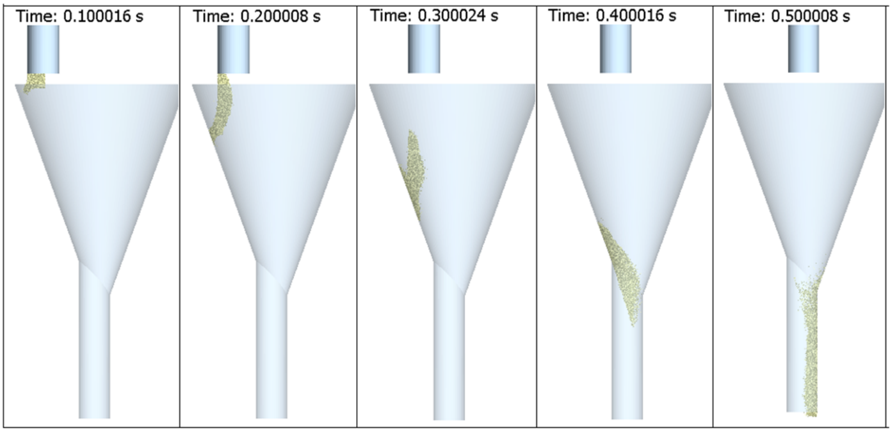


b)

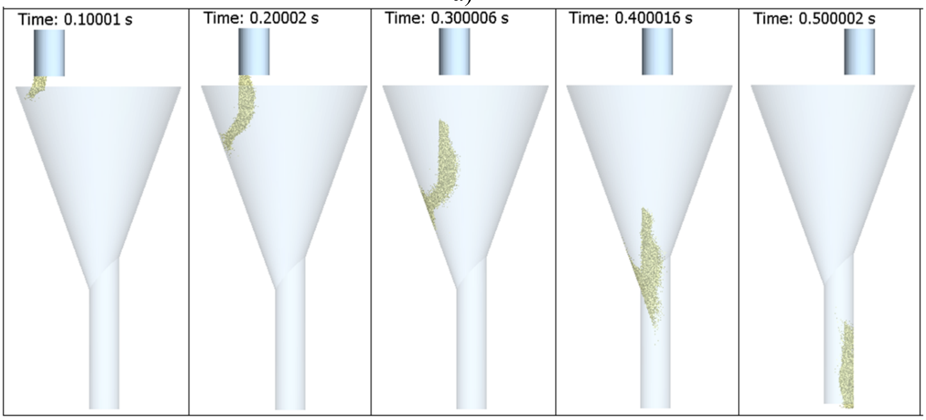


c)

Figure 12. Characteristic views of trajectory of movement of bulk products dose in feeding device at e =0.0 mm and axial velocities of measuring cup:
a – v_{x0} = 0.316 m/sec; b – v_{x0} = 0.628 m/sec; c – v_{x0} = 0.84 m/sec



a)



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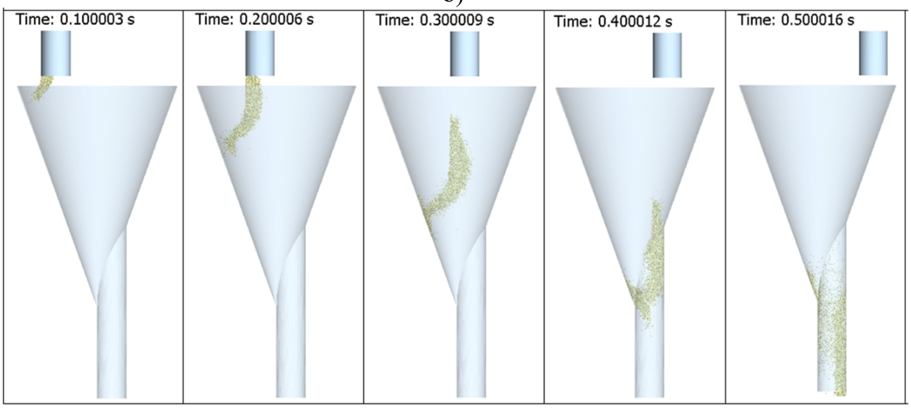
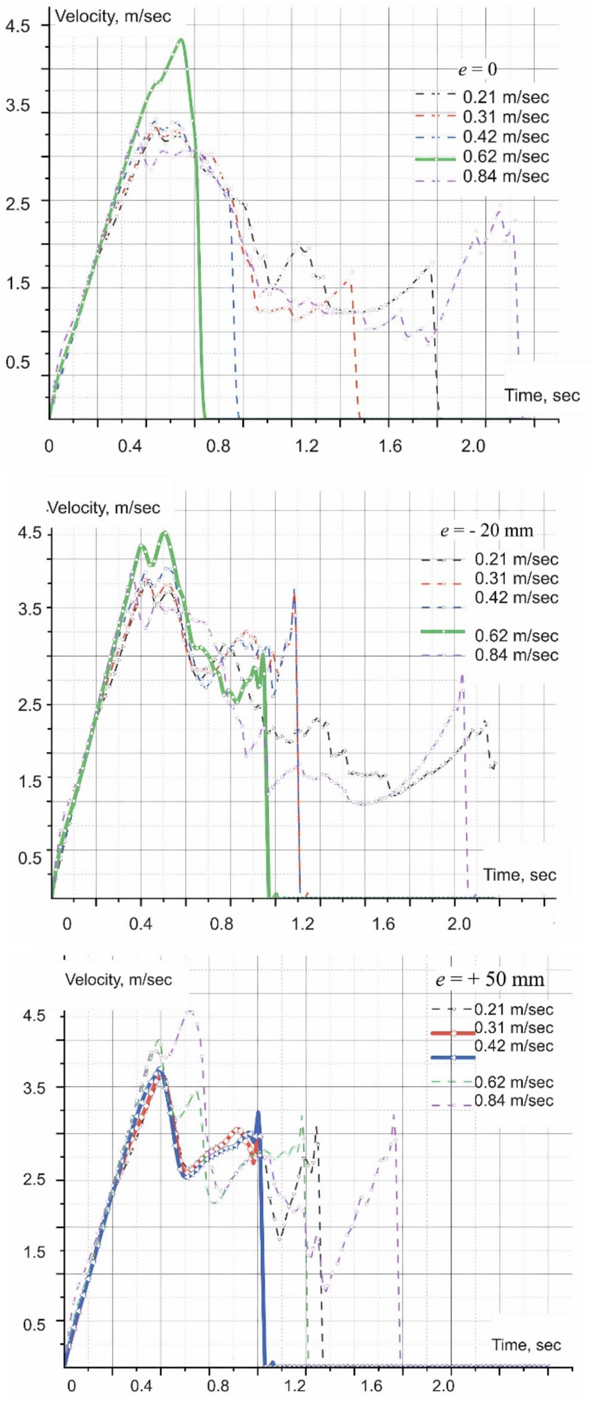


c)

Figure 13. Characteristic types of trajectory of movement of dose of bulk products in feeding device at:
a – e = -20.0 mm, v_{x0} = 0.42 m/s; b – e = 20.0 mm, v_{x0} = 0.628 m/s; c – e = 50 mm, v_{x0} = 0.84 m/s



a

b

c

Figure 14. Change in the speed of movement of bulk products along funnel:
a – *e* = 0.0 mm; b – *e* = -20 mm, c – *e* = 50 mm

The simulated trajectories of bulk product movement in the feeding device confirm the theoretical assumption that offsetting the cylindrical section of the funnel relative to the symmetry axis of its conical section makes it possible to minimize the contact time of bulk products along the conical surface. To analyze the kinetics of the movement of bulk products in the packaging device, it is appropriate to use the schedule of changes in the speed of movement of products along the length of the funnel (Figure 14).

When comparing the duration of bulk product feeding at e >=0.0 mm and at e >0.0 mm at different values of the axial speed of movement of the measuring cup, it was established that with a rational value of e, it is possible to reduce the duration of contact of the products with the surface of the funnel and the total duration of bulk product feeding to 10–11%. These conclusions confirm the accepted assumptions in the theoretical study of the movement of a characteristic particle of the product dose. At the stages of project calculations, formula (33) can be used to determine the rational value of e.

Cundall and Strack (1979), Bertrand et al. (2004) and Burmistenkov and Statsenko (2018) investigated the movement of bulk products into a storage hopper using DEM methods. Such bulk products lack impact interactions with working surfaces and change, within wide limits, the trajectory of particle movement. Such tasks, for the most part, are of the same stage and do not require taking into account power loads of different nature. The results of the analyzed studies confirm their incompleteness and the absence of a holistic method of creating the latest samples of adaptronic modules for dosing bulk products in a volumetric way with continuous movement of the rotor with measuring cups.

Experimental studies

Checking the adequacy of the regimes of theoretical studies in comparison with experimental data established that the deviation in the duration of dose formation does not exceed 12% (Figure 15).

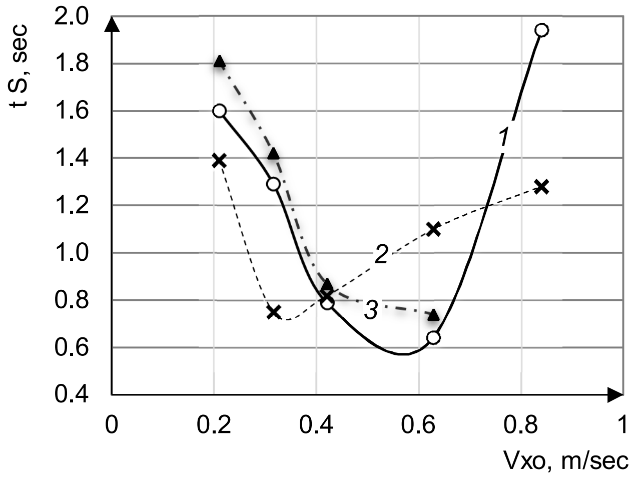


Figure 15. Effect of measuring cup axial speed on the duration of bulk product packaging: 1 – e = 0.0 mm; 2 – e = 50.0 mm; 3 – results of experimental studies

Technical offer

Analysis of the trajectory of movement of bulk products of their kinematic parameters made it possible to improve the design of the feeding device (Figure 16)

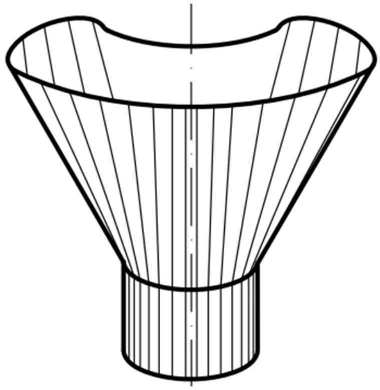


Figure 16. Improved design of feeding device for bulk products

This design of the feeding device minimizes its dimensions and metal capacity, and with a certain eccentricity of the displacement of the cylindrical part relative to the axis of the conical part of the funnel minimizes the duration of packaging.

Conclusions

1. The movement of characteristic particles of the dose of bulk products in feeding devices during continuous rotation of the rotor with measuring cups is characterized by a complex trajectory and interaction with the inner surface of the conical part of the funnel, which leads to an increase in the duration of product packaging.
2. One effective way to reduce the duration of packaging is to minimize the duration of contact of the bulk product particles with the inner conical surface of the funnel by increasing the cross-sectional area of the conjugation of the conical part of the funnel with the cylindrical part. With the geometric shape of the feeding device unchanged, this task can be solved due to the eccentric displacement of the axis of the cylindrical part relative to the axis of the conical part of the funnel.
3. The value and direction of the eccentricity depends on the linear speed of movement of the measuring cup and cannot be greater than $e \leq 0.5d$. The limit is set from the layout of the conical-cylindrical funnel.
4. To ensure the specified productivity of the dosing and feeding module, the diameter of the base of the cone part of the funnel is calculated taking into account the kinematic and geometric parameters of the rotor with measuring cups, the dimensions of the measuring cup, the diameter of the cylindrical part of the funnel and the angle of inclination of the side cone surface of the funnel.
5. Simulation modeling of the movement of the dose of bulk products in the feeding device confirmed the multi-stage operation and the significant influence of eccentricity on the

duration of packaging. With a rational ratio of kinematic and geometric parameters of the movement of bulk products, when choosing a rational value of eccentricity, it is possible to reduce the duration of bulk product feeding to 11%.

6. The adequacy of the results of theoretical research is confirmed by experimental studies performed on a real-life automatic machine. The deviation of the duration of packaging according to theoretical calculations and experimental experiments does not exceed 10–12%.
7. Analysis of particle trajectories and bulk product flow allows designers of feeding devices to recommend rational values for the eccentricity of the cylindrical section's axis relative to the conical section's axis of symmetry. To minimize the device's size and weight, the conical section can be shaped like a torus.

References

Gavva O.M., Kryvoplias-Volodina L.O. (2023), *System Engineering of Automatic Packaging Machines*, Kyiv, Production «Stal».

Grewal B.S. (2008), *Higher Engineering Mathematics*, 43rd Edition, Khanna Publishers.

Behjani M. A., Motlagh Y. G., Bayly A., Hassanpour A. (2019), Assessment of blending performance of pharmaceutical powder mixtures in a continuous mixer using Discrete Element Method (DEM), *Powder Technology*, 366, pp. 73–81, https://doi.org/10.1016/j.powtec.2019.10.102

Benvenuti L., Kloss Ch., Pirker S. (2015), DEM parameter identification by means of artificial neural network for iron ore sintering. *Eleventh International Conference on CFD in the Minerals and Process Industries,* Melbourne, Australia, 7-9 December 2015.

Bertrand F., Leclaire L.A., Levecque G. (2005), DEM-based models for the mixing of granular materials, *Chemical Engineering Science*, 60, pp. 2517–2531, https://doi.org/10.1016/j.ces.2004.11.048

Bila T.Ya., Statsenko V.I.N. (2012), Study of the movement of mixture particles in the step rotor of a continuous centrifugal mixer, *Bulletin of the Kyiv National University of Technology and Design*, 6, pp. 17-21.

Burmistenkov O. P., Statsenko V.V. (2018), Using the method of discrete elements to study the movement of bulk materials in bunker devices, *II International Scientific and Practical Conference Mechatronic Systems: Innovations and Engineering*, June 15, 2018, pp. 95-97, Kyiv, KNUTD.

Burmistenkov O.P., Bila T.Ya., Statsenko V.I. (2019), Research on the energy efficiency of equipment for mixing bulk materials, *Bulletin of the Kyiv National University of Technology and Design, Series Technical Sciences,* 4, pp. 42-48, https://doi.org/10.30857/1813-6796.2019.4.4

Cundall P.A., Strack O.D.L. (1979), A discrete numerical model for granular assemblies, *Géotechnique,* 29(1), pp. 47–65, https://doi.org/10.1680/geot.1979.29.1.47

Derenivska A., Gavva O., Kryvoplias-Volodina, L., Kokhan O. (2014), Optimization of transportation bulk solids food products in the liner heightener of packing machine. *Journal of Food and Packaging Science, Technique and Technologies*, 3, pp. 20-23.

Di Renzo A., Di Maio F. (2004), Comparison of contact-force models for the simulation of collisions in DEM-based granular flow codes, *Chemical Engineering Science*, 59(3), pp. 525–541, https://doi.org/10.1016/j.ces.2003.09.037

Dubey A., Sarkar A., Ierapetritou M., Wassgren C.R., Muzzio F.J. (2011), Computational approaches for studying the granular dynamics of continuous blending processes, 1 – DEM based methods, *Macromolecular Materials and Engineering*, 296(3-4), pp. 290–307, https://doi.org/10.1002/mame.201000389

Kafashan J., Wiącek J., Abd Rahman N., Gan J. (2019), Two-dimensional particle shapes modelling for DEM simulations in engineering: A review, *Granular Matter.* 21(3), 80, https://doi.org/10.1007/s10035-023-01383-2

Lemos N.A. (2018), *Analytical Mechanics*, 2nd Edition, Cambridge University Press.

Maslo M.A. (2013), Improvement of weight dispensers, *Packaging*, 28, pp. 29-32.

Munjiza A. (2004), *The Combined Finite-Discrete Element Method*, Wiley, https://doi.org/10.1002/0470020180

O'Sullivan C., Bray J. (2004), Selecting a suitable time step for discrete element simulations that use the central difference time integration scheme, *Engineering Computations,* 23(21), pp. 278-303, https://doi.org/10.1108/02644400410519794

Otsubo M., O'Sullivan C., Shire T. (2017), Empirical assessment of the critical time increment in explicit particulate discrete element method simulations, *Computers and Geotechnics*, 86, pp. 67-79, https://doi.org/10.1016/j.compgeo.2016.12.022

Sarkar A., Wassgren C.R. (2009), Simulation of a continuous granular mixer: Effect of operating conditions on flow and mixing, *Chemical Engineering Science*, 64(11), pp. 2672–2682, https://doi.org/10.1016/j.ces.2009.02.011

Sarkar A., Wassgren C. (2010), Continuous blending of cohesive granular material, *Chemical Engineering Science*, 65(2), pp. 5687–5698, https://doi.org/10.1016/j.ces.2010.04.011

Sholoviy Y.P., Maherus N.I. (2014), Development of the mathematical model of the fine dispersion material behavior under vibration in the conical hole in the dispenser. *Bulletin of the Lviv Polytechnic National University, Optimization of Production Processes and Technological Control in Mechanical and Instrument Engineering*, 786, pp. 24-29.

Statsenko V.V., Burmistenkov O.P., Bila T.Ya., Lischuk V. (2021), *Modeling the Movement of Loose Materials in Mixing Complexes by the Method of Discrete Elements,* Kyiv, KNUTD.

Stypnytskyy V.V. (2013), Principles of functional oriented technology manufacturing products engineering production, *Bulletin of the Lviv Polytechnic National University*, *Optimization of Production Processes and Technological Control in Mechanical and Instrument Engineering*, 760, pp. 26–34.

Vera P.M., Brøchner T., Strøm J.S., Takai H. (2015), Report 12: Flow of salt particles on a spinning spreader disk, *External influences on spray patterns (EPAS)*, https://pure.au.dk/ws/portalfiles/portal/87361608/Report12_Flow_of_salt_particles_03jun.pdf

Williams J.R., O'Connor R. (1999), Discrete element simulation and the contact problem, *Archives of Computational Methods in Engineering*, 6(4), pp. 279–304, https://doi.org/10.1007/BF02818917

Yan Z., Wilkinson S. K., Stitt E.H., Marigo M. (2015), Discrete element modeling (DEM) input parameters: understanding their impact on model predictions using statistical analysis, *Computational Particle Mechanics*, 2, pp. 283–299, https://doi.org/10.1007/s40571-015-0056-5

Yuu S., Umekage T. (2011), Simulation of granular flows and pile formation in a flat-bottomed hopper and bin, and experimental verification, *Materials*, 4(8), pp. 1440–1468, https://doi.org/10.3390/ma4081440

Zhu H.P., Zhou Z.Y., Yang R.Y., Yu A.B. (2007), Discrete particle simulation of particulate systems: Theoretical developments, *Chemical Engineering Science*, 62(13), pp. 3378–3396, https://doi.org/10.1016/j.ces.2006.12.089

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