

MODELING THE MOTION AND PLACEMENT OF SMALL-SEED CROPS USING THE DISCRETE ELEMENT METHOD

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Contemporary theoretical investigations of mechanical and technological processes related to seed motion under the influence of machine working elements are predominantly based on analytical approaches. These approaches typically result in complex systems of differential equations supplemented by initial and boundary conditions. Among advanced computational techniques for simulating the behavior of granular materials, such as seed mixtures, particular attention is given to methods founded on the discrete representation of matter, including particle dynamics and the Discrete Element Method (DEM).

The Discrete Element Method is a numerical engineering approach used to simulate the behavior and interaction of numerous discrete bodies, most commonly solid particles. The objective of this study is to simulate the motion and spatial distribution of small-seed crops using DEM within the CAE software environment Simcenter STAR-CCM+.

The simulation framework implemented in Simcenter STAR-CCM+ incorporates a range of physical and mathematical models, including a three-dimensional formulation, an unsteady implicit scheme, a single-component gas model representing air, and an ideal gas approximation. Additionally, turbulent airflow is described using the $k-\epsilon$ turbulence model alongside the Reynolds-averaged Navier–Stokes equations. The setup also includes segregated flow modeling, gradient and boundary condition methods, a Lagrangian multiphase approach, multiphase interaction modeling, DEM, and the influence of gravitational forces.

As a result of the conducted study, a mathematical model describing the random packing of small-seed crops within a container was developed. This enabled the derivation of a regression relationship for packing density as a function of the effective seed diameter and its coefficient of variation. The findings indicate that a decrease in the average effective diameter (D_{μ}) combined with an increase in the coefficient of variation (δ) leads to a higher packing density (φ) of spherical seeds. This phenomenon can be explained by the ability of smaller particles to occupy voids between larger ones.

Keywords: seeds, numerical modeling, simulation, motion, parameters, Discrete Element Method.

Eq. 21. Fig. 4. Table. 3. Ref. 20.

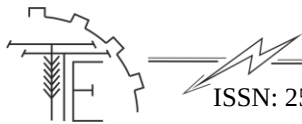
1. Problem formulation

During the sowing of small-seeded crops on variety testing plots and preliminary propagation areas, electromechanical seeders have become widely used [1]. However, a significant problem in their application is the insufficient uniformity of seed distribution along the row, which is associated with random processes occurring during sowing. As a result, crops emerge unevenly—with plant thickening or thinning along the row—which ultimately leads to a decrease in the yield of valuable breeding small-seeded crops.

The sowing of small-seeded crops in an electromechanical metering device is reduced to the processes of dosing and transporting seeds to the seed tube [2, 3]. In most designs of electromechanical metering devices, seeds are discharged into the hopper of the metering unit, where, from a mathematical point of view, they form a random packing. Then, using a gate through the formed metering openings, the seeds enter the distributor and are transported to the seed tube. Taking the above into account, the research was conducted with the aim of developing a model of random packing of small-seeded crops in the hopper of the metering unit of a breeding seeder.

Modern theoretical studies of mechanical and technological processes of seed movement under the action of working elements of technical equipment are reduced to analytical methods, which leads to the formulation of complex systems of differential equations with boundary and initial conditions [4]. These





systems are practically unsolvable by traditional methods, which necessitates their numerical solution using computer modeling.

These numerical solutions are extremely important for determining the optimal design and technological parameters of working elements acting on seeds. Computer modeling is an effective tool for studying these processes, as it allows rapid and accurate calculation of various parameter configurations, which can help improve the efficiency of the technological process and reduce its cost. In addition, computer modeling makes it possible to study the influence of various factors on seed movement and to find optimal solutions for improving its performance [5].

Numerical modeling of mechanical and technological processes makes it possible to study processes that are difficult for analytical analysis. For example, the calculation of seed movement processes taking into account non-stationary operating modes of technical equipment, such as variable pressure, motion velocity, etc., is possible only using numerical methods [6].

The application of computer modeling of mechanical and technological processes of seed movement is particularly important under modern conditions, when industry increasingly uses automated processes and technical equipment. Therefore, ensuring the quality and efficiency of these processes is an important task that can be achieved through the use of computer modeling.

2. Analysis of recent research and publications

Among modern methods of computer modeling of mechanical and technological processes of granular media movement (seed mixtures), particular interest is given to methods based on the concept of discrete representation of matter—namely, the particle dynamics method and the Discrete Element Method.

The particle dynamics method consists in representing the medium as a set of interacting particles—material points or rigid bodies. Their motion is described by the equations of classical mechanics. When modeling particle motion using the particle dynamics method, at each step, the Cauchy problem is solved using iterative methods—that is, differential equations are integrated under given initial conditions. The most well-known software packages for calculations using the particle dynamics method include AMBER, CHARMM, GROMACS, GROMOS, and NAMD [7].

The Discrete Element Method (DEM) is an engineering numerical method for modeling the motion of many interacting discrete objects, which are typically solid particles. The Discrete Element Method can be considered as a generalization of the finite element method. When modeling a process using this method, the initial positions and velocities of particles are specified. Then, based on these initial data and the given physical laws of particle interaction, the forces acting on each particle are calculated. Various interaction laws can be taken into account, provided that solvable equations exist to describe them. For each particle, the resultant force is determined, and the Cauchy problem is solved over a selected time interval. As a result, new initial data for the next step are obtained [8].

Although DEM modeling requires significant computational power, it provides a level of detail that other methods cannot achieve. Developed by Cundall and Strack, the DEM model is an extension of the Lagrangian modeling methodology to include dense particle flows. A distinctive feature of DEM is that contact forces between particles are included in the equations of motion. These forces cannot be neglected for highly loaded flows, i.e., systems with many interacting particles.

The most well-known software implementing the Discrete Element Method includes Chute Maven (Hustrulid Technologies Inc.), PFC2D and PFC3D, EDEM (DEM Solutions Ltd.), GROMOS 96, ELFEN, MIMES, PASSAGE, and Simcenter STAR-CCM+ [9–10]. The Discrete Element Method is based on the laws of conservation of momentum and angular momentum for Lagrangian models of multiphase media [11]. However, for the construction of a physical and mathematical model, it is necessary to assume that the component particles are represented as spheres with a defined density and effective diameter.

3. The purpose of the article

The aim of the research is to model the motion and packing of small-seeded crops using the Discrete Element Method within the CAE software package Simcenter STAR-CCM+.

Numerical simulation of the processes of motion and packing of seed material of small-seeded crops will be carried out using the CAE software package Simcenter STAR-CCM+.



4. Results and discussion

The geometric shape of small-seeded crops (rapeseed, mustard, camelina, millet, etc.) will be approximated as spheres with an effective diameter D . According to previous studies [12–13], even calibrated seed mixtures contain seeds with different effective diameters. Therefore, it is assumed that the effective seed diameter follows a normal distribution and is characterized by the probability density function:

$$f(D, D_\mu, \sigma_D) = \frac{1}{\sigma_D \sqrt{2\pi}} \exp\left(-\frac{(D - D_\mu)^2}{2\sigma_D^2}\right), \quad (1)$$

where D_μ – average effective seed diameter, m; σ_D – standard deviation of the effective seed diameter, m

At the same time, the seeds may have an effective diameter ranging from $D \in [D_{\min}; D_{\max}]$, where $D_{\min}$ – minimum effective seed diameter, m; $D_{\max}$ – maximum effective seed diameter, m.

Assuming that the density of the seeds is uniform and equal to ρ , the mass of 1,000 seeds is calculated using the formula:

$$m_{1000} = \frac{500}{3} \rho \pi D^3, \quad (2)$$

where ρ – seed density, kg/m³

The container has the shape of a rectangular prism of height h , the base of which is a square with side length a .

The generation of a random arrangement consists of sequentially releasing spherical seeds with randomly selected coordinates on the upper face of the container (Fig. 1) in the direction of its bottom. The initial settling velocity for all particles is set to be the same. For the random generation of seeds, we assume that the upper plane of the container is divided into $N_G = 4a^2/(\pi D^2)$ cells of the same size. In these cells, seeds are either generated (1) or not generated (0). The probability of a seed being generated in each cell is 0.5.

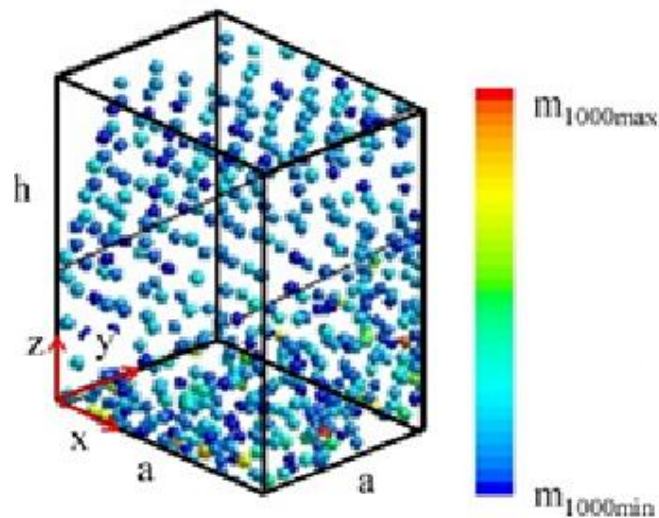
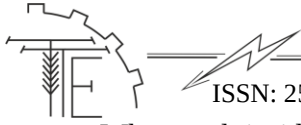


Fig. 1. Simulation of a container filled with spherical seeds

The movement of the released seeds is then tracked. To avoid calculating the seed's movement from the top of the container to its first contact with the already formed package, the seed is actually released from a specific point inside the container above the package, where the moving seed is close enough to the packing level. Coordinate z' the controlled seed takes on a value $z' = z + D_1/2 + D_2/2$, where z – the coordinate of the center of the largest seed among those that have settled at the bottom of the container; D_1 – the diameter of the moving seed and D_2 – the diameter of the seed from the package, centered at z . Coordinates x' and y' are determined by a random number generator that generates values with equal probability from $0,5a - (\lambda - D_1/2)$ до $0,5a + (\lambda - D_1/2)$, where λ – a predefined number between $D_{\min}/2$ і $D_{\max}/2$. Setting the λ value allows you to specify the size of the seed source. When $\lambda = D_1/2$ The seeds that are being planted are in a row $x' = 0,5a$ and $y' = 0,5a$.



When seeds inside a package collide with one another, a spring-dampened contact occurs. It is assumed that the following forces may act on a seed:

– gravitational force [14]:

$$\overline{F}_g = \pi D^3 \rho g / 6, \quad (3)$$

where $\overline{F}_g$ – gravitational force vector, N.

– the total force of contact interaction between the seeds and the wall, based on the Hertz–Mindlin spring-damper contact model [15–16]:

$$\overline{F}_{\text{contact}} = \overline{F}_n + \overline{F}_t, \quad (4)$$

where $\overline{F}_{\text{contact}}$ – the force of interaction between the seed and the wall, N; $\overline{F}_n$ – normal component of force, N; $\overline{F}_t$ – tangential component of the force, N

The normal component of the force is given by the equation:

$$\overline{F}_n = -K_n \overline{d}_n - N_n \overline{V}_n, \quad (5)$$

where K_n – normal stiffness coefficient of the elastic component, kg/cm²;

$$K_n = \frac{4}{3} E_{\text{eq}} \sqrt{d_n R_{\text{eq}}}, \quad (6)$$

where N_n – normal damping coefficient of the damping component, kg/s;

$$N_n = \sqrt{(5K_n M_{\text{eq}})} N_{n \text{ damp}}. \quad (7)$$

According to studies [15–16], the tangential component of the force is defined as

$$\overline{F}_t = -K_t \overline{d}_t - N_t \overline{V}_t, \quad (8)$$

If $|K_t \overline{d}_t| < |K_n \overline{d}_n| C_{fs}$, where C_{fs} – the coefficient of static friction between the seeds and the wall. Otherwise, the tangential component of the force is determined by the following equation:

$$\overline{F}_t = |K_n \overline{d}_n| C_{fs} \overline{d}_t / |\overline{d}_t|, \quad (9)$$

where K_t – tangential stiffness coefficient of the elastic component, kg/s²;

$$K_t = 8G_{\text{eq}} \sqrt{d_t R_{\text{eq}}}, \quad (10)$$

where N_t – tangential damping coefficient of the damping component, kg/s;

$$N_t = \sqrt{(5K_t M_{\text{eq}})} N_{t \text{ damp}}, \quad (11)$$

where N_{damp} – damping coefficient.

$$N_{\text{damp}} = -\ln(C_{n \text{ rest}}) / \sqrt{\pi^2 + \ln(C_{n \text{ rest}})^2}, \quad (12)$$

where R_{eq} – the equivalent radius of two seeds A and B, m;

$$R_{\text{eq}} = \left(\frac{2}{D_A} + \frac{2}{D_B} \right)^{-1}, \quad (13)$$

where M_{eq} – the equivalent mass of two seeds, A and B, in kilograms;

$$M_{\text{eq}} = \left(\frac{1}{M_A} + \frac{1}{M_B} \right)^{-1}, \quad (14)$$

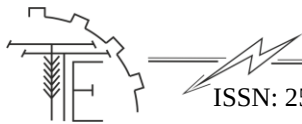
where E_{eq} – young's modulus of two seeds A and B, Pa;

$$E_{\text{eq}} = \left(\frac{1 - \nu_A^2}{E_A} + \frac{1 - \nu_B^2}{E_B} \right)^{-1}, \quad (15)$$

where G_{eq} – the equivalent shear modulus of two seeds A and B, Pa;

$$G_{\text{eq}} = \left(\frac{2(2 - \nu_A)(1 + \nu_A)}{E_A} + \frac{2(2 - \nu_B)(1 + \nu_B)}{E_B} \right)^{-1}, \quad (16)$$

where M_A, M_B – Mass of seeds A and B, kg; d_n, d_t – Virtual overlap of seeds A and B in the normal and tangential directions, m; D_A, D_B – Effective diameters of seeds A and B, m; E_A, E_B – Young's moduli of seeds A and B, Pa; ν_A, ν_B – Poisson's ratios for seeds A and BB, Pa; $\overline{V}_n, \overline{V}_t$ – the normal and tangential components of the relative surface velocity of the seed at the point of contact, m/s;



For the interaction between the seeds and the wall, equations (5)–(16) are appropriate; however, for the wall, a radius of $D_{\text{wall}} = \infty$ and wall thickness $M_{\text{wall}} = \infty$. As a result, expressions (13) and (14) become

$$R_{\text{eq}} = D_p/2, \quad M_{\text{eq}} = M_p. \quad (17)$$

Taking into account the forces mentioned above, let us write down the system of differential equations describing the motion of a single spherical seed in a container

$$\begin{cases} \frac{1}{6} \pi D^3 \rho \frac{d_p \bar{V}_p}{dt} = \frac{1}{6} \pi D^3 \rho \bar{g} + \bar{F}_n + \bar{F}_t, \\ \frac{d_p \bar{S}_p}{dt} = \bar{V}_p, \\ \frac{d_p}{dt} = \frac{\partial}{\partial t} + \bar{V}_p \cdot \bar{\nabla}, \end{cases} \quad (18)$$

where $\bar{V}_p$ – the velocity vector of the seed, m/s;

$\bar{S}_p$ – seed displacement vector, m.

To determine the position of each seed in the container, it is necessary to solve the system of differential equations (17) taking into account formulas (3)–(16), which is analytically quite complex. Therefore, we will use the Simcenter STAR-CCM+ software package, which is based on the presented mathematical framework.

The factors for numerical modeling are the average effective seed diameter D_μ (0.001 m; 0.002 m; 0.003 m) and the coefficient of variation δD (0.1; 0.2; 0.3), which is calculated as the ratio of the standard deviation of the effective seed diameter σD to its mean value (Table 1). Modeling was performed for a full factorial experiment with two factors and a total of 9 treatments in five replicates.

Table 1.

Factors and levels in numerical modeling of random seed distribution in a container

№	Effective seed diameter D_μ , m	Coefficient of variation δ	Standard deviation of the effective seed diameter σD , m	Minimum seed diameter D_{min} , mm	Maximum seed diameter D_{max} , m
1	0,001	0,1	0,0001	0,0007	0,0013
2	0,001	0,2	0,0002	0,0004	0,0016
3	0,001	0,3	0,0003	0,0001	0,0019
4	0,002	0,1	0,0002	0,0014	0,0026
5	0,002	0,2	0,0004	0,0008	0,0032
6	0,002	0,3	0,0006	0,0002	0,0038
7	0,003	0,1	0,0003	0,0021	0,0039
8	0,003	0,2	0,0006	0,0012	0,0048
9	0,003	0,3	0,0009	0,0003	0,0057

The evaluation criterion is the compaction density, which is determined as follows:

$$\varphi = \frac{\sum_{i=1}^N \frac{1}{6} \pi D_i^3}{a^2 h}, \quad (19)$$

where i – seed number; N – total number of seeds.

Note that for one-dimensional spheres, the densest packing in space is a regular icosahedron, which has 12 vertices (Fig. 2a). The centers of the spheres are located at the vertices of this three-dimensional figure. As noted in [16], the average packing density of such a packing is 0.74048. For simple packings (4 spheres)–cubic (Fig. 2, b) and hexagonal (Fig. 2, c)–the density is 0.5236 and 0.6043, respectively. Given the above, it can be stated that for one-dimensional spheres in space, the packing density can range from 0.5236 to 0.74048.

The physical models available for simulation in the Simcenter STAR-CCM+ software package include: a three-dimensional model, a transient implicit model, a mathematical model of a single-component gas (air), an ideal gas model (air), a turbulent air flow model, a k - ε turbulence model, isothermal fluid energy equation, Reynolds-averaged Navier-Stokes equations, separated flow, gradient and boundary methods, Lagrangian multiphase model, multiphase interaction model, discrete element model (DEM), and gravitational field [17–20].

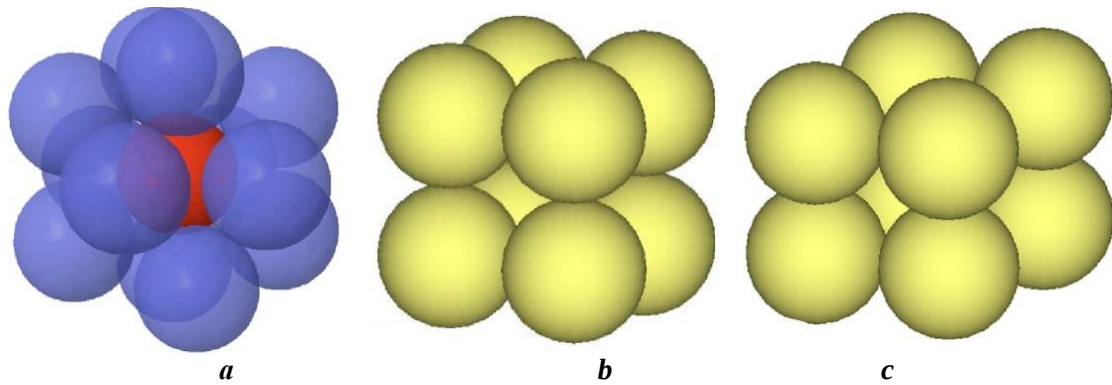


Fig. 2. Examples of packings of spheres of a single size in space

The seeds are modeled as a Lagrangian phase according to the following models: constant density, pressure gradient force, particle resistance force, spherical particles, single-component solid particles, and DEM particles. For example, rapeseed was selected as the seed, which, according to a review of the literature, has the following physical and mechanical properties: Poisson's ratio – 0.2; Young's modulus – 0.2 MPa; density – 700 kg/m³; coefficient of static friction – 0.58; normal coefficient of recovery – 0.5; tangential coefficient of recovery – 0.5; coefficient of rolling resistance – 0.3 [4–6].

Based on the results of numerical modeling, a visualization of the random packing of small-seeded crops in a container was obtained for various seed geometric dimensions (Fig. 3). For each numerical experiment, the packing porosity was calculated, and the data are summarized in Table 2.

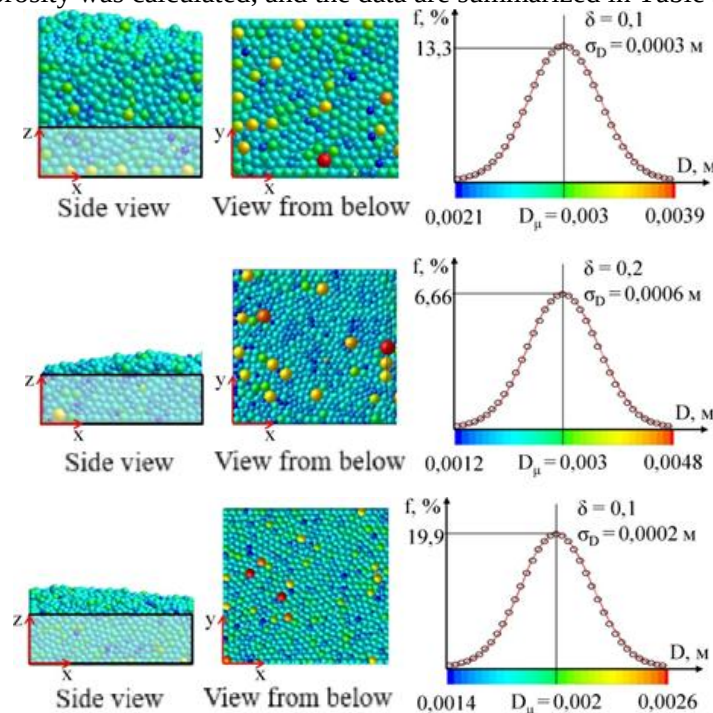


Fig. 3. Visualization of the random distribution of small-seeded crop seeds in a container

Using the Wolfram Cloud software package, we will present the data from the table as a second-order regression equation in encoded form:

$$\varphi = 0,592558 - 0,00560667 x_1 + 0,00171333 x_1^2 + 0,0246133 x_2 - 0,001995 x_1 x_2 - 0,011786 x_2^2. \quad (20)$$



Table 2.

Results of modeling the random distribution of seeds from small-seeded crops in a container

Effective seed diameter		Coefficient of variation in diameter		Laying density φ							
				Repetition					$\bar{\varphi}$	σ_{φ}	δ_{φ}
D_{μ} , mm	x_1	δ	x_2	1	2	3	4	5			
0,001	-1	0,1	-1	0,5628	0,5684	0,5552	0,5611	0,5594	0,5614	0,0048	0,0086
0,001	-1	0,2	0	0,5991	0,6024	0,5955	0,5970	0,5969	0,5982	0,0027	0,0045
0,001	-1	0,3	1	0,6164	0,6227	0,6112	0,6192	0,6130	0,6165	0,0046	0,0075
0,002	0	0,1	-1	0,5587	0,5611	0,5524	0,5585	0,5559	0,5573	0,0033	0,0059
0,002	0	0,2	0	0,5944	0,5977	0,5912	0,5930	0,5939	0,5940	0,0024	0,0040
0,002	0	0,3	1	0,6041	0,6063	0,5975	0,6048	0,6010	0,6027	0,0035	0,0058
0,003	1	0,1	-1	0,5532	0,5564	0,5496	0,5546	0,5522	0,5532	0,0026	0,0046
0,003	1	0,2	0	0,5884	0,5938	0,5842	0,5923	0,5857	0,5889	0,0041	0,0070
0,003	1	0,3	1	0,5995	0,6048	0,5952	0,6032	0,5990	0,6003	0,0038	0,0063

$\bar{\varphi}$ – average packing density; σ_{φ} – standard deviation of packing density; δ_{φ} – coefficient of variation in packing density.

The statistical analysis of the resulting equation (20) is presented in Table 3. Taking into account the number of degrees of freedom of the resulting matrix of results, the tabulated Student's t-statistic is $t(0.05;36) = 2.03$. By comparing the tabulated Student's t-statistic with the one calculated in Table 3, we can reject the insignificant coefficients of regression equation (20) and finally obtain:

$$\varphi = 0,592558 - 0,00560667 D_{\mu} + 0,0246133 \delta - 0,001995 D_{\mu} \delta - 0,0117867 \delta^2. \quad (21)$$

Table 3

Statistical analysis of equation (20)

Coefficient	Meaning	Student's t-test
a_{00}	0,592558	465,7
a_{10}	-0,00560667	-8,04488
a_{20}	0,0246133	35,3171
a_{12}	-0,001995	-2,33729
a_{11}	0,00171333	1,41937
a_{22}	-0,0117867	-9,76439

A graphical representation of equation (21) is shown in Fig. 4.

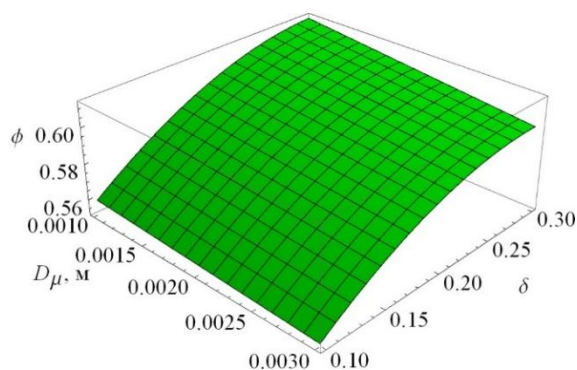
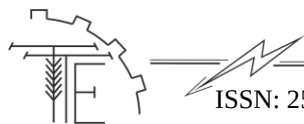


Fig. 4. Dependence of the random packing density φ of small-seeded crops in a container on the effective seed diameter D_{μ} and its coefficient δ



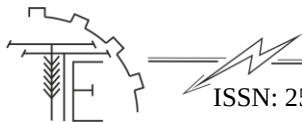
As the effective seed diameter D_{μ} decreases and the coefficient of variation δ increases, the random packing density φ of small, spherical seeds of small-seeded crops in a container increases. This is because seeds with a smaller diameter fill the voids between seeds with a larger diameter.

5. Conclusion

Based on the research findings, a mathematical model of the random packing of small-seeded crops in a container was developed, which made it possible to determine the regression equation for seed density as a function of the effective seed diameter and the coefficient of variation of that diameter. It was found that as the effective seed diameter D_{μ} decreases and the coefficient of variation δ increases, the density φ of the random packing of spherical small-seeded crops in a container increases. This is explained by the fact that seeds with a smaller diameter fill the voids between seeds with a larger diameter.

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МОДЕЛЮВАННЯ РУХУ ТА РОЗМІЩЕННЯ КУЛЬТУР З ДРІБНИМ НАСІННЯМ З ВИКОРИСТАННЯМ МЕТОДУ ДИСКРЕТНИХ ЕЛЕМЕНТІВ

Сучасні теоретичні дослідження механічних і технологічних процесів руху насіння під дією робочих органів технічного обладнання переважно базуються на аналітичних методах. Такі підходи призводять до формування складних систем диференціальних рівнянь із відповідними початковими та граничними умовами. Серед сучасних методів комп'ютерного моделювання руху гранульованих середовищ (насінневих сумішей) особливу увагу приділяють підходам, що ґрунтуються на дискретному представленні речовини, зокрема методу динаміки частинок і методу дискретних елементів (DEM).

Метод дискретних елементів є чисельним інженерним методом, який застосовується для моделювання руху та взаємодії великої кількості дискретних об'єктів, зазвичай твердих частинок. Метою даного дослідження є моделювання руху та розміщення дрібнонасінневих культур із використанням DEM у середовищі CAE-програми Simcenter STAR-CCM+.

У процесі моделювання в Simcenter STAR-CCM+ використано комплекс фізичних і математичних моделей, зокрема тривимірну постановку задачі, нестационарну неявну модель, модель однокомпонентного газу (повітря), модель ідеального газу, турбулентний рух повітря з використанням k - ϵ моделі турбулентності та рівнянь Рейнольдса–усереднених Нав'є–Стокса. Також враховано сегрегований потік, методи градієнтів і граничних умов, лагранжеву багатофазну модель, модель взаємодії фаз, метод дискретних елементів та дію гравітаційного поля.

За результатами дослідження було розроблено математичну модель випадкового ущільнення дрібнонасінневих культур у контейнері, що дало змогу отримати регресійне рівняння щільності укладання залежно від ефективного діаметра насіння та коефіцієнта його варіації. Встановлено, що зі зменшенням середнього ефективного діаметра насіння (D_{μ}) та збільшенням коефіцієнта варіації (δ) спостерігається зростання щільності випадкового укладання (ϕ) сферичних частинок. Це пояснюється тим, що дрібніші частинки заповнюють порожнини між більшими.

Ключові слова: насіння, чисельне моделювання, симуляція, рух, параметри, метод дискретних елементів.

Ф. 21. Рис. 4. Табл. 3. Літ. 20.

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